National, regional, and global sex ratios of infant, child, and under-5 mortality and identification of countries with outlying ratios: a systematic assessment

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Summary

Background Under natural circumstances, the sex ratio of male to female mortality up to the age of 5 years is greater than one but sex discrimination can change sex ratios. The estimation of mortality by sex and identification of countries with outlying levels is challenging because of issues with data availability and quality, and because sex ratios might vary naturally based on differences in mortality levels and associated cause of death distributions.

Methods For this systematic analysis, we estimated country-specific mortality sex ratios for infants, children aged 1–4 years, and children under the age of 5 years (under 5s) for all countries from 1990 (or the earliest year of data collection) to 2012 using a Bayesian hierarchical time series model, accounting for various data quality issues and assessing the uncertainty in sex ratios. We simultaneously estimated the global relation between sex ratios and mortality levels and constructed estimates of expected and excess female mortality rates to identify countries with outlying sex ratios.

Findings Global sex ratios in 2012 were 1·13 (90% uncertainty interval 1·12–1·15) for infants, 0·95 (0·93–0·97) for children aged 1–5 years, and 1·08 (1·07–1·09) for under 5s, an increase since 1990 of 0·01 (–0·01 to 0·02) for infants, 0·04 (0·02 to 0·06) for children aged 1–4 years, and 0·02 (0·01 to 0·04) for under 5s. Levels and trends varied across regions and countries. Sex ratios were lowest in southern Asia for 1990 and 2012 for all age groups. Highest sex ratios were seen in developed regions and the Caucasus and central Asia region. Decreasing mortality was associated with increasing sex ratios, except at very low infant mortality, where sex ratios decreased with total mortality. For 2012, we identified 15 countries with outlying under-5 sex ratios, of which ten countries had female mortality higher than expected (Afghanistan, Bahrain, Bangladesh, China, Egypt, India, Iran, Jordan, Nepal, and Pakistan). Although excess female mortality has decreased since 1990 for the vast majority of countries with outlying sex ratios, the ratios of estimated to expected female mortality did not change substantially for most countries, and worsened for India.

Interpretation Important differences exist between boys and girls with respect to survival up to the age of 5 years. Survival chances tend to improve more rapidly for girls compared with boys as total mortality decreases, with a reversal of this trend at very low infant mortality. For many countries, sex ratios follow this pattern but important exceptions exist. An explanation needs to be sought for selected countries with outlying sex ratios and action should be undertaken if sex discrimination is present.

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Introduction

Girls tend to have advantages over boys with respect to survival up to age 5 years, resulting in a mortality sex ratio, defined as the ratio of male to female mortality, greater than one.[1] This survival advantage for girls tends to increase as total (both sexes combined) mortality levels decrease because of changes in the associated cause of death distributions, which are generally more favourable for girls' survival at lower mortality levels.[2–4] However, additional factors that cause unusually high or low sex ratios might be at play, such as disadvantaging treatment of girls compared with boys, as reported in various, mostly Asian countries.[5–20] Pinpointing countries with unusually low or high sex ratios, where differential treatment is possibly at play, is of key importance for monitoring sex discrimination.

The monitoring of sex differences in mortality in children younger than 5 years (hereon in referred to as under-5 mortality) is challenging because of issues with data availability and quality, and because country-specific sex differentials tend to change over time as total mortality levels decrease. Although estimates of mortality sex ratios for all countries have been reported in previous analyses,[21–23] these studies did not account for data quality issues such as standard errors in the estimated sex ratios (which can be substantial), they did not produce or publish uncertainty intervals, they did not assess country-specific data-driven time trends for all countries, and the extent to which the estimates were validated is not clear.

Moreover, these studies did not provide sufficient insight into countries with outlying sex ratios, where sex discrimination might be present. The pinpointing of countries with outlying sex ratios is complicated because of difficulties in defining a standard expected sex ratio in the absence of sex discrimination—sex ratios tend to vary with total mortality and the associated cause of death distribution. To overcome this difficulty, some studies assessed female disadvantage on the basis of the relation between sex ratios and either male or total mortality using data from selected countries with high-quality vital registration data,[24–26] but we know of no study that used all globally available data to estimate the relation between sex ratios and total mortality in a systematic fashion to pinpoint countries with outlying sex ratios.

For this systematic assessment, we estimated levels of and trends in sex ratios for rates of infant mortality (IMR; 0–1 year), child mortality (CMR; 1–4 years), and under-5 mortality (U5MR; 0–4 years) for 195 countries from 1990 (or earlier, depending on data availability) to 2012. Additionally, we assessed the global relation between sex ratios and total mortality rates and used this relationship to estimate expected and excess female mortality rates, to pinpoint countries with outlying sex ratios.

See Online for appendix

Methods

Data sources

The data used in this study were observed sex ratios for IMR, CMR, and U5MR from vital registration systems, sample registration and surveillance systems, surveys, and censuses. We used vital registration and sample registration and surveillance data to obtain sex ratios for IMR and CMR through standard life-table methods. For data from full birth histories collected in demographic and health surveys, world fertility surveys, and selected surveys from the Pan-Arab Programme on Family Health, sex ratios for IMR were calculated for periods of varying optimised lengths, according to the method by Pedersen and Liu[27] to capture shorter-term changes for country-years with sufficient information. For sex ratios of CMR, we used 5-year estimates because the sampling errors associated with the estimates tend to be too large to obtain informative estimates for periods shorter than 5 years. For all sources, we used sex ratios for the U5MR only if sex ratios for IMR and CMR were not available.

For surveys and censuses in which only summary birth histories were obtained, we calculated sex-specific estimates of U5MR using the Brass method,[28] either from microdata or from published tabulations of number of children ever born and children living (we chose the U5MR because it is more robust to the choice of model life table than the IMR, which can vary substantially according to the model selected). When microdata or tabulations were not available, we used estimates from published surveys or census reports.

Inclusion criteria for data series from censuses and surveys and vital registration and sample registration and surveillance observation years followed the inclusion criteria used for total U5MR estimation used by the UN IGME.[28] Additionally, extreme observations, with sex ratios greater than 5 or smaller than 0·2, were removed (less than 1% of the largest and smallest observations were removed because of this criterion; the excluded observations were mainly from vital registration systems in small countries). The appendix shows an overview of all data sources used, broken down by country.

