Articles

Estimation of daily risk of neonatal death, including the day of birth, in 186 countries in 2013: a vital-registration and modelling-based study

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Summary

Background The days immediately after birth are the most risky for human survival, yet neonatal mortality risks are generally not reported by day. Early neonatal deaths are sometimes under-reported or might be misclassified by day of death or as stillbirths. We modelled daily neonatal mortality risk and estimated the proportion of deaths on the day of birth and in week 1 for 186 countries in 2013.

Methods We reviewed data from vital registration (VR) and demographic and health surveys for information on the timing of neonatal deaths. For countries with high-quality VR we used the data as reported. For countries without high-quality VR data, we applied an exponential model to data from 206 surveys in 79 countries (n=50 396 deaths) to estimate the proportions of neonatal deaths per day and used bootstrap sampling to develop uncertainty estimates.

Findings 57 countries (n=122 757 deaths) had high-quality VR, and modelled data were used for 129 countries. The proportion of deaths on the day of birth (day 0) and within week 1 varied little by neonatal mortality rate, income, or region. 1·00 million (36.3%) of all neonatal deaths occurred on day 0 (uncertainty range 0·94 million to 1·05 million), and 2·02 million (73.2%) in the first week (uncertainty range 1·99 million to 2·05 million). Sub-Saharan Africa had the highest risk of neonatal death and, therefore, had the highest risk of death on day 0 (11·2 per 1000 livebirths); the highest number of deaths on day 0 was seen in southern Asia (n=392 300).

Interpretation The risk of early neonatal death is very high across a range of countries and contexts. Cost-effective and feasible interventions to improve neonatal and maternity care could save many lives.

Funding Save the Children's Saving Newborn Lives programme.

Introduction

Birth and the following few days are biologically and emotionally remarkable, but are also the riskiest for survival. The Millennium Development Goals (MDGs) have galvanised efforts to substantially reduce maternal and child mortality, yet deaths in the neonatal period (the first 4 weeks after birth) have decreased more slowly.[1,2] The estimated average annual rate of mortality reduction for neonates was 2·2% from 1990 to 2013,[3] compared with 4·0% for children aged 1–59 months[3] and 2·6% for maternal deaths.[4] The risk of death in the first days after birth is strikingly high. In 2013, 2·8 million (44%) of the 6·3 million deaths in children younger than 5 years occurred during the neonatal period,[3] along with an estimated 1·2 million intrapartum stillbirths.[5] Around three-quarters of neonatal deaths are estimated to occur during the first week of life.[6,7]

Deaths on the day of birth (day 0) are particularly important to assess because they account for a large number of deaths that can be targeted by interventions at birth. Risk of death falls substantially even within hours of birth: risk in the first hour after birth in the USA is 0·91 per 1000 livebirths,[8] but in the following 23 h is 1·58 per 1000 livebirths, which translates to a

much lower average hourly risk of about 0·07. The causes of death shortly after birth are similar to those of intrapartum stillbirths and change later in the neonatal period. This similarity has led to the proposal of an indicator that combines intrapartum deaths and those on the day of birth as a marker of the quality of intrapartum care.[9] Yet no systematic, nationally comparable estimates of risk during the first day of life are reported, despite increasing programmatic focus on this important time period.

Vital-registration (VR) data, which are collected from birth and death certificates, are available for more than half of the 193 UN member states,[10] but only about half of those datasets (generally from the wealthiest nations) are reliable, and account for fewer than 5% of neonatal deaths worldwide.[11] For most countries, data by day of the neonatal period are either unavailable or are derived from cross-sectional surveys,[12] which ask women of reproductive age how many of their children have died and the child's age at death. These data are susceptible to error, with possible under-reporting of deaths, including stillbirths, and misreporting of the day of death.[13–15] Of particular importance for this study is the potential for misrecording of deaths (day 1 instead of day 0) and

Panel 1: Challenges to the measurement of neonatal death

Time periods

The neonatal period refers to the first 28 days of life. The early neonatal period is the first 7 days and the late neonatal period the remaining 21 days. The first day of life is typically called day 0 in survey and vital-registration data or day 1 in clinical practice (ie, from days 0–27 or days 1–28 for the full neonatal period). In this Article we use the neonatal periods day 0 for the first day of life, days 0–6 for the early neonatal period, days 7–27 for the late neonatal period, and days 0–27 for the full neonatal period.

Misclassification between stillbirths and livebirths

The probability of recording the baby as being alive at birth is associated with the perception of viability of survival. For example, if babies are not assessed at birth and resuscitated, a live baby born at term that is not breathing might be misclassified as a stillbirth.[5,16] Misclassification of livebirths and stillbirths is most common in this direction.

Variation of registration with gestational age

As complexity of care increases and even very preterm babies before 25 weeks of gestation are given intensive care, the registration of livebirths at less than 28 weeks increases, as documented in Denmark.[17] Some countries without care for extremely preterm babies still might not count some of these babies as livebirths.

Classification of day of death

The perception of what time period comprises the first day of life can lead to important differences in recording practices. Different ways in which the end of the first day of life is indicated include the first 24 h after birth, until sundown of the day of birth, or the change in calendar date. These variations can lead to differences in the recording of whether death occurred on day 0 or day 1 in surveys, dependent on respondents' and interviewers' understanding, which can affect interpretation of survey results.

See **Online** for appendix

For **MEASURE DHS** see http://www.measuredhs.com/

misclassification of deaths as stillbirths rather than very early neonatal deaths (panel 1).

To provide estimates for countries without VR data of adequate quality, modelling remains necessary. Estimates of mortality in children younger than 5 years, including neonatal mortality, are regularly published per country by the UN and the Institute for Health Metrics and Evaluation.[3,11,18,19] Nevertheless, multicountry analyses of the daily risk of death within the neonatal period do not seem to be available. Standard life tables and survival curves generally group data into time periods of months or years rather than days.[20] Although the information on the modelling of survival curves within the neonatal period is sparse, some work suggests that exponential functions are suitable for modelling mortality risk in the neonatal period and that other functions, such as the Gompertz or Weibull functions, are better for later periods in the lifespan.[21,22] Exponential functions have been used to counteract the propensity for reporting deaths on certain days, for instance at 1 week (termed heaping).[13]

Analyses of survey data have suggested that up to 50% of neonatal deaths occur in the first 24–48 h after birth but highlighted data limitations, including the misclassification of deaths on day 0 as being on day 1 and heaping of death reports on particular days.[6]

We used VR data and applied a mathematical model to survey data to estimate risks and numbers of neonatal deaths for the day of birth, in the first week of life, and in the late neonatal period for 186 countries in 2013.

