Divergent age patterns of under-5 mortality in south Asia and sub-Saharan Africa: a modelling study

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Summary

Background Understanding the age pattern of under-5 mortality is essential for identifying the most vulnerable ages and underlying causes of death, and for assessing why the decline in child mortality is slower in some countries and subnational areas than others. The aim of this study is to detect age patterns of under-5 mortality that are specific to low-income and middle-income countries (LMICs).

Methods In this modelling study, we used data from 277 Demographic and Health Surveys (DHSs), 58 Health and Demographic Surveillance Systems (HDSSs), two cohort studies, and two sample-registration systems. From these sources, we collected child date of birth and date of death (or age at death) from LMICs between 1966 and 2020. We computed 22 deaths rates from each survey with the following age breakdowns: 0, 7, 14, 21, and 28 days; 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 15, 18, and 21 months; and 2, 3, 4, and 5 years. We assessed how probabilities of dying estimated for the 22 age groups deviated from predictions generated by a vital registration model that reflects the historical mortality of 25 high-income countries.

Findings We calculated mortality rates of 81 LMICs between 1966 and 2020. In contrast with the other regions of the world, we found that under-5 mortality in south Asia and sub-Saharan Africa was characterised by increased mortality at both ends of the age range (ie, younger than 28 days and older than 6 months) at a given level of mortality. Observed mortality in these regions was up to 2 times higher than predicted by the vital registration model for the younger-than-28 days age bracket, and up to 10 times higher than predicted for the older-than-6 months age bracket. This age pattern of under-5 mortality is significant in 17 countries in south Asia and sub-Saharan Africa. Excess mortality in children older than 6 months without excess mortality in children younger than 28 days was found in 38 countries. In south Asia, results were consistent across data sources. In sub-Saharan Africa, excess mortality in children younger than 28 days was found mostly in DHSs; the majority of HDSSs did not show this excess mortality. We have attributed this difference in data sources mainly to omissions of early deaths in HDSSs.

Interpretation In countries with age patterns of under-5 mortality that diverge from predictions, evidence-based public health interventions should focus on the causes of excess of mortality; notably, the effect of fetal growth restriction and infectious diseases. The age pattern of under-5 mortality will be instrumental in assessing progress towards the decline of under-5 mortality and the Sustainable Development Goals.

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Introduction

The under-5 mortality rate is the probability that a newborn baby will die before reaching 5 years of age, and is a key mortality indicator routinely used for tracking progress in child health and social development in populations. As such, the under-5 mortality rate featured prominently in the UN Millennium Development Goals, and it remains an important component of the UN Sustainable Development Goals (SDGs). This indicator, however, conceals important information about the distribution of mortality within the 0–5-year age range. For guiding and evaluating health policies, it is important to examine how the risk of mortality varies within this range; not only by the standard breakdowns at 28 days of age (which indicates neonatal mortality, and which now features alongside under-5 mortality in the SDGs) and 1 year of age (which indicates infant mortality), but by weeks, months, and years of age throughout the first 5 years of life.

Using a fine degree of granularity in the study of age patterns of under-5 mortality is important for identifying ages at which children are particularly vulnerable, and thus how to target resources.[1,2] Childhood causes of death have different age signatures, and accurate detailed age patterns can help identify these causes.[3] Greater precision in empirical estimates of age-specific mortality is also necessary for modelling mortality in settings in which empirical data are not available.[4,5]

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Research in context

Evidence before this study

Age patterns of under-5 mortality characterised by higher-than-expected rates of mortality at ages 1–4 years, relative to mortality below the age of 1 year, have been observed in sub-Saharan Africa since the 1960s. Since then, existing knowledge has been summarised, and new evidence provided, about the global diversity of age patterns of under-5 mortality, including a study from 2019 that focused on sub-Saharan Africa. However, the existing evidence was mostly analysed in broad age brackets (0 years *vs* 1–4 years), and there have been concerns about the quality of data, meaning that age patterns of under-5 mortality that are specific to sub-Saharan Africa have not been fully described and rigorously validated. The 2019 study stressed the importance of examining under-5 mortality by month of age in sub-Saharan Africa in order to monitor the progress of the UN Sustainable Development Goals. However, this study did not aim to explore what makes the sub-Saharan age patterns of under-5 mortality different from the other world regions. We searched Google Scholar and Web of Science on Feb 15, 2022 for all articles published since inception, in English, French, and Spanish, using the search terms 'age pattern' and 'age distribution' combined with 'under-5 mortality' or 'child mortality'. We did not find other publications that have studied under-5 mortality by month of age in low-income and middle-income countries.