Statistical analysis

We developed a statistical model to estimate trends in sex ratios for IMR, CMR, and U5MR over time for each country. Details on model specification, implementation, and validation are given in detail in the appendix. Briefly, for infants, we used a flexible regression model (penalised B-splines regression) to represent the global relation between sex ratios and total mortality rates. We modelled country-specific sex ratios using the product of the expected sex ratio (based on the regression model and the infant mortality rate in the country-year) and a country-specific multiplier, which represents the relative advantage or disadvantage of girls to boys compared with other countries at similar total mortality rates. We modelled these multipliers with a flexible time series model in which they were assumed to fluctuate around

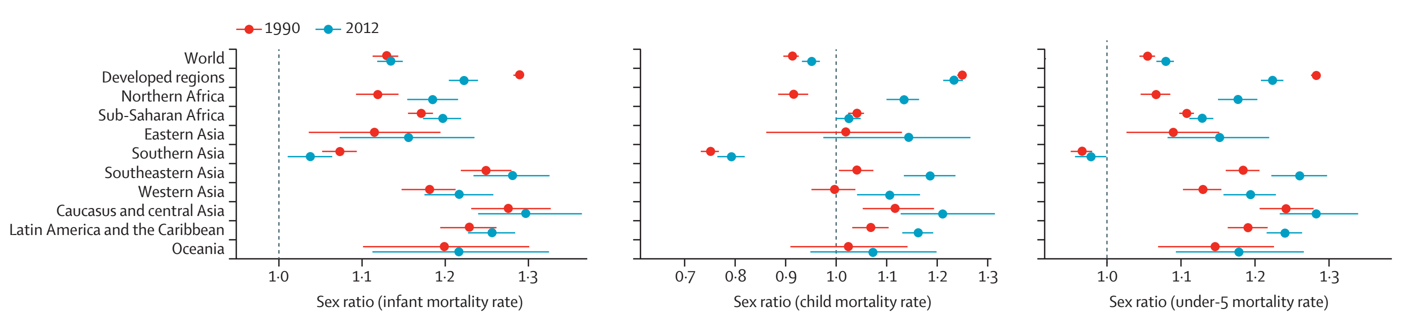

Figure 1: **Sex ratios by age group, year, and regions**
Error bars are 90% uncertainty intervals.

country-specific average levels. We estimated these country-specific average levels using a Bayesian hierarchical model, allowing for outlying countries where greater male or female advantages might be seen. By simultaneously estimating the global regression model fit and the country-specific sex ratios, country-specific information informs the global relation and, vice versa, the global relation informs the country-specific estimates.

We constructed country-specific estimates for the sex ratio for CMR and estimated the global relation between total child mortality and its sex ratio in a similar fashion. For each country-year, we derived the sex ratios for the U5MR and the global relation between total U5MR and its sex ratio from the estimated sex ratios for IMR and CMR.

Sex ratio estimates were based on all available data in a country. The data quality model incorporated stochastic and sampling variance (caused by a small number of observed livebirths and deaths or by small samples from the overall population) and non-sampling error variance (which might differ across different source types). By including both variance terms, observations that were deemed to be less informative of true sex ratios were down-weighted compared with more informative observations. We used t distributions