Methods

Selection of data

Eligible data were WHO VR data or data derived from MEASURE demographic and health surveys (DHS) (appendix). We reviewed the latest publicly available WHO VR data from the years 2006–10, except for Canada, for which the data from Statistics Canada were used because they were more recent. DHS data from 1986 to 2011 were acquired with the STATcompiler tool from MEASURE DHS. Finally, to estimate risk of death and numbers of deaths by time period, we applied our results to the 2013 estimates of neonatal deaths and livebirths produced by the UN Inter-agency Group for Child Mortality Estimation.[3]

We used the VR data to generate national risk estimates if the country had VR coverage of adult mortality of at least 80%[10] and the data on neonatal deaths were categorised in the time periods day 0, days 1–6, and days 7–27 (appendix), which is the most detailed breakdown of data that WHO provides. For countries with more than 50 neonatal deaths recorded in the latest year with available data, we used those data. For countries with fewer than 50 neonatal deaths in the latest year with available data, we combined deaths from the previous 2–5 years until the total number of neonatal deaths was at least 50, to avoid instability because of small numbers. We took reports of 20% or less of deaths occurring on day 0 or no deaths occurring on days 1–6 to indicate poor data quality and excluded data from these countries (appendix).

Statistical analysis

All statistical analyses were done with Stata (version 12). For countries without adequate VR data we postulated a three-parameter model for the daily risk of neonatal death that we applied to the DHS data to estimate the proportion of deaths occurring on each day of the neonatal period. The model assumed that the probability of dying on day t, conditional on surviving until that day, declines exponentially. Additionally, the model allowed the probability of dying on day 0 to differ from this pattern. Mathematically, this can be expressed as:

Equation 1:

$$h_t = \begin{cases} \alpha & t=0 \\ \beta\gamma^{t-1} & 1 \le t \le 27 \end{cases}$$

where h_t is the probability of dying on day t conditional on survival until that day. The unconditional probability of dying on day t of the neonatal period, p_t, can be derived from the multinomial distribution (appendix). The likelihood of observing $n_0, ..., n_{27}$ deaths in the neonatal period conditional on N livebirths, and the proportion surviving the neonatal period, p_s, can be expressed as:

Equation 2:

$$p_0{}^{n_0} \times p_1{}^{n_1} \times p_2{}^{n_2} ... \times p_{27}{}^{n_{27}} \times p_S{}^{N-\sum_0^{27} n_t} = p_S{}^{N-\sum_0^{27} n_t} \times \Pi_0^{27} p_t{}^{n_t}$$

To deal with potential misclassification between days 0 and 1 in the DHS data, we combined observed deaths on days 0 and 1 and rewrote the likelihood calculation as:

Equation 3:

$$(p_0 + p_1)^{n_0 + n_1} \times p_2{}^{n_2} ... p_{27}{}^{n_{27}} \times p_S{}^{N-\sum_0^{27} n_t} = p_S{}^{N-\sum_0^{27} n_t}$$
$$\times (p_0 + p_1)^{n_0 + n_1} \times \Pi_2^{27} p_t{}^{n_t}$$

We used maximum likelihood to estimate the parameters α, β, and γ (appendix). This model allowed us to estimate a corrected proportion of neonatal deaths on day 0 under the assumption encoded in the model that the probability of dying on subsequent days declines. With use of these estimates, we calculated the expected proportion of neonatal deaths on a given day (appendix) and during the time periods days 1–6, days 7–27, and week 1 (days 0–6). We initially applied the model to the aggregated DHS data, followed by fitting the model to subsets of the data (neonatal mortality rates, national income category and geographic region [appendix], and survey period) to investigate whether these affected the proportional distribution of deaths.

We compared our postulated model with a simpler two-parameter model that assumes γ=1, by use of a likelihood ratio test (appendix). To enable us to correct for misreporting between days 0 and 1, we fitted a model in which the relation between day 1 deaths and those on subsequent days was constrained.

We calculated the proportions of deaths on day 0 and in week 1 directly from the VR data for countries with high-quality VR data, and from our DHS-based model for the countries with inadequate VR data. We excluded countries with fewer than 1000 livebirths. We calculated the number of deaths by applying the day 0 and in week 1 proportions to the UN Inter-agency Group for Child Mortality Estimation 2013 neonatal death estimates. We then derived the risk values for day 0, week 1, and days 7–27 by dividing the time-period-specific mortality values by the number of livebirths in the country in 2013.

We developed uncertainty estimates for the modelled proportions by drawing 1000 bootstrap samples with replacement from the 206 DHS in the input dataset. We reran the analysis to estimate the model parameters and used these to estimate the proportion of deaths by day for each of the 1000 datasets. Finally, we took centiles 2·5 and 97·5 from the resulting distributions of these proportions as the boundaries of uncertainty. Our uncertainty estimates do not include uncertainty in the total number of neonatal deaths. For countries with adequate VR data, we calculated the uncertainty for the
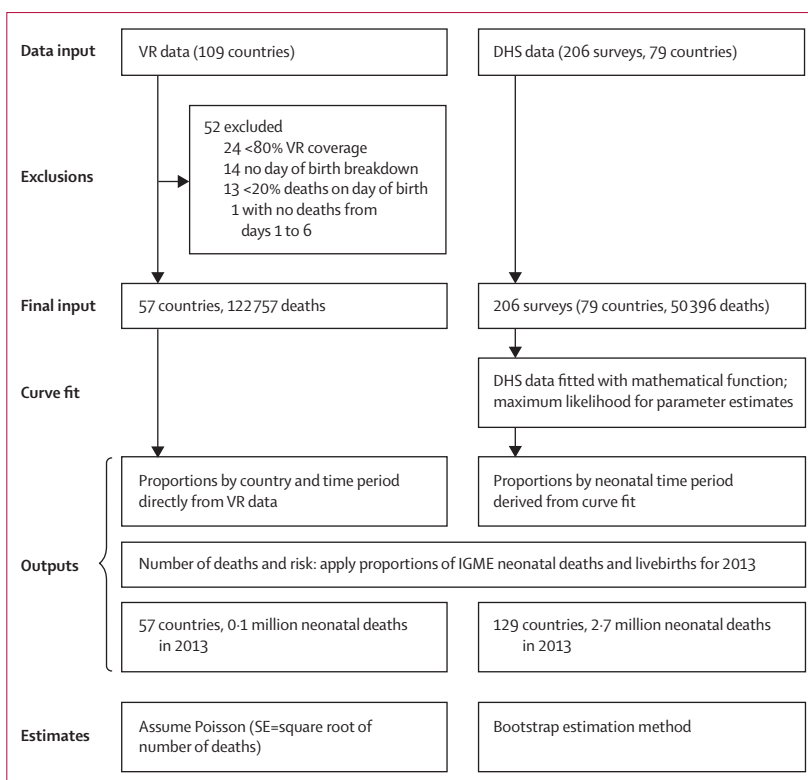

