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*Kenneth Hill*



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## NOTES



The term “country” as used in this paper also refers, as appropriate, to territories or areas.

This publication has been issued without formal editing.

# PREFACE

This technical paper focuses on the current state of knowledge about analytical methods to evaluate the completeness and quality of death registration. A variety of methods have been proposed for assessing the completeness and quality of child and adult death registration. Almost all measures describe the completeness of registration in comparison to the completeness of population data. This paper summarizes available methods and compares their performance. It shows that methods to evaluate the completeness of registration for child deaths rely primarily on comparisons with known empirical regularities or with other types of data deemed more accurate. Concerning adult deaths, methods for assessing completeness of registration rely on comparisons with other types of data, specifically census age distributions, and on mathematical relationships between deaths and population by age. Results from systematic evaluations of death distribution methods have shown that these methods work well when applied to data that conform to their assumptions, but that these methods are sensitive to the effects of migration and errors that are not proportional by age. Those evaluations have also shown that more reliable estimates of completeness can be obtained by combining two of these methods (the Generalized Growth Balance method and the Synthetic Extinct Generations method) and using appropriate age ranges to exploit maximally the respective strengths of each method.

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## ANALYTICAL METHODS TO EVALUATE THE COMPLETENESS AND QUALITY OF DEATH REGISTRATION: CURRENT STATE OF KNOWLEDGE

*Kenneth Hill*

### 1. INTRODUCTION

The United Nations' Sustainable Development Goal 3 includes specific targets for reducing maternal mortality and under-five mortality and calls for the strengthening of systems for early warning of national and global health risks. Monitoring progress towards the targets is best achieved through fully-functional civil registration and vital statistics (CRVS) systems, which also serve as effective early warning systems for emerging health risks. Almost all countries have a civil registration (CR) system, but in most low- and middle-income countries the systems are not fully-functional and fail to provide accurate vital statistics: they lack completeness or quality or both. In order to use the systems for monitoring vital statistics, it is essential to be able to evaluate both completeness and quality. Analytical methods have been developed over the past half-century for carrying out such evaluations; it is the purpose of this paper to summarize available methods and compare their performance.

### 2. CONCEPTUAL ISSUES

In discussions of CRVS systems, the words coverage and completeness are often used interchangeably. However, they describe different concepts. The coverage of a CRVS system describes the target population for which civil events are to be recorded. The target population is generally the usually-resident national population, and the United Nations recommendations are that "a vital statistics system should include all vital events occurring in every geographical area and in every population group of the country" (United Nations, 2014), but in some instances it may be the population of citizens, resident or otherwise, or the population of legal residents. This paper will assume that the target population is the usually-resident national population. The completeness of a national CRVS system describes the extent to which the system records events that occur to the target population; in the most common situation, this will be the proportion recorded of events that occur to members of the usually-resident national population. A crude demographic rate calculated from events adjusted for completeness divided by the resident national population would therefore be unbiased. If measures are to be calculated for sub-national populations, events should be classified by place of usual residence rather than place of occurrence, and populations by usual residence. (See United Nations (2004) for a more detailed discussion).

The analytical methods reviewed in this paper all focus on the calculation of unbiased measures of mortality, typically rates and summary measures such as life expectancy generated from rates. Since rates are calculated as numbers of events divided by exposure time, estimates of completeness of death recording are all relative to the completeness of recording of exposure time. For the purposes of mortality monitoring or analysis, it is such relative estimates that matter. However, from the perspectives of social protection or seeking evidence on how to improve a CR system, it is absolute completeness that is important and relative completeness is an imperfect yardstick for assessing the functioning of a CRVS system. Although absolute completeness and relative completeness will be closely related, they are not the same thing, and analytical methods do not directly address the former. The only approaches that do address the former are dual- or multiple-record methods, addressed in a companion paper (Rao, 2017).

Quality describes the accuracy of the information collected about recorded events. The minimum pieces of information that must be collected about recorded deaths if the data are to be of use for monitoring purposes are sex, age and cause of death, but additional pieces of information, such as place of residence, place of occurrence, education and occupation will greatly enrich potential analyses. A further source of error arises from delayed registration, whereby events are not registered within the time limits, often a month, prescribed by legislation. Delayed registration is typically a larger problem for birth registration than death registration, but still raises the question of how to treat such deaths: should one analyze deaths registered in a year, regardless of year of occurrence, or deaths that occur in a year, a number that is subject to future modification as late registrations are recorded? This issue is treated in more detail in United Nations (2004); this paper will only consider the quality of sex and age recording and will focus on deaths recorded by date of registration.