	Sex ratio			Ratio of estimated-to-expected female mortality rate		
	1990	2012	Change (1990–2012)	1990	2012	Change (1990–2012)
Infant mortality rate						
World*†	1·13 (1·11 to 1·14)	1·13 (1·12 to 1·15)	0·01 (–0·01 to 0·02)	1·05 (1·03 to 1·06)‡	1·06 (1·04 to 1·07)‡	0·01 (–0·01 to 0·03)
Developed regions	1·29 (1·28 to 1·29)	1·22 (1·20 to 1·24)	–0·07 (–0·08 to –0·05)§	0·97 (0·96 to 0·98)‡	0·99 (0·98 to 1·01)	0·03 (0·01 to 0·04)§
Northern Africa*†	1·12 (1·09 to 1·14)	1·18 (1·15 to 1·22)	0·07 (0·03 to 0·10)§	1·07 (1·05 to 1·10)‡	1·06 (1·03 to 1·09)‡	–0·01 (–0·05 to 0·02)
Sub-Saharan Africa	1·17 (1·16 to 1·19)	1·20 (1·17 to 1·22)	0·03 (0·00 to 0·05)§	1·00 (0·98 to 1·01)	1·00 (0·98 to 1·02)	0·00 (–0·02 to 0·02)
Eastern Asia*	1·11 (1·04 to 1·19)	1·15 (1·07 to 1·24)	0·04 (–0·03 to 0·12)	1·10 (1·02 to 1·18)‡	1·08 (1·01 to 1·16)‡	–0·02 (–0·09 to 0·06)
Southern Asia*†	1·07 (1·05 to 1·09)	1·04 (1·01 to 1·06)	–0·04 (–0·07 to 0·00)§	1·10 (1·07 to 1·12)‡	1·17 (1·14 to 1·21)‡	0·08 (0·04 to 0·12)§
South-eastern Asia*	1·25 (1·22 to 1·28)	1·28 (1·23 to 1·33)	0·03 (–0·01 to 0·08)	0·96 (0·93 to 0·98)‡	0·97 (0·94 to 1·01)	0·01 (–0·02 to 0·05)
Western Asia	1·18 (1·15 to 1·21)	1·22 (1·18 to 1·26)	0·04 (–0·01 to 0·08)	1·02 (1·00 to 1·05)	1·02 (0·98 to 1·06)	0·00 (–0·04 to 0·03)
Caucasus and central Asia*†	1·27 (1·23 to 1·33)	1·30 (1·24 to 1·36)	0·02 (–0·03 to 0·07)	0·93 (0·90 to 0·97)	0·94 (0·89 to 0·99)‡	0·01 (–0·03 to 0·05)
Latin America and the Caribbean	1·23 (1·19 to 1·26)	1·26 (1·23 to 1·28)	0·03 (0·00 to 0·06)	0·99 (0·96 to 1·02)	0·99 (0·97 to 1·02)	0·01 (–0·02 to 0·03)
Oceania	1·20 (1·10 to 1·30)	1·22 (1·11 to 1·32)	0·02 (–0·06 to 0·09)	1·00 (0·92 to 1·09)	1·00 (0·91 to 1·09)	0·00 (–0·07 to 0·07)
Child mortality rate						
World*	0·91 (0·90 to 0·93)	0·95 (0·93 to 0·97)	0·04 (0·02 to 0·06)§	1·11 (1·09 to 1·13)‡	1·07 (1·05 to 1·09)‡	–0·04 (–0·06 to –0·01)§
High-income regions	1·25 (1·24 to 1·26)	1·23 (1·21 to 1·25)	–0·02 (–0·04 to 0·00)	0·97 (0·95 to 0·98)‡	0·99 (0·97 to 1·01)	0·02 (0·00 to 0·04)§
Northern Africa*	0·91 (0·89 to 0·94)	1·13 (1·10 to 1·16)	0·22 (0·18 to 0·26)§	1·14 (1·10 to 1·19)‡	1·07 (1·04 to 1·10)‡	–0·07 (–0·12 to –0·03)§
Sub-Saharan Africa*	1·04 (1·02 to 1·06)	1·02 (1·00 to 1·05)	–0·02 (–0·04 to 0·01)	0·98 (0·96 to 0·99)‡	0·98 (0·96 to 1·01)	0·01 (–0·01 to 0·03)
Eastern Asia	1·02 (0·86 to 1·13)	1·14 (0·97 to 1·27)	0·12 (0·05 to 0·20)§	1·07 (0·96 to 1·28)	1·06 (0·95 to 1·24)	–0·01 (–0·10 to 0·06)
Southern Asia*†	0·75 (0·73 to 0·77)	0·79 (0·76 to 0·82)	0·04 (0·01 to 0·07)§	1·34 (1·30 to 1·37)‡	1·38 (1·33 to 1·43)‡	0·04 (–0·02 to 0·10)
South-eastern Asia	1·04 (1·01 to 1·07)	1·18 (1·13 to 1·24)	0·15 (0·10 to 0·19)§	0·99 (0·95 to 1·02)	0·98 (0·93 to 1·02)	–0·01 (–0·05 to 0·03)
Western Asia	0·99 (0·95 to 1·04)	1·10 (1·04 to 1·17)	0·11 (0·05 to 0·17)§	1·05 (1·00 to 1·10)‡	1·03 (0·97 to 1·09)	–0·02 (–0·08 to 0·04)
Caucasus and central Asia	1·11 (1·05 to 1·19)	1·21 (1·13 to 1·31)	0·10 (0·03 to 0·16)§	0·95 (0·88 to 1·01)	0·94 (0·85 to 1·01)	–0·01 (–0·08 to 0·05)
Latin America and the Caribbean	1·07 (1·03 to 1·10)	1·16 (1·13 to 1·19)	0·09 (0·06 to 0·13)§	1·01 (0·97 to 1·05)	1·01 (0·98 to 1·03)	0·00 (–0·04 to 0·03)
Oceania	1·02 (0·91 to 1·14)	1·07 (0·95 to 1·20)	0·05 (–0·02 to 0·12)	1·00 (0·90 to 1·13)	1·00 (0·88 to 1·14)	0·00 (–0·09 to 0·09)
Under-5 mortality rate						
World*†	1·05 (1·04 to 1·06)	1·08 (1·07 to 1·09)	0·02 (0·01 to 0·04)§	1·06 (1·05 to 1·08)‡	1·06 (1·05 to 1·07)‡	–0·01 (–0·02 to 0·01)
High-income regions	1·28 (1·28 to 1·29)	1·22 (1·21 to 1·24)	–0·06 (–0·07 to –0·04)§	0·97 (0·96 to 0·98)‡	0·99 (0·98 to 1·01)	0·03 (0·01 to 0·04)§
Northern Africa*†	1·07 (1·05 to 1·09)	1·18 (1·15 to 1·20)	0·11 (0·08 to 0·14)§	1·09 (1·07 to 1·11)‡	1·06 (1·04 to 1·09)‡	–0·03 (–0·06 to 0·00)
Sub-Saharan Africa*	1·11 (1·10 to 1·12)	1·13 (1·11 to 1·14)	0·02 (0·00 to 0·04)§	0·99 (0·98 to 1·00)‡	0·99 (0·98 to 1·01)	0·00 (–0·01 to 0·02)
Eastern Asia*	1·09 (1·03 to 1·15)	1·15 (1·08 to 1·22)	0·06 (0·00 to 0·13)	1·09 (1·03 to 1·16)‡	1·08 (1·02 to 1·15)‡	–0·01 (–0·08 to 0·05)
Southern Asia*†	0·97 (0·95 to 0·98)	0·98 (0·96 to 1·00)	0·01 (–0·01 to 0·04)	1·16 (1·14 to 1·18)‡	1·21 (1·19 to 1·24)‡	0·05 (0·02 to 0·09)§
South-eastern Asia*	1·18 (1·16 to 1·21)	1·26 (1·22 to 1·30)	0·08 (0·04 to 0·11)	0·97 (0·95 to 0·99)	0·97 (0·94 to 1·00)	0·00 (–0·02 to 0·03)
Western Asia*	1·13 (1·10 to 1·15)	1·19 (1·16 to 1·23)	0·06 (0·03 to 0·10)§	1·03 (1·01 to 1·06)‡	1·02 (0·99 to 1·05)	–0·01 (–0·04 to 0·02)
Caucasus and central Asia*†	1·24 (1·21 to 1·28)	1·28 (1·23 to 1·34)	0·04 (0·00 to 0·08)§	0·94 (0·91 to 0·97)‡	0·94 (0·90 to 0·98)‡	0·00 (–0·03 to 0·04)
Latin America and the Caribbean	1·19 (1·16 to 1·22)	1·24 (1·22 to 1·26)	0·05 (0·02 to 0·08)§	0·99 (0·97 to 1·02)	1·00 (0·98 to 1·02)	0·00 (–0·02 to 0·03)
Oceania	1·14 (1·07 to 1·23)	1·18 (1·09 to 1·27)	0·03 (–0·03 to 0·09)	1·00 (0·93 to 1·07)	1·00 (0·92 to 1·08)	0·00 (–0·06 to 0·06)

Data are ratios (90% uncertainty interval). *Sex ratio outlying for 1990. †Sex ratio outlying for 2012. ‡Ratio of estimated-to-expected female mortality significantly different from one. §Change significantly different from zero.

Table 1: **Sex ratios and ratios of estimated-to-expected female mortality, by age group and region**

for more robust inference for U5MR sex ratios (where more outlying observations were present). For 11 countries without any data, estimates were inferred from the relation between sex ratios and total mortality: expected sex ratios followed from the global model and estimates for total mortality, and country-specific multipliers were simulated from the time series model to include the substantial uncertainty associated with the estimates in such countries.

We combined estimates of IMR and CMR sex ratios with estimates of total IMR and CMR from the UN Interagency Group on Child Mortality Estimation (UN IGME) to obtain sex-specific IMR, CMR, and U5MR, accounting for the uncertainty in total IMR and CMR.[28] We obtained estimates for the number of deaths through a standard life table approach adopted by the UN IGME,[29] using information about population numbers from the 2012 Revision of World Population Prospects[30] and life table entries set by WHO. Aggregate estimates for the world and all Millennium Development Goal regions were based on the totals for the number of deaths and population numbers by region.

The global relation between expected sex ratios and mortality in both sexes implicitly defines a relation between male mortality and the expected sex ratio. We used this relation to calculate the expected sex ratio based on the estimated male mortality rate for each country-year. To identify countries with outlying sex ratios, we defined and calculated the expected female mortality rate that is associated with the expected sex ratio and estimated male mortality for a given country-year, and defined and calculated excess female mortality as the difference between the expected female mortality rate and the estimated rate for the country-year (where negative outcomes refer to lower-than-expected female mortality).

We used a Markov Chain Monte Carlo (MCMC) algorithm to generate samples of the posterior distributions of the parameters.[31] This approach produced a set of trajectories of sex ratios for all age groups for each country, and associated measures of sex-specific mortality, excess female mortality, and deaths. We computed 90% uncertainty intervals (UIs) for all indicators of interest using the 5th and 95th percentiles of the posterior distributions (90% UIs are the standard choice in IGME reporting as opposed to the more standard 95% intervals in view of the inherent uncertainty in child-mortality-related outcomes; the uncertainty in estimates follows from the limitations of the available data at the country level). We defined country-years to have outlying sex ratios if the absolute value of the point estimate for excess female mortality was greater than one per 1000 livebirths for excess IMR and U5MR and one per 1000 survivors up to age 1 year for excess CMR, and if the posterior probability that the excess female mortality is either negative or positive is more than 90%, corresponding to a chance of one in ten of incorrectly flagging an outlying country.