Figure 1: Analysis strategy
VR=vital registration. DHS=demographic and health surveys. IGME=Inter-agency group for Child Mortality Estimation.
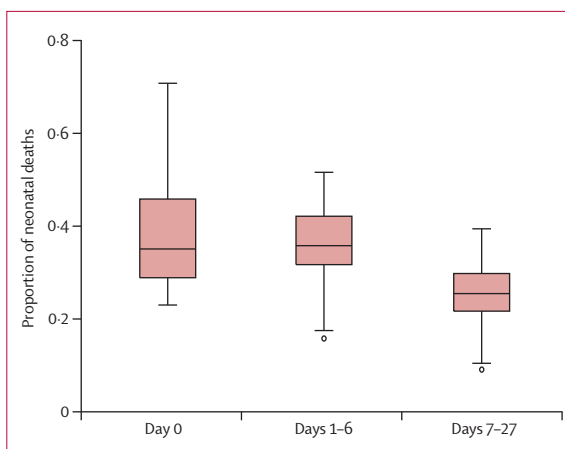

Figure 2: Proportions of neonatal deaths for 57 countries with vital-registration data on days 0, 1–6, and 7–27
Horizontal lines=median. Boxes=IQR. Vertical lines=upper and lower adjacent values. Circles=outliers.

proportions by assuming a Poisson distribution for the number of deaths during those periods (ie, the SE is equal to the square root of the reported number of deaths). Finally, we did validation exercises, including out-of-sample validation and the addition of VR data to the model (appendix).
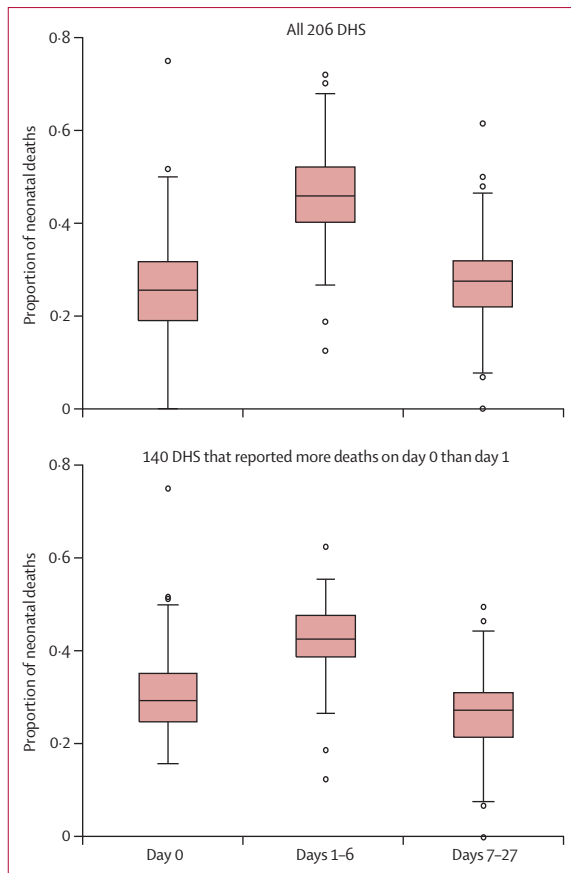
Figure 3: **Proportions of neonatal deaths on day 0, days 1–6, and 7–27 derived from DHS**
DHS=demographic and health surveys. Horizontal lines=median. Boxes=IQR. Vertical lines=upper and lower adjacent values. Circles=outliers.
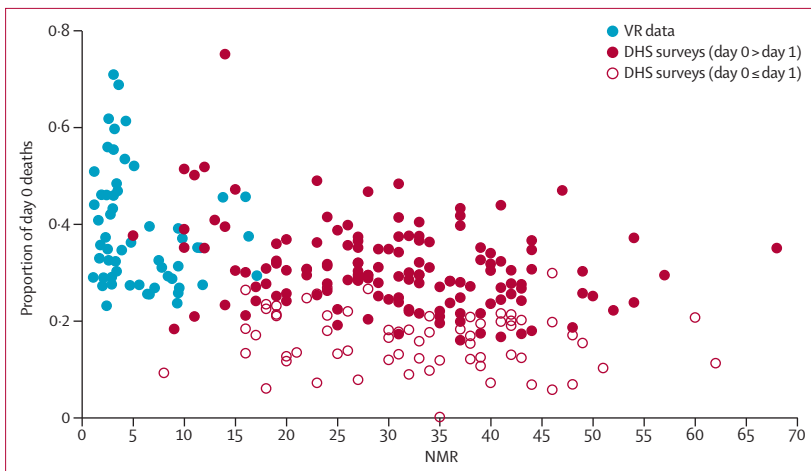

Figure 4: **Proportion of reported deaths on day 0 for national VR datasets and DHS datasets organised by NMR**
DHS=demographic and health survey. VR=vital registration. NMR=neonatal mortality rate.

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding author had full access to

all the data in the study and had final responsibility for the decision to submit for publication.

Results

Of 109 countries with VR data, 52 were excluded (figure 1, appendix). Among the 57 countries with high-quality VR data, seven reported fewer than 50 neonatal deaths in the latest year of available data. Of the 206 DHS, 15 reported fewer than 50 neonatal deaths, but we did not exclude these because deaths from all surveys were combined in our mathematical model. After exclusions, therefore, the input dataset comprised 57 countries with adequate VR data (median reporting year 2010) on 122 757 neonatal deaths and 206 DHS (median reporting year 1999) from 79 countries reporting on 50 396 neonatal deaths in the previous 5 years. Nine countries had VR and DHS data. Thus, the final input dataset contained information from 127 countries and included data on 173 153 neonatal deaths.