Added value of this study

This study identified and validated the existence of age patterns of under-5 mortality that are specific to South Asia and sub-Saharan Africa. These age patterns are characterised by high rates of mortality at both ends of the 0–5-year age range at a given level of under-5 mortality. These divergent age patterns were, to our knowledge, not previously identified. This finding was only made possible thanks to a variety of data and the availability of a new reference model based on detailed age groups (22 age groups between 0 years and 5 years, including weeks, months, trimesters, and years).

Implications of all the available evidence

The age pattern of under-5 mortality reflects the effect of underlying causes of death at different ages and allows us to identify excess and preventable mortality. This study sheds new light on the slower decline of child mortality in South Asia and sub-Saharan Africa compared with the rest of the world. Future progress in under-5 mortality in these two regions will require a multi-faceted policy approach that focuses on both neonatal causes of death and risk factors (in particular, foetal growth restriction and low birthweight) and causes of death after 6 months or 1 year of age (including malaria and other parasitic and infectious diseases). Evidence also shows that the age pattern of under-5 mortality will be instrumental in monitoring and understanding the effect of public policy that aims to reduce mortality in children younger than 5 years.

Case studies focusing on rural zones of The Gambia and Senegal between 1961 and 1983 identified an unusual age pattern of under-5 mortality.[3,6–8] A 1985 study[8] summarised these findings and showed that, in these populations, mortality was 2-to-3 times higher between the ages of 1 year and 5 years than would be expected on the basis of Brass's African Standard (an existing model for mortality in Africa). Supporting this finding, global studies of the relationship between infant and child mortality across a variety of data showed that in most sub-Saharan African countries, mortality after 1 year of age was higher than expected on the basis of a larger set of standard models.[9–11] However, a 2021 study[9] observed that, before 1 year of age, the relationship between neonatal and postneonatal mortality (age between 28 days and 1 year) was similar in sub-Saharan Africa and high-income countries. In contrast, a 2006 study[12] found that, in India, the ratio between neonatal and postnatal mortality was about one-third higher in the Indian National Family Health Surveys (ratio between 0·8 and 0·6 in the surveys of 1992–93 and 1998–99) than in historical data of England and Wales (ratio between 0·6 and 0·4 at the same levels of infant mortality). However, this deviation was not considered an indication of a different age pattern of mortality, but instead attributed to errors in the data.

In this paper, we show that detecting age patterns of under-5 mortality that are specific to low-income and middle-income countries (LMICs) is only possible when a fine degree of age granularity is available in the data sources and retained in the modelling approach. We used a model developed in 2022 that is based on high-quality historical and contemporary vital registration data from 25 high-income countries sourced from the Under-5 Mortality Database.[4] Using a multiplicity of retrospective and prospective data sources, we compared age patterns of under-5 mortality in LMICs with predictions from the vital registration model, which allowed us to assess the extent to which these age patterns diverge from those seen historically in high-income countries at similar rates of under-5 mortality.

Methods

Study design and data sources

In this modelling study, we used data from 277 standard Demographic and Health Surveys (DHSs). DHSs are the most comprehensive and publicly available source of data for the study of under-5 mortality in LMICs. We

For more on the **Demographic and Health Surveys** see http://www.dhsprogram.com

selected all the publicly available standard surveys with few exceptions; exclusion criteria are listed in the appendix (p 16). DHSs retrospectively collect data from reproductive-age women, including the date of birth and the age at death of their liveborn children (age at death is recorded by day for the first month of age and by month for the first 2 years of age, otherwise in years). We used the date of birth and the age at death from all records collected between 1986 and 2020 to estimate death rates by detailed age with a standard event–exposure method.[13] There were no missing data in DHS datasets and no exclusion criteria.

To validate the divergent age patterns found in DHSs, we searched for all publicly available alternative prospective data providing the same detailed age breakdowns over similar periods of time in a given country. The largest alternative source of data that we identified is the Health and Demographic Surveillance Systems (HDSSs), which is a population-based health and vital event registration system that is publicly available on the INDEPTH data repository. We also relied on bilateral agreements to access some additional non-public data, including case studies and sample-registration systems (appendix p 16).

As a result, the prospective data include 58 HDSSs, two cohort studies, and two sample-registration systems. HDSS and cohort studies include similar variables as DHSs (date of birth and date of death) and allowed a similar mortality estimation method. The sample-registration systems data required a different procedure (appendix p 16). Using each data source, we computed 22 deaths rates with the following age breakdowns: 0, 7, 14, 21, and 28 days; 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 15, 18, and 21 months; and 2, 3, 4, and 5 years. This study was approved by the Institutional Review Board of the University of Pennsylvania.