We assessed model performance using an out-of-sample validation exercise (appendix). We implemented the MCMC sampling algorithm using JAGS 3·2·0 Open Source software,[32] and did statistical analyses using R (version 3.0).[33] Software programs and data are available from the authors.

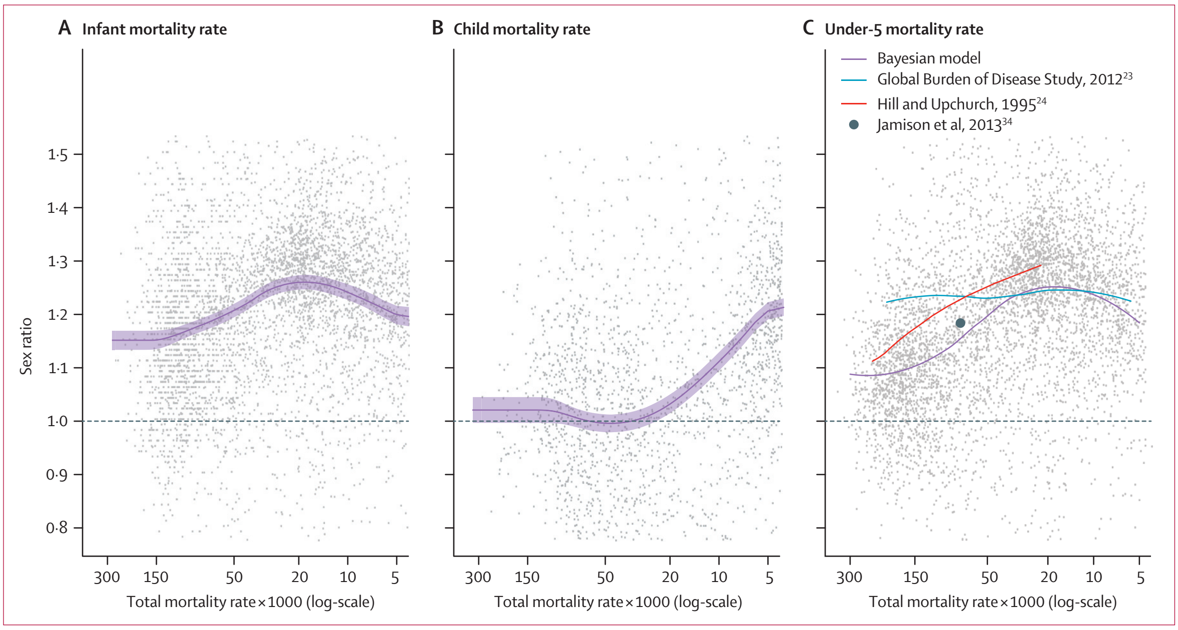

Figure 2: **Overview of the global relation between sex ratios and total mortality levels**
Sex ratios are plotted against decreasing total mortality (grey dots) and the estimated global relation between expected sex ratios and total mortality for the infant mortality rate (A) and child mortality rate (B) are shown in purple. Shaded areas are 90% uncertainty intervals. For under-5 mortality (C), the purple line shows the relation between sex ratios and total mortality based on the relations for IMR and CMR for all included country-years.

Role of the funding source

The funders of the study had no role in the study design, data analysis, data interpretation, or writing of the report. The corresponding author had full access to all data in the study and had final responsibility for the decision to submit for publication.

Results

The dataset consisted of 10084 observations. More information on country-specific sources is given in the appendix. Figure 1 and table 1 show estimates of sex ratios for the IMR, CMR, and U5MR for 1990 and 2012 for the world and Millennium Development Goal regions. Levels and trends varied across regions. Sex ratios of mortality were lowest in southern Asia for 1990 and 2012 for all age groups; it is the only region where the CMR and U5MR sex ratios were lower than one for both 1990 and 2012. In 2012, the highest mortality sex ratios were estimated for Caucasus and central Asia for infants and children younger than 5 years, whereas developed regions had the highest CMR sex ratio (table 1). In most regions and age groups, sex ratios increased between 1990 and 2012. We saw the largest increase in U5MR sex ratio in northern Africa (table 1). Sex ratios decreased in developed regions in all age groups, in southern Asia for IMR, and in sub-Saharan Africa for CMR (table 1).