For countries with adequate VR data, the median proportions of neonatal deaths, by neonatal time period, were as follows: 0·35 (IQR 0·29–0·46) on day 0; 0·36 (0·32–0·42) on days 1–6; and 0·25 (0·22–0·30) on days 7–27 (figure 2). The median proportion of deaths in week 1 was 0·75 (IQR 0·70–0·78). The proportion of deaths across countries on day 0 varied more than for the other time periods. The three countries with the highest proportions of deaths on day 0 were Switzerland (0·71 [SD 0·04]), Canada (0·69 [0·02]), and Austria (0·62 [0·07]), and the three with the lowest proportions were the Czech Republic (0·23 [0·06]), Belize (0·24 [0·10]), and Macedonia (0·25 [0·07]).

Of the 79 countries with DHS data, 29 had one survey and the remaining 50 had between two and six surveys each. Across all surveys, the median proportion of reported deaths was 0·26 (IQR 0·19–0·32) on day 0, 0·19 (0·15–0·24) on day 1, 0·46 (0·40–0·52) on days 1–6 (figure 3), and for week 1 was 0·72 (0·68–0·78). The median proportion for days 0 and 1 combined was 0·46 (IQR 0·39–0·52). 66 (32%) DHS datasets had higher proportions of deaths on day 1 than day 0, which suggests substantial misclassification of deaths between these days. For surveys with higher proportions of deaths on day 0 than day 1, the median proportion of reported deaths by time period was 0·29 (IQR 0·25–0·35) on day 0, 0·16 (0·13–0·21) on day 1, 0·43 (0·39–0·48) for days 1–6 (figure 3), and for week 1 was 0·73 (0·69–0·78).

Figure 4 shows a comparison of the reported proportion of deaths on day 0 in the VR and DHS data with neonatal mortality rates and identifies DHS data with severe (number of day 0 deaths less than or equal to the number of day 1 deaths) under-reporting, misrecording, or both, of day 0 deaths. Even DHS with higher day 0 than day 1 deaths might have some misclassification. The only discernible pattern is that several countries with high-quality VR data and very low neonatal mortality rates (fewer than five deaths per 1000 livebirthds) had high reported proportions of deaths on day 0 deaths.

Our three-parameter model fitted the observed DHS data better than the two-parameter model (p<0·0001). Visual inspection of the modelled versus the observed distribution of deaths by day in the DHS data also indicated a good fit (figure 5). The poorest fit was seen on days 7, 14, and 15, which probably reflects the propensity to report deaths at 1 and 2 weeks (figure 5). The estimated parameter values from equation 1 were α=0·012 (uncertainty range 0·010–0·014), β=0·003 (0·002–0·003), and γ=0·872 (0·868–0·875).

The modelled proportions for deaths during the neonatal period were 0·36 (uncertainty range 0·34–0·38) on day 0 and 0·73 (0·72–0·74) for week 1. These estimates are similar to the median proportions seen in the VR data (0·35 for day 0 and 0·75 for week 1). Without correction for misclassification between day 0 and day 1 (ie, running the model with data for these days separated), the estimated proportions for the DHS data are 0·26 (uncertainty range 0·24–0·27) for day 0 and 0·73 (0·72–0·74) for days 0–6 (full daily proportion results are presented in the appendix). The out-of-sample validation analysis suggested good overall agreement between the observed and modelled results across surveys, and the inclusion of VR data in the model yielded similar results to DHS data alone (appendix).

The estimated proportion of deaths on day 0 did not vary importantly when assessed by neonatal mortality rate or income (table 1, figure 6). Some variation was seen between regions and survey timings (table 1, figure 6). We combined the 28 datasets from the northern Africa, western Asia, and Caucasus and central Asia Millennium Development Goals regions to form a mid-east region for our DHS analysis to avoid small numbers and because of similarities in the data and health systems. 21 (75%) of 28 DHS from this mid-east region reported fewer deaths on day 0 than on day 1, which suggests widespread undercounting of day 0 deaths, misreporting of day 0 deaths as day 1 deaths, or both. By comparison, ten (26%) of 38 DHS reported more day 1 than day 0 deaths in the Latin America and Caribbean region, which had the next highest percentage of surveys, reported with these issues. The estimated proportions of day 0 deaths did not differ substantially between the other regions. When we excluded the mid-east region from the analysis, the overall results remained largely unchanged (proportion of deaths 0·36 [uncertainty range 0·35–0·38] for day 0 and 0·73 [0·72–0·74] for week 1). For survey period, earlier surveys had, on average, lower proportions of deaths in the first few days than did later surveys. When we assessed only surveys done in 2000 or later, the proportions of day 0 and week 1 deaths were 0·39 (uncertainty range 0·37–0·41) and 0·75 (0·73–0·76).

In theory, our model requires the total number of livebirths to be known as well as the numbers of neonatal deaths per day. We found, however, that varying the number of livebirths while keeping the number of deaths fixed across a wide range of neonatal mortality rates
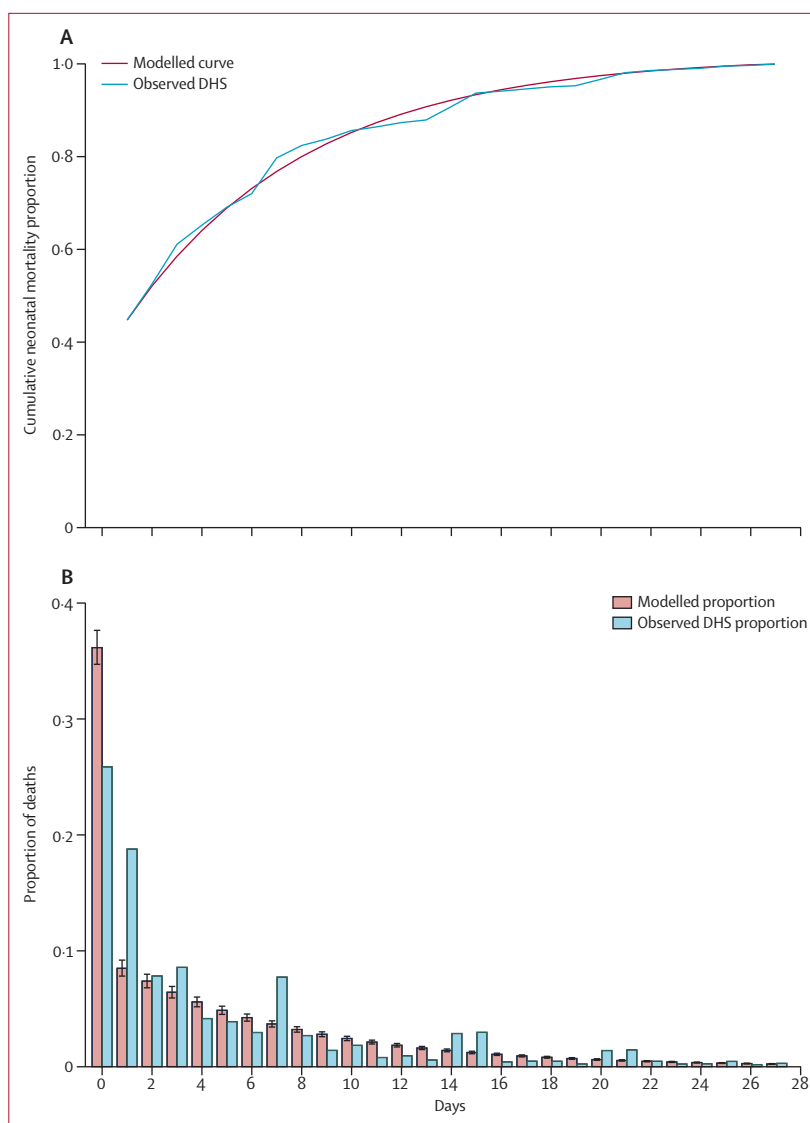