Vital registration model

The vital registration model summarises how under-5 mortality is distributed across the same 22 age groups in 25 high-income countries between 1920 and 2016. The model is based on two parameters: the under-5 mortality rate as an indicator of the overall level of mortality and a parameter, k, that determines the earliness or lateness of the age pattern of mortality relative to the model's average. Predictions can be obtained from any single mortality rate within the age range 0 years to 5 years (appendix p 2).[4]

Data analysis

For each data source from LMICs, we cumulated the death rates in order to obtain 22 probabilities of dying from birth to age x (represented by $q[x]$) or probabilities of dying from age z to age x (represented by $q[z, x]$). Cumulative probabilities of dying include standard mortality indicators such as the neonatal mortality and under-5 mortality rates.

Cumulative probabilities of dying were compared with those predicted by the vital registration model, controlling for a given level of under-5 mortality (appendix p 2). We used ratios between observed and predicted probabilities of dying to detect age patterns of under-5 mortality in LMICs that diverge from the vital registration model. For each DHSs and each age group, we calculated 95% uncertainty ratios using a standard jackknife variance estimation method.[14]

To quantify how different age ranges contributed separately to deviations from the vital registration model's predictions, we used the probability of dying between age 4 months and 6 months instead of the under-5 mortality rate as a predictor. Using the probability of dying between age 4 and 6 months as a predictor has the advantage of bringing out the role of underlying causes of death: perinatal conditions and congenital anomalies before 28 days of age and infectious diseases after 6 months of age. Another advantage of using the probability of dying between age 4 months and 6 months is the robustness to potential omissions of early deaths, an issue of concern in data from LMICs. Therefore, this predictor enables us to better understand whether divergent age patterns found are real or biased by data errors. By controlling for the probability of dying between 4 months and 6 months of age, we are able to compare age patterns across different geographical areas and to verify the existence of divergent age patterns in a given country.

See Online for appendix

For more on the **INDEPTH data repository** see https://www.indepth-ishare.org

Role of the funding source

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

Results

We analysed 277 DHSs across 80 countries, covering the period 1976–2020. We classified the DHSs results into five categories depending on the ratio of observed to predicted cumulative probabilities of dying between the ages of 0 years and 5 years, and assessed the degree of overlap or deviation from the range of predictions allowed by the model (figure 1). A representation of the corresponding cumulative probabilities of dying ($q[x]$) used to compute the ratios is provided in the appendix (p 2). Three categories correspond to age patterns that fall within the scope of the vital registration model, and two categories correspond to age patterns that diverge from it. The comparison of the blue and red areas in figure 1 shows the extent to which age patterns of under-5 mortality observed by DHSs correspond to, or deviate from, those observed in the vital registration data, which represent under-5 mortality in high-income countries historically. Results for each individual survey are in the appendix (p 21).

Surveys for which ratios are more than 1 (37 [13%] of 277 surveys; appendix p 6) display an early age pattern