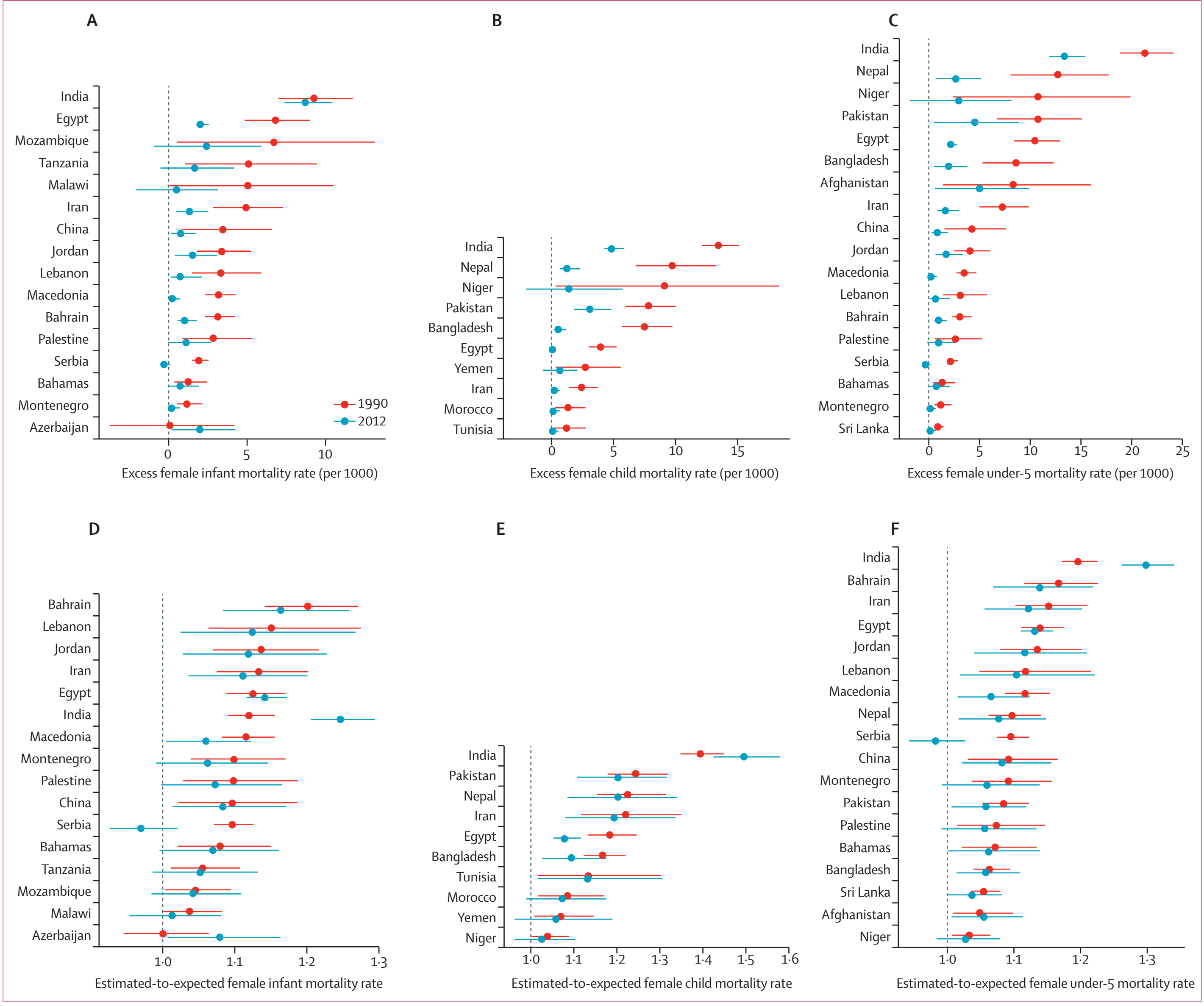

Figure 3: **Overview of excess female mortality (A–C) and the ratio of estimated-to-expected female mortality (D–F) for countries with outlying sex ratios and higher-than-expected female mortality in 1990 or 2012**

Countries are ordered by decreasing point estimates for the year 1990. Error bars are 90% uncertainty intervals. IMR=infant mortality rate. CMR=child mortality rate. U5MR=under-5 mortality rate.

	Infant mortality rate	Child mortality rate	Under-5 mortality rate
Afghanistan	..	..	*†
Azerbaijan	†	..	..
Bahamas	*	..	*
Bahrain	*†	..	*†
Bangladesh	..	*	*†
China	*	..	*†
Egypt	*†	*	*†
India	*†	*†	*†
Iran	*†	*	*†
Jordan	*†	..	*†
Lebanon	*	..	*
Macedonia	*	..	*
Malawi	*	..	..
Montenegro	*	..	*
Morocco	..	*	..
Mozambique	*	..	..
Nepal	..	*†	*†
Niger	..	*	*
Pakistan	..	*†	*†
Serbia	*	..	*
Sri Lanka	..	..	*
Palestine	*	..	*
Tanzania	*	..	..
Tunisia	..	*	..
Yemen	..	*	..

*Sex ratio outlying for 1990. †Sex ratio outlying for 2012.

Table 2: **Countries with higher-than-expected female mortality for 1990 or 2012, by age group**

Much of the differences and changes in sex ratios can be explained by differences and changes in total mortality and associated expected sex ratios. Figure 2 shows the estimated expected sex ratios for a given level of total mortality based on the global relation between mortality levels and sex ratios for the IMR, CMR, and U5MR. For the IMR, the expected sex ratio is about 1·15 (UI 1·14–1·17) for high levels of mortality (about 150 deaths per 1000 livebirths). This ratio increased to 1·26 (1·25–1·27) as mortality decreased to about 20 deaths per 1000 livebirths and decreased to 1·20 (1·18–1·22) as total IMR decreased to five deaths per 1000 livebirths. For CMR, expected sex ratios were close to one (1·01 [0·99–1·02]) for total mortality above 30 deaths per 1000 survivors past the age of 1 year. The ratio increased to 1·21 (1·19–1·22) as mortality decreased to five per 1000 survivors. The expected sex ratio for the U5MR is driven by the expected sex ratios for the IMR and CMR. The relation between total U5MR and its sex ratio based on all country-years suggests an increase in the U5MR sex ratio from about 1·09 to 1·25 as the U5MR decreased from around 400 deaths to 20 deaths per 1000 livebirths. This increase was followed by a decrease in the expected sex ratio from about 1·25 to 1·18 as U5MR decreased from 20 deaths to five deaths per 1000 livebirths.

Globally, ratios of estimated-to-expected female mortality rates were significantly greater than one in 1990 and 2012 for all age groups, being lowest for IMR in 1990 and highest for CMR in 1990 (table 1). Globally, the ratio decreased statistically significantly between 1990 and 2012 only for CMR (table 1). Levels and changes differed across regions. Ratios were lowest in the Caucasus and central Asia and highest for southern Asia for all age groups in 2012 (table 1). The largest increase in ratios of estimated-to-expected female mortality from 1990 to 2012 was in infants in southern Asia; the largest decrease was in children in northern Africa (table 1).

Outlying sex ratios occur in regions with country-specific sex ratios of mortality that are higher or lower than expected based on the global relation between total mortality and sex ratios. For example, estimates for south Asia are driven by the estimates for India. Country-specific estimates of sex ratios, ratios of estimated to expected female mortality, excess mortality, and excess deaths for all age groups for all countries in 1990 and 2012 are given in the appendix. Figure 3 shows an overview of excess mortality for countries with outlying sex ratios, where female mortality is higher than expected for 1990, 2012, or both for infants, children, and under 5s separately. Table 2 gives an overview of all countries with higher-than-expected female mortality. For the IMR, 15 countries from different regions, but mostly from Asia and Africa, were identified to have excess infant female mortality in 1990. In all countries, excess mortality decreased between 1990 and 2012 but was still present in 2012 in five of these 15 countries (Bahrain, Egypt, India, Iran, and Jordan), as well as in Azerbaijan (table 3). The highest excess female IMR in 2012 was in India (table 3). Decreases in excess female mortality were mostly related to decreases in overall mortality; the ratios of estimated-to-expected female mortality did not change substantially in most countries. Exceptions are India, where this ratio increased, and Serbia, where a substantial and statistically significant decrease was observed. Compared with IMR, we identified fewer countries as having outlying CMR sex ratios and excess female CMR—ten countries in 1990 (including seven countries for which the IMR was not identified as an outlier), of which three were still identified as outliers by 2012. India had the highest excess female mortality for children aged 1–4 years for 2012 (table 3) and the ratio of estimated to expected female CMR increased between 1990 and 2012. Decreases in the ratio of estimated to expected female CMR were minor for most countries but notable for Bangladesh and Egypt (table 3).