Figure 5: Observed and modelled mortality during the neonatal period
(A) Observed and modelled cumulative mortality curves. The combined proportion of day 0 and day 1 deaths is about 0·45 in the observed data and modelled estimates. (B) Daily proportions with 95% CIs. DHS=demographic and health survey.

(from 1 to 1000) resulted in negligible changes (<0·5 percentage points) to the estimated day 0 and week 1 proportions of deaths. Thus, in practice, the results do not appear to be sensitive to the number of livebirths.

Around 2·76 million neonatal deaths occurred in the 186 countries in this anaylsis.[3] Of these, an estimated 1·00 million (36·3%) occurred on day 0 (uncertainty range 0·94–1·05 million) and 2·02 million (73·2%) occurred within week 1 (1·99–2·05 million).

Of the Millennium Development Goals regions, sub-Saharan Africa had the highest risk of deaths per 1000 livebirths on day 0 and in week 1 (table 2). The risk of death for Southern Asia was slightly lower, but this region had the largest number of births and, therefore,

	Day 0 (uncertainty range)	Week 1 (uncertainty range)
Neonatal mortality rate		
≥5–<15	0·34 (0·31–0·38)	0·72 (0·71–0·74)
≥15–<30	0·37 (0·35–0·39)	0·73 (0·71–0·74)
≥30	0·36 (0·33–0·38)	0·74 (0·72–0·76)
Income		
Low	0·36 (0·34–0·39)	0·73 (0·72–0·74)
Lower-middle	0·36 (0·33–0·38)	0·73 (0·72–0·74)
Upper-middle	0·38 (0·35–0·41)	0·73 (0·70–0·75)
Region		
East Asia and southeast Asia	0·39 (0·33–0·43)	0·74 (0·72–0·78)
Southern Asia	0·36 (0·33–0·39)	0·73 (0·71–0·75)
Sub-Saharan Africa	0·37 (0·34–0·39)	0·74 (0·72–0·75)
Latin America and the Caribbean	0·39 (0·36–0·42)	0·72 (0·70–0·74)
Northern Africa, western Asia, and Caucasus and central Asia	0·28 (0·25–0·32)	0·70 (0·68–0·71)
Survey period		
1986–95	0·32 (0·30–0·35)	0·71 (0·69–0·73)
1996–2005	0·37 (0·35–0·39)	0·73 (0·72–0·75)
2006–11	0·41 (0·37–0·43)	0·76 (0·73–0·78)
Overall	0·36 (0·34–0·38)	0·73 (0·72–0·74)

Table 1: Estimated proportions of deaths on day 0 and in week 1, by subgroup

the largest number of deaths (table 2). Figure 7 shows the risk of death on the day 0 and during the neonatal period, alongside perterm brith rates, for 31 industrialised countries with high-quality VR data. In the USA and Canada, the risk of death on day 0 was 2·4 and 2·3 per 1000 livebirths, respectively, whereas in several northern European countries (eg, Norway, Sweden, and Finland) the risk was 0·6 or lower (figure 7).

Full results for the 186 countries are available in the appendix. The risk of death per 1000 livebirths ranged widely across countries in all time periods (table 3, appendix). Nine of the ten countries with the highest risk were in sub-Saharan Africa. The risk of death for these ten countries ranged from 14 to 17 per 1000 livebirths on day 0 and from 29 to 34 per 1000 livebirths in week 1 (table 3). The number of deaths during each time period also varied widely. The ten countries with the highest numbers of deaths (range 14 300–270 100 on day 0 and 28 900–546 300 in week 1, table 4) were all populous but were also affected by the level of risk.

Discussion

We estimated the risk of dying and numbers of deaths for the day of birth, first week of life, and the late neonatal period in 2013 for 186 countries in follow-up to our preliminary results.[24] Of the 2·76 million neonatal deaths worldwide, an estimated 36·3% of deaths occurred on the day of birth and 73·2% within week 1. Hence, around
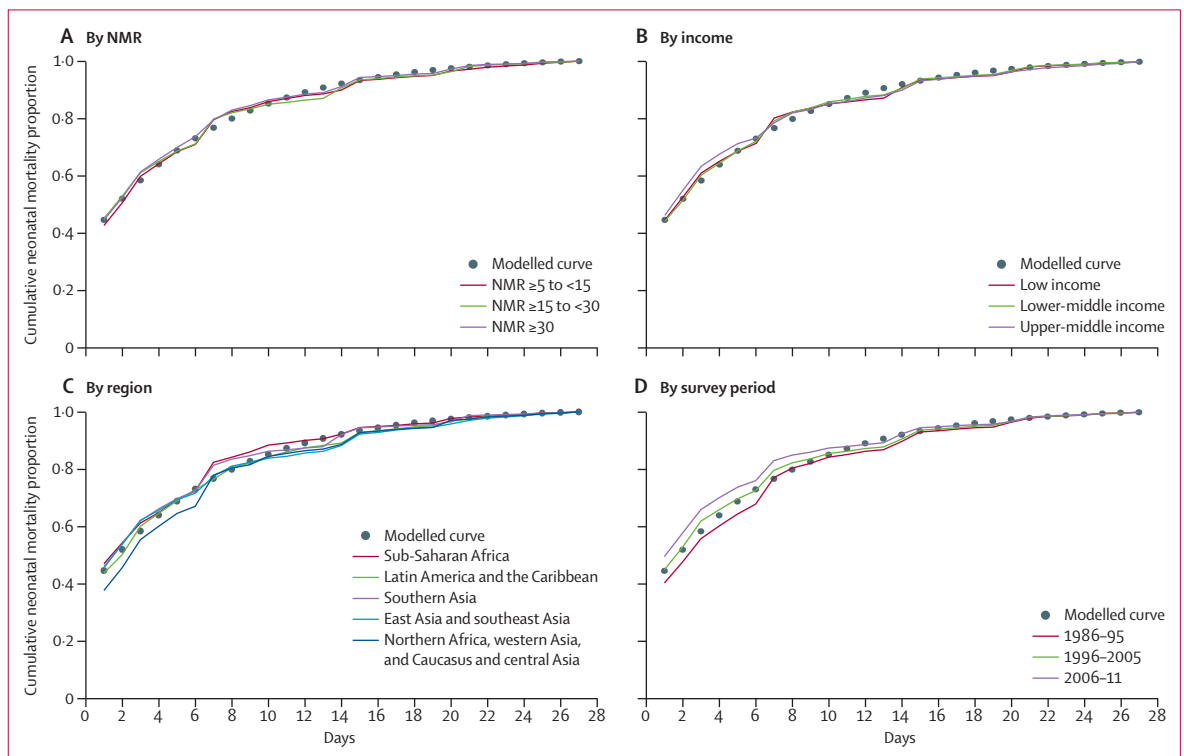