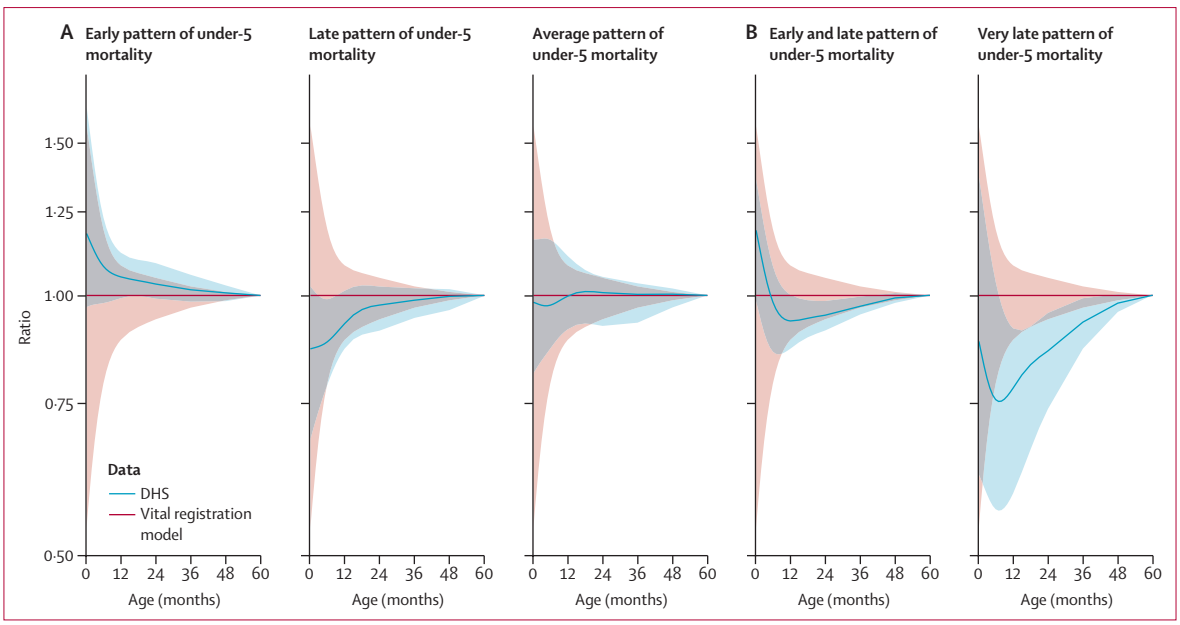

Figure 1: **Ratio of observed to predicted cumulative probabilities of dying from birth to age *x* (*q*[*x*]), controlling for the level of the under-5 mortality rate, including DHS age patterns that are within the range predicted by the vital registration model (A) and DHS age patterns that diverge from the vital registration model (B)**

Ratios were computed by dividing observed by predicted probabilities of dying from birth to age *x* values for 22 age groups between age 0 years and age 5 years. Ratios are presented on a log scale. The blue area covers the range of DHS estimates. The blue line represents the mean ratios across DHS. The red area represents the range of predictions of the vital registration model. Curves were smoothed with splines. The unsmoothed curves and spread of the raw data are shown in the appendix (p 4). DHS=Demographic and Health Surveys.

of under-5 mortality, which is suggestive of a higher rate of mortality before 28 days of age in the DHS data than the average age pattern of the vital registration model at a given level of under-5 mortality. Surveys with ratios of less than 1 (59 [21%] of 277 surveys) captured a late age pattern, which suggests a higher rate of mortality after 28 days in the DHS data than the average age pattern of the vital registration model (appendix p 2). Nevertheless, the ratios for the early and late categories remain within the range of predictions of the model. We classified the average category as surveys that also remain within the limits of the model but that have several crossovers more than 1 or less than 1 (35 [13%] of 277 surveys). These crossovers reflect random variation around the model average. Populations that fall into these first three categories are well represented by the vital registration model.

We then identified 144 surveys (52%) with an age pattern of under-5 mortality that clearly falls outside the range of predictions of the model, indicating divergent age patterns. In the fourth category, early and late, we identified 22 (8%) of 277 surveys that remain within the limits of the model but that have a single crossover. These surveys have ratios more than 1 at the younger-than-6 months age range and ratios less than 1 at the older-than-6 months age range. This crossover reflects a higher concentration of mortality than predicted at both ends of the age range between 0 years and 5 years (appendix p 2). The fifth category includes 120 (43%) of 277 surveys with a very late age pattern that falls outside the range of values predicted by the model. This category is potentially an amplified version of the early and late category in which the high mortality after 6 months of age tends to conceal excess mortality at younger ages.

These categories of age patterns of under-5 mortality are clustered regionally (figure 2). The large majority (138 [97%] of 142 surveys) of divergent age patterns (ie, early and late and very late categories) are in south Asia and sub-Saharan Africa (appendix p 6). South Asian divergent surveys (12 [52%] of 23) are mostly comprised of the early and late divergence (10 [83%] of 12 surveys). These divergent patterns are observed in three countries: Bangladesh, India, and Nepal (appendix p 21). Sub-Saharan African divergence (126 [89%] of 142 surveys) mainly comprises very late divergence (114 [90%] of 126 surveys). However, this finding is not the case for southern Africa, for which only two (22%) of nine surveys captured a divergent age pattern. The other world regions have patterns that are within the range of prediction of the vital registration model.

Regional clustering has remained stable over time, but some divergent age patterns have converged towards the age patterns represented by the vital registration model. In south Asia, countries with an early and late age pattern have transitioned towards the early pattern over time, especially after 2012 (appendix p 21). In sub-Saharan Africa, the change in age patterns has been slower than in south Asia; however, few

