Under-five cause- and age-specific mortality in the US: An adaptation of the log-quadratic model

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Abstract

Young children under five years of age are at elevated overall mortality risk with respect to adults, which is closely related to specific causes such as pneumonia and premature birth. The mortality pattern from birth to age five is also expected to vary by cause. However, to date the causes of child death have only been described for broad age categories such as neonates (0–27 days), infants (1–11 months) and children age 12 to 59 months, or among older children, and existing methods have not comprehensively estimated under-five cause- and age-specific mortality (U5-CASM). Previous research has attempted to quantify U5-CASM in China by extending the log-quadratic model originally proposed by Wilmoth and colleagues to estimate all-cause mortality. However, this study is limited by the quality of the Chinese sample registration data, which is likely suboptimal compared to that of many well-functioning vital registration (VR) systems. In this context, our present research has two main goals. First, to investigate U5-CASM patterns in the United States using a high age resolution, with especial focus on the US context, some of its main causes of death such as congenital malformations and preterm births, and the potential effects of the opioid crisis. Second, to validate the extension of the log-quadratic model for U5-CASM using high quality VR data from the US.

1 Introduction

Reducing under-five (child) mortality has been a priority for countries and the broader international community for decades, but was given added impetus by the Millennium Development Goals (MDGs) established by the United Nations in 2000. In the past

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decade, estimates for the causes of death among young children have become available for all countries, including those where health system and vital registration functioning is low (Liu et al. 2016b; Naghavi et al. 2017). These estimates are a necessary input to governments and international organizations for planning health programs, government and program accountability, and other tracking purposes. The Sustainable Development Goals (SDGs), which followed on from the MDGs, include targets of 25 or fewer under-five deaths and 12 or fewer neonatal deaths per 1,000 live births for all countries by 2030 (United Nations 2015).

As governments and the international community increase their investment in developing and implementing age-targeted disease-specific childhood interventions and policy (Victora et al. 2000; Aponte et al. 2009; Glass et al. 2012; Sobanjo-ter Meulen et al. 2015; Penny et al. 2016; World Health Organization 2017) their effectiveness requires more detailed knowledge of the age patterns of under-five mortality and the primary causes at each age. The majority of these deaths, however, occur in low and middle-income countries (LMICs) without high quality vital registration (Liu et al. 2016b), creating massive uncertainty about cause- and age-specific child mortality. Moreover, national under-five cause of death estimates for LMICs are usually available for two age groups, 0–27 days and 1–59 months (Liu et al. 2016a), but empirical evidence indicates that under-five causes of death are not uniform within broad age groups (Snow et al. 1997; Ahmed et al. 1999; Wolfson et al. 2009; Fischer Walker et al. 2013). The Global Burden of Disease study further disaggregates 1–59 months into 1–11 months and 12–59 months (Wang et al. 2016), yet it still hides heterogeneity among 1–11-month and 12–59-month olds.

In the United States, high quality vital registration (VR) data on causes of death is available at CDC WONDER (2018) (see Sect. 3 for additional details). A recent study by Cunningham et al. (2018) analyzes these data and provides estimates and time trends on causes of death from 1999 to 2016. However, their estimates are for a broad age group from 1 to 19 years, which includes children and adolescents. Hence, a study focusing specifically on under-five cause- and age-specific mortality (U5-CASM) in the US with high age resolution is still needed.

Existing methods have not comprehensively estimated U5-CASM. Instead, they often estimate cause distributions for broad age groups in different frameworks (Liu et al.

2016a). In addition, these estimates do not appear to capture sufficient variation in cause of death by age. For example, 72% of diarrhea and 81% of pneumonia deaths occur in the first two years of life (Fischer Walker et al. 2013). Pneumonia- and diarrhea-specific mortality fractions peak at 0–11 months, then decline substantially at 12–23 months to stabilize at a very low level at 23–59 months. Malaria (Snow et al. 1997), measles (Wolfson et al. 2009), and injury are other examples with important age patterns (Ahmed et al. 1999). A complete mortality profile for a given age group would account for the complex interplay of causes of child mortality, across the spectrum of ages under five in a systematic estimation framework.

To address this gap in the literature, Perin et al. (2019) have recently developed an extension of the log-quadratic model proposed by Wilmoth et al. (2012), which estimates cause- and age-specific mortality using data from the Chinese Maternal and Child Health Surveillance System. However, the study is limited by the quality of these data, which is likely suboptimal compared to that of many well-functioning VR systems. In this context, our present research has two main goals. First, to investigate U5-CASM patterns and trends over time in the US using a high age resolution, with especial focus on the US context, some of its main causes of death such as congenital malformations and preterm births, and the potential effects of the opioid crisis. Second, to validate the model by Perin et al. (2019) using high quality VR data from CDC WONDER (2018).