Figure 6: Observed and modelled cumulative mortality during the neonatal period by NMR, income, region, and survey period
Data are for 206 demographic and health surveys (n=50 396 neonatal deaths) from 1986 to 2011. NMR=neonatal mortality rate.

	Day 0		Week 1		Weeks 2–4	
	Risk (uncertainty range)*	Deaths (uncertainty range)*	Risk (uncertainty range)*	Deaths (uncertainty range)*	Risk (uncertainty range)*	Deaths (uncertainty range)*
Sub-Saharan Africa	11·2 (10·6–11·8)	385·2 (362·6–404·9)	22·7 (22·4–23·0)	779·1 (767·5–-788·9)	8·4 (8·1–8·7)	286·2 (276·6–297·8)
Southern Asia	10·6 (10·0–11·2)	392·3 (369·1–412·5)	21·5 (21·2–21·8)	793·3 (781·5–-803·3)	7·9 (7·7–8·2)	292·0 (282·2–303·9)
Oceania	7·7 (7·3–8·1)	2·0 (1·9–2·1)	15·6 (15·4–15·8)	4·1 (4·1–4·2)	5·7 (5·6–6·0)	1·5 (1·5–1·6)
Caucasus and central Asia	5·4 (5·1–5·7)	9·5 (8·9–10·0)	11·0 (10·8–11·2)	19·2 (18·8–19·5)	3·8 (3·6–3·9)	6·6 (6·3–6·9)
Southeastern Asia	5·2 (4·9–5·5)	58·0 (54·5–60·9)	10·5 (10·4–10·6)	117·2 (115·5–118·7)	3·9 (3·7–4·0)	43·1 (41·7–44·9)
Western Asia	4·9 (4·6–5·2)	24·0 (22·6–25·3)	10·0 (9·8–10·1)	48·6 (47·9–49·3)	3·7 (3·6–3·8)	18·0 (17·3–18·7)
Northern Africa	4·8 (4·5–5·1)	19·3 (18·1–20·3)	9·7 (9·6–9·8)	39·0 (38·4–39·5)	3·6 (3·5–3·7)	14·3 (13·9–14·9)
Latin America and the Caribbean	3·2 (3·1–3·4)	35·4 (33·8–36·9)	6·8 (6·7–7·0)	74·3 (72·7–75·9)	2·4 (2·3–2·5)	26·2 (25·1–27·3)
Eastern Asia	2·8 (2·6–2·9)	54·3 (51·1–57·1)	5·6 (5·5–5·7)	109·8 (108·2–111·2)	2·1 (2·0–2·2)	40·4 (39·1–42·1)
Developed regions	1·6 (1·5–1·7)	22·9 (21·6–24·2)	2·6 (2·5–2·7)	36·6 (35·2–38·1)	0·8 (0·7–0·9)	11·5 (10·6–12·4)
World	7·3 (6·9–7·6)	1002·7 (944·2–1054·1)	14·7 (14·4–14·9)	2021·3 (1989·7–2048·5)	5·4 (5·2–5·6)	739·8 (714·3–770·6)

*Uncertainty estimates do not include uncertainty in total neonatal deaths.

Table 2: Risk of death per 1000 livebirths and numbers of deaths (in thousands) in 2013, by Millennium Development Goals region and neonatal time period

1·0 million babies die on the day of birth, and these deaths are in addition to the 1·2 million intrapartum stillbirths that occur each year. This observation highlights the fact that the hours just before birth and the first few days of life are the most risky in the human lifespan. The risk for mothers is also increased during this period.[2]