As a result of excess IMR, CMR, or both, 18 countries had excess female U5MR in 1990 and ten countries had excess U5MR in 2012 (figure 3). Table 4 shows excess female U5MR and associated number of excess deaths for all countries with outlying U5MR sex ratios in 2012. India had the largest excess female U5MR, followed by

	Sex ratio			Excess female mortality (per 1000 livebirths for infant mortality rate and per 1000 survivors up to age 1 year for child mortality rate)		Ratio of estimated-to-expected female mortality rate		
	1990	2012	Change (1990–2012)	1990	2012	1990	2012	Change (1990–2012)
Infant mortality rate								
Azerbaijan*	1·18 (1·11 to 1·25)	1·15 (1·07 to 1·23)	–0·03 (–0·11 to 0·05)	0·2 (–3·8 to 4·2)	2·1 (0·2 to 4·2)	1·00 (0·95 to 1·06)	1·08 (1·01 to 1·16)‡	0·08 (0·00 to 0·16)§
Bahamas†	1·16 (1·10 to 1·23)	1·17 (1·08 to 1·26)	0·00 (–0·08 to 0·09)	1·4 (0·4 to 2·5)	0·9 (–0·1 to 1·9)	1·08 (1·02 to 1·15)‡	1·07 (1·00 to 1·16)	–0·01 (–0·08 to 0·07)
Bahrain†*	1·05 (0·99 to 1·10)	1·05 (0·97 to 1·13)	0·00 (–0·07 to 0·08)	3·2 (2·3 to 4·2)	1·1 (0·6 to 1·8)	1·20 (1·14 to 1·27)‡	1·17 (1·08 to 1·26)‡	–0·04 (–0·11 to 0·04)
China†	1·11 (1·03 to 1·19)	1·15 (1·06 to 1·23)	0·04 (–0·04 to 0·12)	3·6 (0·8 to 6·6)	0·9 (0·1 to 1·7)	1·10 (1·02 to 1·19)‡	1·09 (1·01 to 1·17)‡	–0·01 (–0·09 to 0·06)
Egypt†*	1·06 (1·02 to 1·10)	1·10 (1·08 to 1·13)	0·04 (0·00 to 0·09)	6·9 (4·9 to 9·0)	2·1 (1·7 to 2·6)	1·13 (1·09 to 1·17)‡	1·14 (1·12 to 1·17)‡	0·02 (–0·03 to 0·06)
India†*	1·05 (1·02 to 1·08)	0·98 (0·95 to 1·01)	–0·07 (–0·11 to –0·03)§	9·4 (7·0 to 11·7)	8·8 (7·4 to 10·4)	1·12 (1·09 to 1·16)‡	1·25 (1·21 to 1·29)‡	0·13 (0·07 to 0·18)§
Iran†*	1·08 (1·02 to 1·14)	1·13 (1·05 to 1·21)	0·05 (–0·03 to 0·13)	5·0 (2·8 to 7·3)	1·4 (0·5 to 2·5)	1·14 (1·07 to 1·20)‡	1·11 (1·04 to 1·20)‡	–0·02 (–0·10 to 0·06)
Jordan†*	1·10 (1·03 to 1·17)	1·12 (1·02 to 1·22)	0·02 (–0·06 to 0·11)	3·5 (1·8 to 5·3)	1·6 (0·4 to 3·1)	1·14 (1·07 to 1·22)‡	1·12 (1·03 to 1·23)‡	–0·02 (–0·10 to 0·07)
Lebanon†	1·09 (0·99 to 1·18)	1·09 (0·97 to 1·19)	0·00 (–0·08 to 0·08)	3·4 (1·5 to 5·9)	0·8 (0·1 to 2·1)	1·15 (1·06 to 1·27)‡	1·13 (1·02 to 1·27)‡	–0·02 (–0·11 to 0·06)
Macedonia†	1·11 (1·08 to 1·15)	1·14 (1·08 to 1·21)	0·03 (–0·04 to 0·10)	3·3 (2·3 to 4·3)	0·4 (0·0 to 0·7)	1·12 (1·08 to 1·16)‡	1·06 (1·00 to 1·12)‡	–0·06 (–0·12 to 0·01)
Malawi†	1·11 (1·07 to 1·15)	1·20 (1·13 to 1·27)	0·09 (0·01 to 0·16)§	5·2 (0·0 to 10·5)	0·6 (–2·1 to 3·1)	1·04 (1·00 to 1·08)‡	1·02 (0·95 to 1·08)	–0·02 (–0·09 to 0·05)
Montenegro†	1·14 (1·07 to 1·21)	1·13 (1·05 to 1·22)	–0·01 (–0·09 to 0·07)	1·3 (0·5 to 2·2)	0·3 (0·0 to 0·7)	1·10 (1·04 to 1·17)‡	1·06 (0·99 to 1·15)	–0·04 (–0·11 to 0·04)
Mozambique†	1·10 (1·05 to 1·15)	1·14 (1·08 to 1·21)	0·04 (–0·03 to 0·12)	6·8 (0·5 to 13·1)	2·5 (–0·9 to 5·9)	1·05 (1·00 to 1·09)‡	1·04 (0·98 to 1·11)	0·00 (–0·07 to 0·07)
Serbia†	1·14 (1·12 to 1·17)	1·24 (1·18 to 1·30)	0·10 (0·04 to 0·16)§	2·0 (1·5 to 2·5)	–0·1 (–0·4 to 0·1)	1·10 (1·07 to 1·13)‡	0·97 (0·93 to 1·02)	–0·13 (–0·18 to –0·07)§
Palestine†	1·13 (1·05 to 1·20)	1·17 (1·08 to 1·26)	0·04 (–0·04 to 0·13)	3·0 (0·8 to 5·3)	1·2 (0·0 to 2·7)	1·10 (1·03 to 1·19)‡	1·08 (1·00 to 1·17)	–0·03 (–0·11 to 0·05)
Tanzania†	1·11 (1·06 to 1·15)	1·17 (1·09 to 1·25)	0·06 (–0·02 to 0·14)	5·2 (1·0 to 9·4)	1·8 (–0·5 to 4·2)	1·06 (1·01 to 1·11)‡	1·05 (0·99 to 1·13)	0·00 (–0·07 to 0·07)
Child mortality rate								
Bangladesh†	0·85 (0·82 to 0·89)	1·04 (0·98 to 1·11)	0·19 (0·13 to 0·26)§	7·7 (5·7 to 9·8)	0·7 (0·2 to 1·2)	1·17 (1·12 to 1·22)‡	1·10 (1·03 to 1·17)‡	–0·07 (–0·15 to 0·00)
Egypt†	0·86 (0·82 to 0·90)	1·12 (1·09 to 1·15)	0·26 (0·21 to 0·30)§	4·1 (3·0 to 5·3)	0·2 (0·1 to 0·3)	1·19 (1·13 to 1·25)‡	1·08 (1·05 to 1·12)‡	–0·10 (–0·17 to –0·05)§
India†*	0·72 (0·69 to 0·74)	0·74 (0·70 to 0·77)	0·02 (–0·02 to 0·06)	13·6 (12·1 to 15·1)	5·0 (4·3 to 5·9)	1·40 (1·35 to 1·45)‡	1·50 (1·42 to 1·58)‡	0·10 (0·02 to 0·19)§
Iran†	0·89 (0·81 to 0·97)	1·01 (0·91 to 1·12)	0·12 (0·05 to 0·20)§	2·5 (1·4 to 3·7)	0·4 (0·2 to 0·7)	1·23 (1·12 to 1·35)‡	1·20 (1·08 to 1·34)‡	–0·03 (–0·12 to 0·06)
Morocco†	0·96 (0·90 to 1·03)	1·12 (1·03 to 1·22)	0·16 (0·09 to 0·24)§	1·5 (0·3 to 2·7)	0·3 (0·0 to 0·7)	1·09 (1·02 to 1·17)‡	1·08 (0·99 to 1·18)	–0·01 (–0·09 to 0·07)
Nepal†*	0·81 (0·76 to 0·86)	0·95 (0·87 to 1·04)	0·14 (0·08 to 0·21)§	9·9 (6·8 to 13·3)	1·4 (0·7 to 2·3)	1·23 (1·15 to 1·31)‡	1·21 (1·08 to 1·34)‡	–0·02 (–0·13 to 0·08)
Niger†	0·98 (0·94 to 1·01)	0·97 (0·90 to 1·04)	–0·01 (–0·07 to 0·06)	9·3 (0·3 to 18·4)	1·6 (–2·0 to 5·7)	1·04 (1·00 to 1·09)‡	1·03 (0·96 to 1·10)	–0·01 (–0·08 to 0·06)
Pakistan†*	0·80 (0·76 to 0·85)	0·87 (0·81 to 0·94)	0·07 (0·01 to 0·13)§	8·0 (6·0 to 10·0)	3·3 (1·8 to 4·8)	1·25 (1·18 to 1·32)‡	1·21 (1·11 to 1·32)‡	–0·04 (–0·13 to 0·06)
Tunisia†	0·97 (0·86 to 1·07)	1·07 (0·93 to 1·19)	0·10 (0·02 to 0·18)§	1·4 (0·2 to 2·8)	0·3 (0·0 to 0·6)	1·14 (1·02 to 1·30)‡	1·14 (1·02 to 1·31)‡	0·00 (–0·09 to 0·09)
Yemen†	0·93 (0·87 to 0·99)	1·01 (0·92 to 1·09)	0·08 (0·01 to 0·15)§	2·9 (0·3 to 5·6)	0·8 (–0·7 to 2·1)	1·07 (1·01 to 1·15)‡	1·06 (0·96 to 1·19)	–0·01 (–0·10 to 0·10)