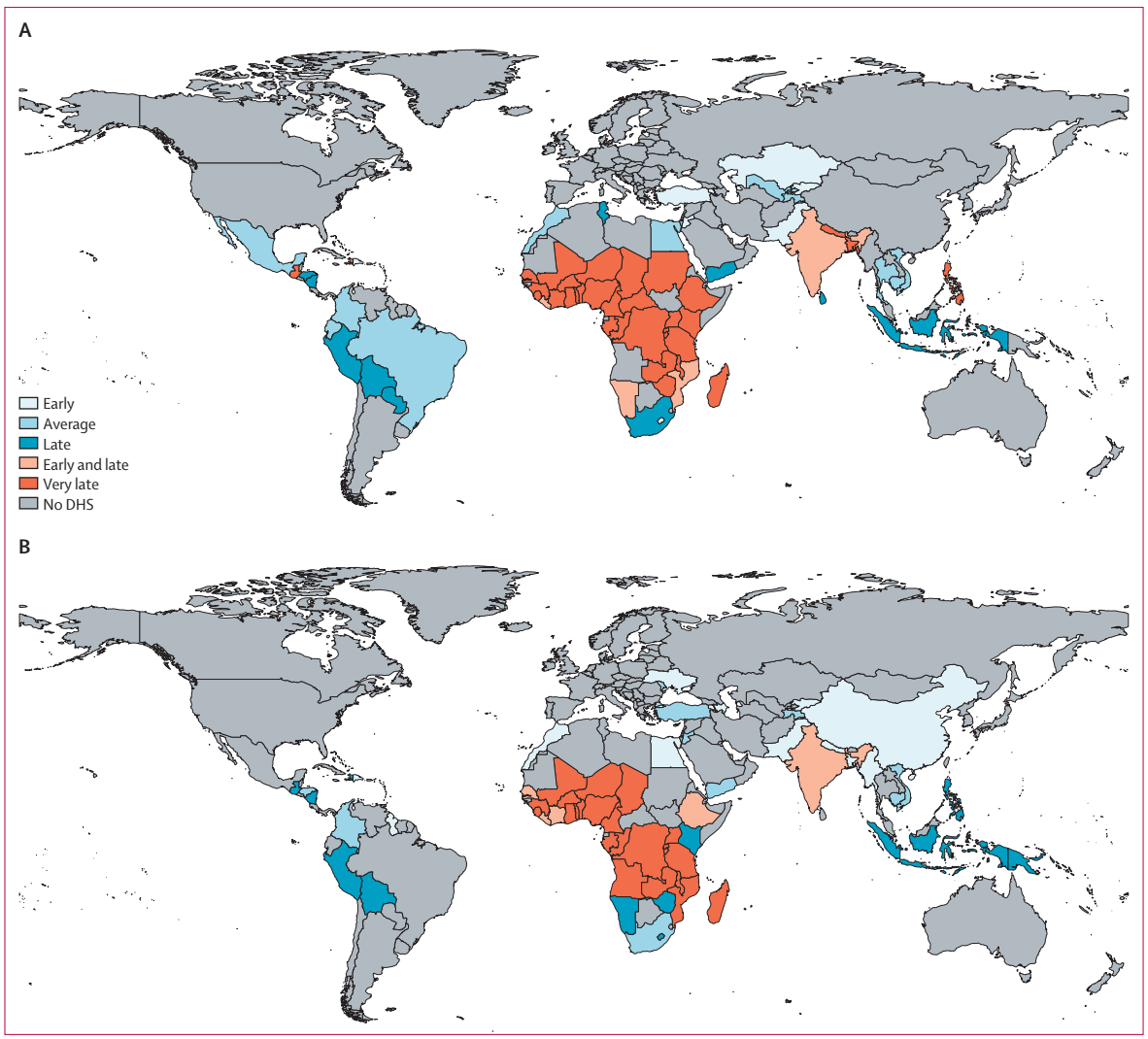

Figure 2: **Clustering of categories of age patterns of under-5 mortality by region, from the first collected DHS in a given country (average year of collection 1993; A) to the last collected DHS in a given country (average year of collection 2014; B)**
For countries with only one survey, the result was shown in A if the data were collected before 2000 and in B if after. As an exception, the data for China come from the National Maternal and Child Health Surveillance System (2001–15; appendix p 5). DHS=Demographic and Health Surveys.

countries, including Kenya, Namibia, and Zimbabwe, transitioned from the very late to the late category after 2000 (appendix p 21).