For countries without high-quality VR data, we estimated the proportional distribution of neonatal deaths by day by aggregating DHS data from countries with a range of neonatal mortality rates. The parameter estimates we obtained (α, β, and γ), therefore, represent average values, which we used to estimate the average distribution of deaths by day. We examined whether application of this average distribution to countries with different neonatal mortality rates was appropriate by fitting the model to subsets of data. The proportion of deaths on day 0 was consistent across countries with different neonatal mortality rates and incomes. The proportions of day 0 deaths varied a little by region, but might reflect under-reporting or misclassification. The proportion of day 0 deaths also varied slightly between earlier and later surveys, with the proportion of day 0 deaths being lower in the former. We chose, however, to include all survey years in our model because whether there was a real change in proportions over time is unclear. Another multicountry study found that enumeration of child deaths was poorer in later than in earlier surveys within countries.[25] We also found that several countries with multiple surveys had wide fluctuations in the proportions of deaths on day 0 that were not in a consistently upward direction. Since the proportion of day 0 deaths was slightly higher when the analysis was restricted to the surveys done in 2000 or later, we chose a conservative approach to estimating proportions of deaths on day 0.
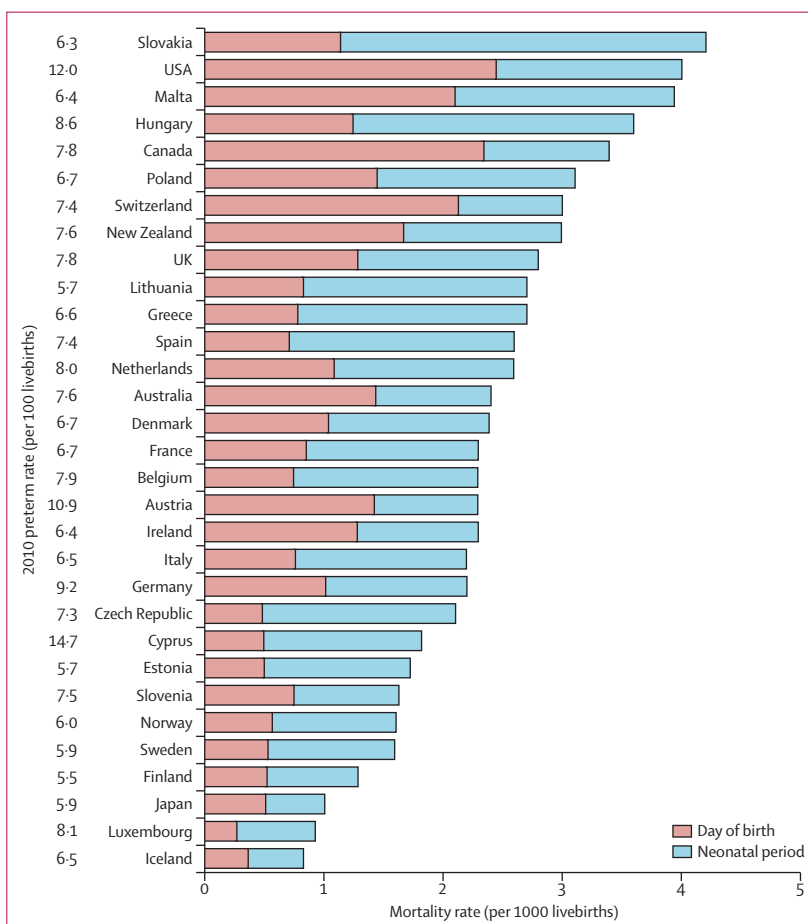

Figure 7: Risk of death on the day of birth and during the neonatal period in 2013 for 31 industrialised countries with high-quality vital registration data, with 2010 preterm rates[23]

We noted variation in the proportion of day 0 deaths for some countries with very low neonatal mortality rates (fewer than five per 1000 livebirths, figure 4). Since the availability of good neotnatal intensive care should avert most later deaths due to infection, countries with comprehensive neonatal intensive care provision might be expected to have higher proportions of neonatal deaths on day 0 and in week 1.[23,26] An effect of neonatal intensive care, however, is to shift day 0 deaths to later days, for example because preterm babies are saved by early intervention but die later from complications, such as intracranial haemorrhage or infection. Thus, while the overall risk might be lower, the proportion of deaths could remain similar owing to deaths occurring later in (or even beyond) the neonatal period.

Although the risk of death on day 0 was 30 times greater in the poorest countries than in the richest, there was also a surprising almost ten times difference in day 0 risk across the richest countries. In view of the high quality of data collection and intensive care in these countries, this variation is probably real and not an artifact of under-

	Day 0	Week 1	Weeks 2–4
Angola	17 (16–18)	34 (34–34)	13 (12–13)
Somalia	17 (16–18)	34 (33–34)	12 (12–13)
Sierra Leone	16 (15–17)	32 (32–33)	12 (12–12)
Guinea-Bissau	16 (15–17)	32 (32–33)	12 (11–12)
Lesotho	16 (15–17)	32 (31–32)	12 (11–12)
Central African Republic	16 (15–16)	31 (31–32)	12 (11–12)
Pakistan	15 (14–16)	31 (30–31)	11 (11–12)
Mali	15 (14–15)	29 (29–30)	11 (10–11)
Chad	14 (14–15)	29 (29–29)	11 (10–11)
Zimbabwe	14 (13–15)	29 (28–29)	11 (10–11)

*Uncertainty estimates do not include uncertainty in total neonatal deaths.

Table 3: Risk of death per 1000 livebirths (uncertainty range)* in different neonatal time periods for the ten countries with the highest risks in 2013

	Day 0	Week 1	Weeks 2–4
India	270·1 (254·1–284·0)	546·3 (538·2–553·1)	201·1 (194·3–209·3)
Nigeria	94·4 (88·8–99·3)	191·0 (188·1–193·4)	70·3 (67·9–73·2)
Pakistan	70·0 (65·9–73·6)	141·6 (139·5–143·3)	52·1 (50·4–54·2)
China	51·8 (48·7–54·4)	104·7 (103·1–106·0)	38·5 (37·2–40·1)
Democratic Republic of the Congo	37·8 (35·6–39·7)	76·4 (75·3–77·4)	28·1 (27·2–29·3)
Ethiopia	30·5 (28·7–32·1)	61·7 (60·8–62·4)	22·7 (21·9–23·6)
Bangladesh	27·7 (26·1–29·2)	56·1 (55·2–56·8)	20·6 (19·9–21·5)
Indonesia	23·8 (22·4–25·0)	48·1 (47·4–48·7)	17·7 (17·1–18·4)
Angola	15·4 (14·5–16·2)	31·1 (30·7–31·5)	11·5 (11·1–11·9)
Kenya	14·3 (13·4–15·0)	28·9 (28·5–29·3)	10·6 (10·3–11·1)
Total†	649·7 (611·3–683·2)	1314·0 (1294·5–1330·5)	483·7 (467·5–503·4)

*Uncertainty estimates do not include uncertainty in total neonatal deaths. †Based on rounded estimates.

Table 4: Number of deaths in thousands (uncertainty range)* in different neonatal time periods for the ten countries with the most neonatal deaths in 2013

reporting. The high preterm birth rate in North America might explain the relatively high proportion of day 0 deaths there, especially in the USA, where more than 500 000 (12%) of all births are preterm each year.[17]

The exponential function we used fitted the DHS data well. We applied the modelled estimates to countries with no day-of-death data, and to those with DHS data because substantial bias from misclassifications of day 0 and day 1 deaths was evident in some DHS. A third of DHS reported more deaths on day 1 than day 0, which is biologically implausible. In countries that had VR and DHS data (and more than 50 neonatal deaths), no DHS that reported more day 1 than day 0 deaths was supported by the VR data. In surveys with more day 0 than day 1 deaths, some deaths being misrecorded as day 1 is possible, but would be more difficult to identify. We tried to correct for this type of error by using our mathematical model on the combined surveys. We did not, however, account for misclassifications of stillbirths and early neonatal deaths, which is another well recognised issue in DHS.[27] If neonatal deaths in the first minutes of life are recorded as stillbirths (which is the most common direction of misclassification), very early neonatal deaths will be undercounted, and we would expect the proportion of deaths during week 1 to be lower than average irrespective of day 0 and day 1 misclassification.