2 Methods: An adaptation of the log-quadratic model

Although there have not been comprehensive methods to estimate U5-CASM, there are existing models for predicting age-specific patterns of all-cause mortality among people of all ages with a matrix decomposition approach (Lee and Carter 1992; Sharrow et al. 2014) or given mortality in a selected age group (Brass 1971; Murray et al. 2003; Wilmoth et al. 2012; Clark 2019). These methods often use a measure of under-five mortality as an index for projecting adult mortality, in part because high quality estimates of under-five mortality are available for most areas and over time with more reliability than for older ages (UN IGME 2017).

Motivated by this general approach, Perin et al. (2019) quantify U5-CASM by ex-

tending the log-quadratic model originally proposed by Wilmoth et al. (2012) to estimate all-cause mortality. The log-quadratic model benefits from a parsimonious use of the all-cause under-five mortality and has a straightforward interpretation. Specifically, the model can be defined by

$$\log({}_xq_0) = a_x + b_x \log({}_5q_0) + c_x \log({}_5q_0)^2 + \nu_x k \ , \tag{1}$$

where ${}_xq_0$ is the probability of dying from birth up to age x, x is a pre-selected age less than five years, and $\log({}_5q_0)$ is the natural logarithm of the probability of dying between birth and age five. Parameters a_x, b_x, c_x, and ν_x are estimated using observed values of ${}_5q_0$ and ${}_xq_0$ for each age group of interest from areas with vital or sample registration of under-five deaths. Parameter ν_x represents the pattern of departure from the typical age-specific mortality at a given ${}_5q_0$ and is estimated from the singular value decomposition of the matrix of residuals, whereas k represents the degree to which a specific life table varies from the average life table at a given ${}_5q_0$. It can be interpreted as the deviation from the average pattern in a life table and can be tailored to fit ${}_xq_0$ for a specific age group x or to match the mortality over a given age range (Wilmoth et al. 2012).

We model cumulative probabilities of death ${}_xq_0$ instead of death rates (as used by Wilmoth and colleagues) to avoid zero values for some narrow age groups in settings with very low mortality. Cumulative probabilities have the advantage of being more stable, although violations are possible if predicted ${}_xq_0$ are lower than ${}_yq_0$ for ages $0 < y < x$, which is contrary to the interpretation of ${}_xq_0$. In the event of these violations, ${}_yq_0$ will be restricted such that ${}_yq_0 < {}_xq_0$ for $0 < y < x$.

Following Perin et al. (2019), we adapt the model defined in (1) to cause-specific relationships. Given cause of death data with known under-five cause-specific probability of dying ${}_5q_{0,c}$, the extended model is given by

$$\log({}_xq_{0,c}) = a_{x,c} + b_{x,c} \log({}_5q_{0,c}) + c_{x,c} \log({}_5q_{0,c})^2 + \nu_{x,c} k \ , \tag{2}$$

for age x and cause c. We focused on children of ages 0–23 hours, 1–6 and 7–27 days, 1–11 months, and single-year age groups from 1 to 5 years. For each of these age groups, we focused on all-cause mortality and the main causes of death among children in the US.

3 Data: CDC WONDER

We use data from the Wide-ranging Online Data for Epidemiologic Research of the Centers for Disease Control and Prevention (CDC WONDER). In particular, we use cause- and age-specific mortality estimates from the Underlying Cause of Death database, which provides estimates for the period 1999–2017. This database contains mortality and population counts for all counties in the United States, based on death certificates. Each death certificate identifies a single underlying cause of death and demographic data. The data publicly available include the number of deaths, crude death rates or age-adjusted death rates, and 95% confidence intervals and standard errors for death rates by place of residence, age group, race, gender, year, cause-of-death (ICD-10 code or group of codes), injury intent and injury mechanism, drug/alcohol induced causes and urbanization categories. Data are also available for place of death, month and week day of death, and whether an autopsy was performed (CDC WONDER 2018).

4 Preliminary results

Preliminary results suggest a strong linear relationship between age-specific mortality for ages under five and the probability of dying between birth and age five ($_5q_0$) in the United States, which makes the log-quadratic model by Wilmoth et al. (2012) suitable. We aim to carry out a more thorough analysis of the CDC WONDER data and model calibration to validate the method proposed by Perin et al. (2019). We expect to provide under-five all-cause and cause- and age-specific estimates for the US for the period 1999 to 2017, with high age resolution and the state as geographical unit of analysis.

While vital and health systems are working to register all under-five deaths, we have an opportunity to leverage information already available from areas with high and medium quality registration. If age and cause patterns were better understood, they have the potential to refine current tools and guide further reduction of child mortality in the era of the Sustainable Development Goals. Future research could determine the appropriateness of these methods for estimating U5-CASM using lower quality verbal autopsy cause of death data.

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