We compared DHS data from south Asia with HDSS data from Matlab, Bangladesh, and sample-registration systems data from India across similar periods, controlling for the level of mortality between 4 and 6 months. Consistently, the three data sources depict the same clear U-shaped pattern reflecting excess mortality at both early and late ages relative to the model prediction; in other words, higher-than-predicted mortality at both ends of the 0–5 year age range (up to 2 times higher before 28 days of age and more than 5 times higher after 2 years of age; figure 3). We also provide the mean values of the deviation ratios and supply additional results for three other sites (HDSS data from Chakaria, Bangladesh, and two case studies collected in Tamil Nadu, India, and Sarlahi, Nepal; appendix p 8). It is notable that the ratios for neonatal mortality are consistent across data sources, at about 2, despite the variety of geographical areas and time periods represented in the study (figure 3; appendix p 8). This finding is particularly striking for the case of Matlab, where data have been collected since 1966. In contrast, the different sources of data support the decreased ratio of observed to predicted mortality in children aged between 6 months and 5 years. However, the regional estimates from the Indian DHS (2005–06) and sample-registration systems (2004–13) show that in some regions excess mortality after 1 year can remain high (particularly in the central and eastern regions; appendix pp 8, 11).

In contrast, the DHS and HDSS findings from sub-Saharan Africa are not consistent (figure 3; appendix p 9).

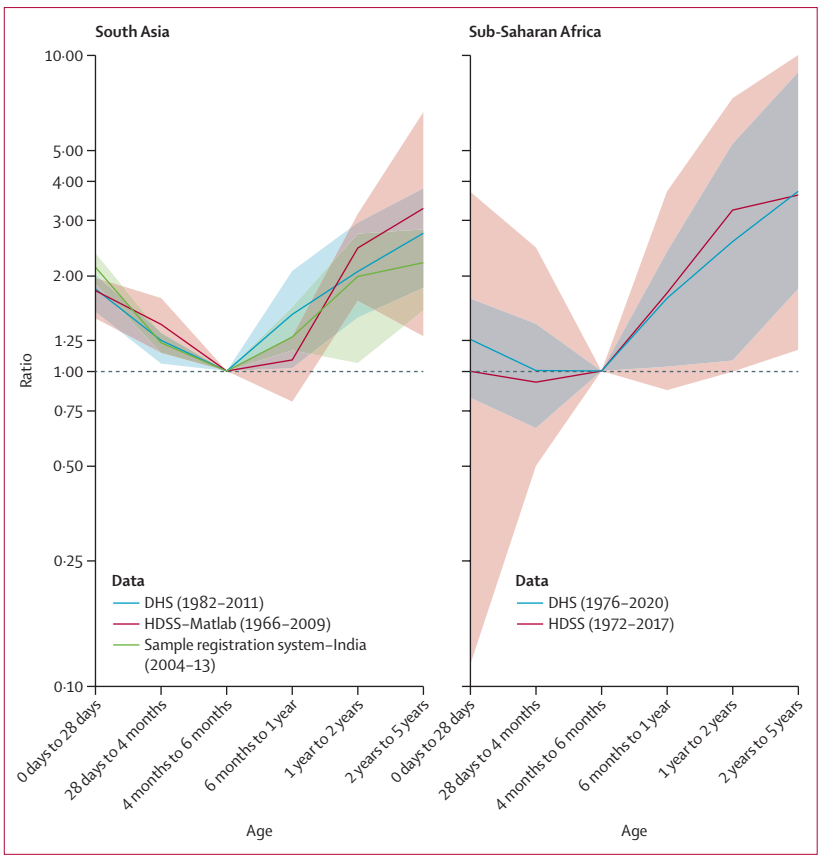

Figure 3: **Ratio of observed versus predicted mortality using DHS data with divergent age patterns and alternative sources of data, by age group and controlling for the level of mortality between 4 and 6 months**
Ratios were computed by dividing observed by predicted probabilities of dying between ages *z* and *x* for six age groups between age 0 years and age 5 years. Ratios are presented on a log scale. The shaded areas cover the range of estimates. The lines represent the mean ratios across estimates. The spread of the raw data is shown in the appendix (p 7). Alternative sources of data include HDSS and sample registration system. DHS=Demographic and Health Surveys. HDSS=Health and Demographic Surveillance Systems.

Both sources of data support the existence of a strong excess mortality after 2 years, up to 10 times higher than predicted by the vital registration model (figure 3). However, we found poor consistency between DHS and HDSS data for neonatal mortality; at a given level of mortality between 4 months and 6 months of age, the HDSS estimates of neonatal mortality are generally lower than the DHS estimates (1·00 average ratio for HDSSs versus 1·26 for DHSs). This finding is observed in most countries separately, with very low ratios in some cases (approximately 0·50 on average in Burkina Faso, Côte d'Ivoire, and Mozambique [appendix p 9]).