Data are estimates (90% uncertainty interval). *Sex ratio outlying for 2012. †Sex ratio outlying for 1990. ‡Ratio of estimated-to-expected female mortality is significantly different from one. §Change significantly different from zero.

Table 3: **Sex ratios, excess female mortality and ratios of estimated-to-expected female mortality for infants and children, for countries with outlying sex ratios and higher-than-expected female mortality in 1990 or 2012**

	Sex ratio (under-5 mortality)	Ratio of estimated-to-expected female mortality rate	Excess female mortality rate (per 1000 livebirths)	Number of excess female deaths	Ratio of excess female deaths to total number of deaths (%)
Afghanistan	1·07 (1·02 to 1·12)	1·06 (1·01 to 1·11)	5·2 (0·6 to 9·9)	2810 (330 to 5390)	2·7%
Bahrain	1·07 (1·00 to 1·15)	1·14 (1·07 to 1·22)	1·1 (0·6 to 1·8)	11 (6 to 18)	5·9%
Bangladesh	1·15 (1·10 to 1·20)	1·06 (1·01 to 1·11)	2·1 (0·5 to 3·8)	3330 (790 to 5880)	2·6%
China	1·15 (1·07 to 1·22)	1·08 (1·02 to 1·16)	1·0 (0·3 to 1·9)	8690 (2330 to 16 100)	3·3%
Egypt	1·10 (1·08 to 1·12)	1·13 (1·11 to 1·16)	2·4 (1·9 to 2·8)	2250 (1860 to 2660)	5·6%
Guinea-Bissau	1·16 (1·11 to 1·22)	0·95 (0·90 to 1·00)	–6·5 (–14·2 to –0·4)	–203 (–450 to –10)	–2·6%
India	0·92 (0·90 to 0·95)	1·30 (1·26 to 1·34)	13·5 (11·9 to 15·4)	166 000 (144 000 to 190 000)	11·7%
Iran	1·11 (1·04 to 1·18)	1·13 (1·06 to 1·20)	1·8 (0·8 to 3·0)	1340 (590 to 2190)	5·2%
Jordan	1·12 (1·03 to 1·20)	1·12 (1·04 to 1·21)	1·9 (0·7 to 3·4)	188 (63 to 333)	5·0%
Kazakhstan	1·36 (1·26 to 1·47)	0·92 (0·85 to 0·99)	–1·3 (–2·6 to –0·1)	–217 (–442 to –22)	–3·4%
Mongolia	1·48 (1·36 to 1·62)	0·84 (0·77 to 0·92)	–4·1 (–7·4 to –1·9)	–137 (–248 to –61)	–7·6%
Nepal	1·13 (1·07 to 1·19)	1·08 (1·02 to 1·15)	2·9 (0·7 to 5·2)	852 (227 to 1520)	3·5%
Pakistan	1·09 (1·04 to 1·15)	1·06 (1·01 to 1·12)	4·7 (0·5 to 8·9)	11 100 (1000 to 21 400)	2·7%
Uganda	1·20 (1·15 to 1·26)	0·94 (0·90 to 0·99)	–3·8 (–7·8 to –0·5)	–2820 (–5880 to –290)	–2·7%
Uzbekistan	1·33 (1·23 to 1·44)	0·92 (0·84 to 1·00)	–2·7 (–8·8 to 0·0)	–872 (–2850 to –11)	–3·5%

Data are estimates (90% uncertainty intervals). Countries are ordered alphabetically. All countries in this table also have outlying sex ratios in 1990.

Table 4: **Sex ratios, excess female mortality, and related outcomes for under 5s in countries with outlying sex ratios in 2012**

Afghanistan and Pakistan (table 4). The largest number of excess female deaths by far was in India (table 4).

We also identified countries with outlying sex ratios and lower-than-expected female mortality (appendix); 17 countries had outlying U5MR sex ratios in 1990 and five had outlying U5MR sex ratios in 2012 (Guinea-Bissau, Kazakhstan, Mongolia, Uganda, and Uzbekistan). Table 4 also includes the excess U5MR and associated number of excess deaths for these five countries in 2012.

Model validation exercises suggest that our model was well calibrated (appendix).