For 19 (9·2%) of the 206 DHS, the proportions of deaths in week 1 had uncertainty values that fell outside our boundaries (centiles 2·5 and 97·5). Of these surveys, seven reported more day 1 than day 0 deaths. The remaining 12 all had low proportions of neonatal deaths for week 1 compared with the other 194 surveys (median proportion 0·60, IQR 0·56–0·63 vs 0·73, 0·69–0·78). This pattern is consistent with undercounting of early neonatal deaths.

Finally, several countries with multiple DHS had fluctuations in proportions of day 0 and week 1 deaths that are unlikely to be explained by real changes. For example, the day 0 proportion of deaths in Ethiopia varied from 0·30 in 2000, to 0·19 in 2005, to 0·42 in 2011. Because of potential poor-quality data and random errors within individual surveys, we chose to apply our model to DHS data overall to predict day 0 and week 1 proportions of neonatal deaths instead of using the raw DHS data. We also developed simple analytical methods to identify DHS with misclassifications and under-reporting (appendix).

We hope that our estimates will be improved on as better data become available. While our DHS-based model seems robust, it is not ideal to apply this one model to all countries without adequate VR data. We believe that, on average, our results adequately represent the day 0 and week 1 proportions for many of the modelled countries, but this approach masks variation between countries. Since the same proportions for day 0 and week 1 were applied to all countries with inadequate VR data, the rankings are tied to variation in neonatal mortality rates and the total number of neonatal deaths per country. Also, our uncertainty ranges do not reflect the uncertainty in

neonatal mortality rates because this information was unavailable for the most recent estimates. Thus, as with all modelled estimates, our results represent a starting point for understanding the burden of deaths on day 0 and in week 1 of the neonatal period in each country.

If relevant high-quality VR data were available for individual days, we would be able to compare our DHS-based model against these survival curves and test more complex models. For example, because we attempted to correct for misclassification of deaths between days 0 and 1, we assumed that from day 1 onwards the daily hazard declines exponentially. Our model seemed to fit the data well, but high-quality day-of-death data would be required for external validation. Currently, the VR data available through WHO are limited to the three time periods, day 0, days 1–6, and days 7–27 and, therefore, cannot be used to construct neonatal survival curves. Additionally, some characteristics, such as income and neonatal mortality rate, differ substantially for countries with high-quality VR and those requiring modelled estimates, thus making a comparison with existing data is difficult.

Another desirable improvement would be subnational estimates, particularly for countries with decentralised systems and high variability, such as India and Nigeria. Subnational estimates are seldom available even for countries with adequate national VR data, but are important for priority setting and sharing lessons within and between health systems. For example, the risk of death at day 0 per 1000 livebirths in the USA ranged from 1·3 in Alaska to 4·8 in the District of Columbia for the years 2007–10.[8] The county-level differences were even wider, from a risk of 0·9 in Hidalgo County, TX, to 6·2 in Baltimore City, MD.[8] Additionally, a few studies have assessed differences in the distributions of causes of neonatal death by day. Striking differences were found not only between deaths in the early and late neonatal periods but also between those on day 0 and on later days.[28,29] Improved understanding of the causal distribution of neonatal deaths by day is needed to improve care, but no systematic nationally comparable estimates yet exist. Finally, we did not assess sex-specific risks during the neonatal period, but this feature will be important to assess in future work.

In the coming years we need to accelerate the impressive progress being made in reducing preventable child deaths, including the burden of nearly 3 million neonatal deaths that are most frequent within the first week of life (panel 2). Effective and low-cost interventions exist but are not accessible to every woman and neonate, especially around the time of birth when both groups are most vulnerable to death and long-term disability.[2] Four simple and cost-effective interventions—steroid injections for women in preterm labour, resuscitation devices, chlorhexidine cord cleansing, and injectable antibiotics—could save the lives of up to 1 million neonates per year.[24] Improved obstetric services and neonatal care linked to

community-based programmes in low-income and middle-income countries[30,31] could prevent almost all these deaths and many of the 1·2 million intrapartum stillbirths, and 289 000 maternal deaths[4] each year.[32,33] The Every Newborn action plan,[34] which was endorsed at the 2014 World Health Assembly by more than 190 countries, is an important step towards accelerating progress. This plan sets explicit targets of ten or fewer neonatal deaths per 1000 livebirths and ten or fewer stillbirths per 1000 total births by 2035 for all countries. Around the world, a marker of development is when a society no longer accepts that stillbirths and neonatal deaths are inevitable, that babies can be named at birth and counted in national data systems, and that a baby's day of birth should not be his or her last.

Panel 2: Research in context

Systematic review

The risk of dying in the first few days of life is much higher than in any other period during the human lifespan. Nevertheless, data on deaths by day during the neonatal period are not collected in most countries. We searched PubMed, Web of Knowledge, and Google Scholar with the terms "neonatal", "newborn", and one or more of "day of birth", "day 0", "day 1", "deaths", "mortality", "risk of death by day", "survival", "survival curves", "day 0 risk", "day 1 risk", "temporal distribution", "day of death", and "time of death", but found no systematic national estimates of the daily risk of death during the neonatal period. We obtained data from WHO for countries with civil registration systems. 57 countries with 122 757 neonatal deaths met our inclusion criteria for high-quality vital registration data. We also searched for nationally comparable surveys that consistently collected information on neonatal deaths by day. We identified 206 suitable demographic and health surveys from 79 countries recording 50 396 neonatal deaths, which we used to develop a model that we applied to 129 countries without adequate vital-registration data. Hence we produced estimates for the risk and number of deaths during the neonatal period for 186 countries.

Interpretation

In 2013, 1·00 million (36·3%) of 2·76 million neonatal deaths occurred on the day of birth (uncertainty range 0·94 million to 1·05 million). In week 1 of life, 2·02 million babies died (1·99 million to 2·05 million). Atlhough substantial progress has been made in other areas of child health, the neonatal period, and particularly the first few days after birth, has been relatively neglected. By understanding the tremendously high risk of death in the days immediately after birth, policy makers and health-care providers can prioritise urgently needed interventions. Improved neonatal care linked to maternity care will be a crucial step for reducing the risk of neonatal mortality. Several simple and cost-effective interventions exist that can substantially reduce early neonatal mortality in even the poorest settings.

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