Further comparisons across all DHSs (appendix p 10) in south Asia and sub-Saharan Africa show that excesses of mortality before 28 days and after 6 months of age, and particularly from 1 year of age, are unique in their magnitude. This finding holds even when examining these two age groups separately (eg, in the comparison of divergent patterns in south Asia with early patterns in the other regions, there were average ratios of 1·82 *vs* 1·31 before 28 days of age, and 2·73 *vs* 0·96 after 2 years of age; appendix p 10). In sub-Saharan Africa, the excess mortality at neonatal ages tends to be concentrated in west Africa (average ratio of 1·28 before 28 days of age; appendix p 10). Results for individual surveys show that the excess mortality at both ends of the 0–5-year age range is significantly higher than 1 in most south Asian and west African countries, but also in Ethiopia (appendix p 12). Excess mortality after 2 years of age is significant in almost all sub-Saharan countries (appendix p 12).

Discussion

To our knowledge, studies of under-5 mortality have mostly focused on early versus late age patterns; that is, higher concentration of mortality either before or after 28 days (or 1 year) of age relative to a reference age pattern. Using detailed age groups, we showed that there were excesses of mortality at both ends of the 0–5-year age range; namely an excess of mortality before 28 days of age and after 6 months of age. Populations with these age patterns of under-5 mortality are primarily located in south Asia and sub-Saharan Africa. These results were found consistently across data sources except for the excess mortality before 28 days of age in sub-Saharan Africa. In contrast with DHSs, a majority of HDSSs did not show excess of mortality before 28 days of age. Later, we suggest that this difference is probably due to omissions of early deaths in HDSSs. Improved understanding and appreciation of this pattern of under-5 mortality will be instrumental for designing interventions to reduce mortality rates.

With the decline in mortality, deaths are increasingly concentrated in the first weeks of life,[15] and the SDGs aim to reduce neonatal mortality to 12 deaths or fewer per 1000 livebirths in all countries by 2030. In south Asia and sub-Saharan Africa, we found that, along with the decline of neonatal mortality, the excess mortality at age 0–28 months has remained stable. Therefore, this specific age pattern of mortality at early ages could explain why south Asia and sub-Saharan Africa have neonatal mortality rates twice or thrice higher than in the other regions of the world.

Neonatal deaths are mainly related to preterm birth, intrapartum events, congenital malformation, and respiratory infection.[16] However, the usual cause-specific mortality fractions do not explain the concentration of deaths during the first weeks of life. In south Asia, where an early age pattern of under-5 mortality was found to be the highest, none of the main causes of neonatal death have been more prominent than in the other world regions. In contrast, the factor that stands out in this region is the exceptionally high prevalence of fetal growth restriction, measured as the prevalence of small for gestational age (defined as birthweight in the lowest 10th percentile of a reference population for a given gestational age and sex), which in 2010 was 45% in south Asia and 24% in sub-Saharan Africa.[17] However, in most sub-Saharan countries in which we found high

concentration of neonatal mortality, particularly in west Africa, the prevalence of small for gestational age was above average and as high as 36% (appendix p 15). Alone or combined with prematurity, previous studies found that small for gestational age was associated with a 2-to-15 times increased risk of neonatal death in populations from south Asia and Africa.[17–20] Access to, and quality of, health care are also important factors that contribute to the specific excess of neonatal mortality in these two regions.[21]

At the other end of the 0–5-year age range, excess mortality from 6 months of age reflects the large effect of infectious and parasitic diseases. In a case study of the village of Ngayokhem in rural Senegal (1963–81), two age periods of high risks were identified.[3] The first period was from 6 months to 17 months and was associated with the loss of the maternal passive immunity; mortality during this period was strongly associated with malaria. Results from 2001 to 2005 showed that this age pattern of malaria mortality was similar across endemic areas of Africa.[22] The second period (18 months to 60 months) was marked by the age-specific rise of diarrhoeal diseases and measles due to the weaning of children. In 2019, parasitic and infectious diseases including malaria, diarrhoeal diseases, measles, and lower respiratory infections were causing 73% of deaths occurring between 1 month and 5 years of age in west and central Africa, compared with less than 9% in children of the same age in high-income countries.[16,23] In east and southern Africa, the percentage of deaths generated by these causes was 52% in 2019, and 4% of deaths were attributed to HIV/AIDS.

In south Asia, the decline of parasitic and infectious diseases (mainly diarrhoea and respiratory infections) probably explains the convergence of the age patterns after 6 months of age towards the age patterns of the other world regions. However, at the subnational level, areas such as the central and east regions of India have maintained strong divergent age patterns of under-5 mortality; pneumonia and diarrhoea are still the leading causes of under-5 mortality in these two regions.[24,25] With the decline in mortality, it is expected that preventable mortality will be increasingly concentrated in subnational areas and hotspots.[26] The age patterns of under-5 mortality, as shown by our study, are important for identifying geographical areas that are susceptible to high, preventable mortality rates.