Discussion

We know of no other study to assess the relation between sex ratios and overall mortality levels using data from all countries, while accounting for data quality issues and countries with outlying levels (panel). Our findings suggest that sex ratios are expected to be greater than one for high levels of total infant mortality but around one for high levels of total child mortality. Both ratios increase as total mortality decreases but there is evidence that the IMR sex ratio decreases again at very low total IMR, consistent with previous findings for some high-income countries.[2] Our estimated global relation between sex ratios and total mortality differs from the one constructed by Hill and Upchurch in 1995, which was based on life tables from 1820 to 1964 from northwestern Europe (figure 2).[24] Although findings from both studies suggest that sex ratios tend to increase as overall mortality decreases, the Hill and Upchurch estimates for sex ratios are greater than those estimated by our model, referred to hereon in as the Bayesian model. The difference between the Hill-Upchurch curve and the Bayesian model might be explained by the use of a more recent and comprehensive dataset that captures data since 1950. More generally, whereas Hill and Upchurch included data for only five selected countries where they judged treatment of male and female infants to be equal and unchanging over time, to establish a so-called discrimination-free standard, we elected to avoid such an a-priori judgment on discrimination by comparing countries to the global pattern. In another study,[34] the expected sex ratio for U5MR for India in 2005 was estimated at 1·18 based on the average value from a set of DHS surveys from low-income and middle-income countries in 2011, which gives an expected value more comparable to our estimate for the expected sex ratio for India in 2005 than the Hill-Upchurch one. Finally, findings from a previous global study also suggested lower average sex ratios at given levels of mortality than depicted by the Hill-Upchurch curve.[21] There is evidence that vaccination against diphtheria, pertussis, and tetanus is related to decreased sex ratios of mortality in high-mortality countries, which might to some degree account for the lower sex ratios seen in contemporary high-mortality countries compared with the historical experience of western countries;[35] different prevailing patterns of infectious disease morbidity and mortality might also play a role.[1]

Important differences exist between our findings and those of the Global Burden of Disease (GBD) 2010 study.[23] We inferred a relation between estimated sex ratios and total U5MR for the GBD study by fitting a Loess smoother to its U5MR and sex ratio estimates, which were published for the years 1970, 1980, 1990, 2000, and 2010. The resulting relation differs from both our global relation as well as the Hill-Upchurch relation because it does not suggest a change in sex ratios with decreasing mortality, which contradicts findings from previous studies.[2–4] Important differences also exist between our country-specific sex ratio estimates and those published in the GBD 2010 study (appendix). For example, the GBD study estimates the sex ratio for U5MR for India for 2010 to be 1·05, which is much higher than our estimate of 0·91. It is not clear to us from the GBD's methodological explanations how such high estimates could be obtained for India in particular, in view of the fact that the vast majority of observed sex ratios from various studies are below one.

We used the estimated global relation between total mortality and sex ratios to calculate excess female mortality and to assess which countries have unusually high or low sex ratios compared with the global standard. Whereas excess female mortality has decreased in most countries with outlying sex ratios, the ratios of estimated-to-expected female mortality did not change much. Exceptions were Serbia, where we saw decreases in the ratio for the IMR, Egypt and Bangladesh, where we saw decreases in the ratio for the CMR, and India, where ratios of estimated-to-expected female mortality increased significantly for all age groups. Further investigation is needed to better understand what causes the outlying levels and trends. Although for India and a few other countries, findings from previous studies have suggested male preference,[5–20] and pinpointed to causes of outlying levels such as male preference in the provision of vaccinations,[36] information about factors that might have caused outlying sex ratios in other countries is very scarce. Explanations could include biological factors—eg, an unusual cause of death distribution in the country as compared with other countries with similar levels of mortality. However, detailed data for causes of death needed to assess this explanation are absent for most developing countries. We hope that the identification of country-years with outlying sex ratios will generate additional research on this important topic.

Although we feel our study improves on previous studies by accounting for data quality issues, in particular, by down-weighting observations that are deemed less informative of true sex ratios, additional data quality issues (eg, in the under-reporting of birth or deaths or changes in the definitions of livebirths) might also affect estimates of sex ratios of mortality. Also, country-years with outlying sex ratios might go unnoticed in countries with scarce data because of the large uncertainty surrounding the estimates in these countries. Finally, sex-selective abortion is a related issue affecting several of the countries that have outlying sex ratios of mortality, but is beyond the scope of this study. For a complete assessment of skewed under-5 population sex ratios in countries where sex discrimination might be present, sex-selective distortions of sex ratios at birth need to be taken into account as well.[37] Further analysis, focusing on a comprehensive assessment of under-5 sex ratios in the population could provide more insights into such issues.

This study provides a response to the call for disaggregation of under-5 mortality rates by sex from international monitoring initiatives.[38,39] The country-specific annual estimates and projections of sex ratios, the assessment of excess female mortality and deaths, as well as the degree of uncertainty around them, provide the global health and development community a new platform for monitoring sex equity and evidence-based policy making and programming.

Panel: Research in context

Systematic review

We attempted to identify all available data for infant, child, or under-5 mortality by sex from vital registration, surveys, and censuses, for all countries of the world. Data from vital registration systems were obtained from the World Health Organization (WHO). Mortality estimates were computed from microdata files obtained from international survey programmes such as the Demographic and Health Surveys, Multiple Indicator Cluster Surveys, World Fertility Surveys, and Pan-Arab Programme on Family Health. Microdata from selected census samples were available from the Integrated Public Use Microdata Series - International (IPUMS-I) at the University of Minnesota. Where microdata files were not available, we obtained data from survey or census reports or data files in the holdings of the United Nations Population Division or UNICEF; through the process by UNICEF's Country Report on Indicators for the Goals and an annual country consultation process conducted by UNICEF and WHO; or from the internet or other sources. Inclusion criteria for data series from censuses and surveys and vital registration or sample registration and surveillance observation years followed the inclusion criteria used for total under-5 mortality rate estimation used by the UN IGME.[28] Additionally, extreme observations, sex ratios that are greater than 5 or smaller than 0·2, were removed.

We constructed estimates of sex ratios using a Bayesian model, accounting for differences between observations with respect to sampling and non-sampling error variance and the presence of outlying observations and countries with outlying sex ratios.

Interpretation

Our findings provide new information about sex ratios worldwide and the relation between sex ratios and total mortality levels, and identify countries with outlying levels or trends in sex ratios. They confirmed findings from previous studies that chances of survival up to the age of 5 years tend to improve more rapidly for girls compared with boys as total mortality decreases, with a reversal of this trend at very low infant mortality, and quantified this relation between sex ratios and total mortality based on data for all countries since 1950. The study provided national and regional estimates of sex ratios. Additionally, we identified regions and countries with unexpectedly high or low sex ratios compared with their level of total mortality. Further research should focus on explaining differences across countries and regions and action should be undertaken if sex discrimination is present.

Contributors

LA led the development of the Bayesian statistical model and oversaw the research. FC and CCS provided input on model specification. FC assisted in assessing and compiling the database, model implementation, and obtaining model-based estimates. CCS and DY provided substantive input on model findings. DY oversaw database construction. JP developed the methodology and software to extract data on sex ratios. LA, FC, DY, JP, and CCS wrote and revised the paper. All authors have seen and approved the final version of the paper.

Declaration of interests

We declare no competing interests.

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