One limitation of our study is the potential errors affecting the data. Two principal sources of errors can affect the variables in this study and potentially bias the age pattern of under-5 mortality: displacements and omissions of deaths.[27] First, the displacement of deaths (through the misreporting of the age at, or date of, death) is reflected by digit preference or age heaping. Transference of deaths across the 28th day of life can either underestimate or overestimate neonatal mortality.[28,29] In DHSs, age heaping can potentially occur at 3, 6, 9, 12, 18, or 24 months of age and could have biased our estimates. However, the triangulation of data collected retrospectively (ie, based on the mother's recall of their entire reproductive history) as in the DHSs, and prospectively (ie, collecting vital events longitudinally in households over recurrent periods of time) as in the HDSSs, means that some part of these potential displacements can be controlled for: prospective data reduces the recall period of the respondent, and so the risk of event displacement is substantially reduced. For example, in contrast with retrospective survey data collected in the same area, the HDSS data from Matlab in Bangladesh (with monthly visits) and Dabat in Ethiopia (with visits twice a year) did not show evidence of age heaping.[28] Nonetheless, in both countries, we found an excess of mortality on both ends of the 0–5-year age range across all sources of data.

Omissions of deaths can also affect the age pattern of under-5 mortality. In particular, omissions of early deaths are a major concern in all sources of data.[9] However, these omissions would make our results conservative, underestimating the true amount of excess mortality before 28 days of age. Evidence of such omissions in the HDSSs of sub-Saharan Africa is shown by the lower-than-predicted rate of neonatal mortality, and the divergence with the DHSs that display excess mortality at this age. Although lower-than-predicted mortality could be associated with the effect of health interventions from which the HDSSs have benefited,[30] the absolute rate of neonatal mortality points to the quality of data. In 25% of the HDSSs from sub-Saharan Africa, the rates of neonatal mortality are as low as 2–13 deaths per 1000 live births. These low mortality rates are implausible given that over the considered period (1995–2020), neonatal mortality declined from 44 to 27 deaths per 1000 livebirths in sub-Saharan Africa, from five to two deaths per 1000 livebirths in west Europe, and from 34 to 17 deaths per 1000 livebirths at the global scale.[31] Although once recorded in HDSSs a birth will probably not be omitted over the following visits, these low rates of neonatal mortality corroborate previous evidence that a pregnancy followed by an early death can easily go unnoticed.[9] Therefore, we think that the age pattern of under-5 mortality is also an important tool to identify data quality issues. Despite these limitations associated with some of the HDSSs, the triangulation of retrospective and prospective data provides key evidence that the divergent age patterns that we have identified are true rather than data artifacts.

Another limitation of our study is the sparsity of direct evidence linking the age patterns we observe to underlying explanations. Even though we provide possible explanations on the basis of existing literature, further research is needed to better understand the factors causing the divergent age patterns that we identified, including proper quantification of the burden of diseases and the risk factors of mortality in narrow age

groups between 0 years and 5 years. Some local sites with divergent age patterns such as the HDSS of Matlab have benefited from evidence-based public health interventions aiming to reduce under-5 mortality.[32] In these sites, the age pattern of under-5 mortality should be used to track progress and understand the effect of these interventions. For example, further work should investigate how maternal nutrition interventions affect the excess mortality before 28 days of age. Thereby, the age pattern of under-5 mortality could potentially become an indicator of the effect of such interventions when specific data such as birthweight are not available.

Availability of mortality estimates by detailed age between age 0 years and age 5 years is essential for interventions aiming to improve child health. In situations in which data are scarce, mortality estimates by detailed age can be inferred on the basis of models representing age patterns of under-5 mortality. Therefore, the divergent age patterns that we identified in south Asia and sub-Saharan Africa call for an important update of existing models, which tend to be heavily based on data from high-income countries.

Contributors

PG, JK, LL, GP, GR, and MG conceptualised the project. AV, JRP, and MG designed the study. AV, JRP, HE-S, DJE, BL, SS, and FV prepared the data for analysis. AV and MG directly accessed and verified the underlying data reported in the manuscript. AV and JRP developed the software. AV and MG did the analysis and wrote the manuscript. All authors reviewed results, discussed interpretations, and contributed to the revision of the manuscript. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Declaration of interests

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Data sharing

The majority of data used in this study are publicly available (appendix p 16). For the additional data that are not publicly available, the authors will share the estimated aggregated death rates on demand. An R package to apply the model used in the study is available on a GitHub repository (https://github.com/verhulsta/logquad5q0).

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