## 3. A TYPOLOGY OF ANALYTICAL METHODS USED IN EVALUATION

Many different evaluation methods have been proposed over the last 50 years or so, but they can be categorized into three broad groups: those that compare CRVS-based estimates to estimates for the same target population derived from other data presumed to be more accurate; those that compare patterns in CRVS data (for example by age or by sex) to empirical regularities from populations with CRVS data presumed to be accurate; and those that employ mathematically-derived relationships of population structure to compare CRVS information with other demographic indicators such as the population age distribution. Different method types tend to be used for different age ranges: child (say up to age 15) death evaluations rely on comparisons with other data or empirical regularities, whereas adult (15 years and over) death evaluations tend to rely on mathematical relationships and to some extent on comparisons with other data and on empirical regularities. Since the methods tend to be different, child and adult registration evaluations will be treated in separate sections.

In what follows, the term “completeness” should be interpreted as completeness relative to some exposure-related denominator, not as absolute completeness. Each section will have two parts, one focused on data completeness and the other on data quality.

## 4. CHILD DEATH REGISTRATION

The focus of the international and non-governmental organization (NGO) communities in recent years has been on reducing under-five mortality, specifically the probability of dying by age five, ${}_5q_0$. However, recent analysis (Hill and others, 2015) has shown that mortality risks between the ages of 5 and 15 years, although much smaller than those before the age of 5 years, are not negligible. It is also more convenient to draw the line between childhood and adulthood at age 15 for methodological reasons: age 15 is close to the inflection age of mortality risks, and mortality up to about age 15 can be reasonably measured by survey birth histories. In what follows therefore, child deaths are regarded as those up to age 15 years and adult deaths as those that occur after age 15 years.

*4.A. Methods for assessing the completeness of child death registration*

As noted in Section 3, evaluations of the completeness of child death registration rely on comparisons with other data or empirical regularities rather than on the use of mathematical population relationships. Mathematical relationships are of little value for a number of reasons. First, one potential basis for comparison, the age distribution of young children, is much more affected by numbers of births than by child mortality, and would therefore be affected by possible errors in birth registration. Second, age distributions of young children are often distorted by age misreporting or age-specific variations of completeness of census or survey enumeration. Third, with a focus that is necessarily on young children because it is at young ages where substantial numbers of deaths occur, the number of comparison points is severely limited, reducing the potential power of formal relationships.

*4. A.1. Comparisons with other estimates*

The value for assessing completeness of CR recording of child deaths based on comparisons with other data depends on the assumption that other data may be more accurate. The most widely available data on child mortality for countries with CRVS systems of uncertain quality are from the full birth histories collected by the Demographic and Health Survey (DHS) programme (Rutstein and Rojas, 2006) and to a lesser extent by the United Nations Children Fund (UNICEF) Multiple Indicator Cluster Survey (MICS) programme (UNICEF, 2015), or other similar household surveys. Analyses of DHS birth history data on child mortality indicate that they are generally of good quality, though some surveys suffer from omission of child deaths relative to births, displacement of events in time, or misreporting of ages at death (Curtis, 1995; Pullum and Becker, 2014). DHS estimates of the overall level of under-five mortality (U5MR, ${}_5q_0$) are thus of generally good quality, though estimates of its components, that is, neonatal, post-neonatal, infant (${}_1q_0$) and child (${}_4q_1$) mortality, may be less accurate. The evaluation comparison involved is straightforward: the ratio of the ${}_5q_0$ calculated from CRVS data to that recorded for a comparable time frame (usually for sampling precision for a 5-year period) from a nationally-representative DHS or MICS.

Comparisons of summary measures of child mortality such as U5MR calculated from CRVS data with birth history estimates can provide measures of CRVS completeness, but are of limited value for deriving estimates from the data. CRVS-based estimates adjusted for completeness on the basis of comparisons with birth history estimates would be no better than the birth history estimates themselves, and the creation of a time series of such estimates would require the assumption that CRVS completeness was constant over time, a strong assumption particularly if efforts to improve completeness are underway. The internal detail in terms of age and sex of such CRVS estimates could well be less accurate than the survey estimates, since completeness of registration is known to vary by sex and age at death of child.

Other widely-available data for estimating child mortality come from women's reports of summary birth histories (number of children ever born and number that have died). The estimation methods applied to such data require strong assumptions about age patterns of child mortality and about recent changes in fertility and mortality; they cannot provide estimates for specific time periods in the past. Historically, the most widely-used indicator of mortality risks in childhood has been the conventional infant mortality rate (IMR), calculated from CRVS data as the ratio of infant deaths in a year divided by live births in the same year, a measure typically quantitatively close to the life table probability of dying by first birthday $_1q_0$. Survey data on the survival of most recent births have been proposed as a basis for estimating $_1q_0$ for a specific time period before the survey (Blacker and Brass, 2005), but because of selection biases the method tends to result in underestimates (Hill, 2013). As discussed in more detail later, population censuses in countries lacking fully-functional CRVS systems sometimes collect information on deaths by age and births in the 12 months before the census. If the census data were deemed accurate, the adequacy of the CRVS data could be assessed by comparing the two IMR's; however, such census data are typically of uncertain accuracy, and would themselves need evaluation before use for such a purpose.

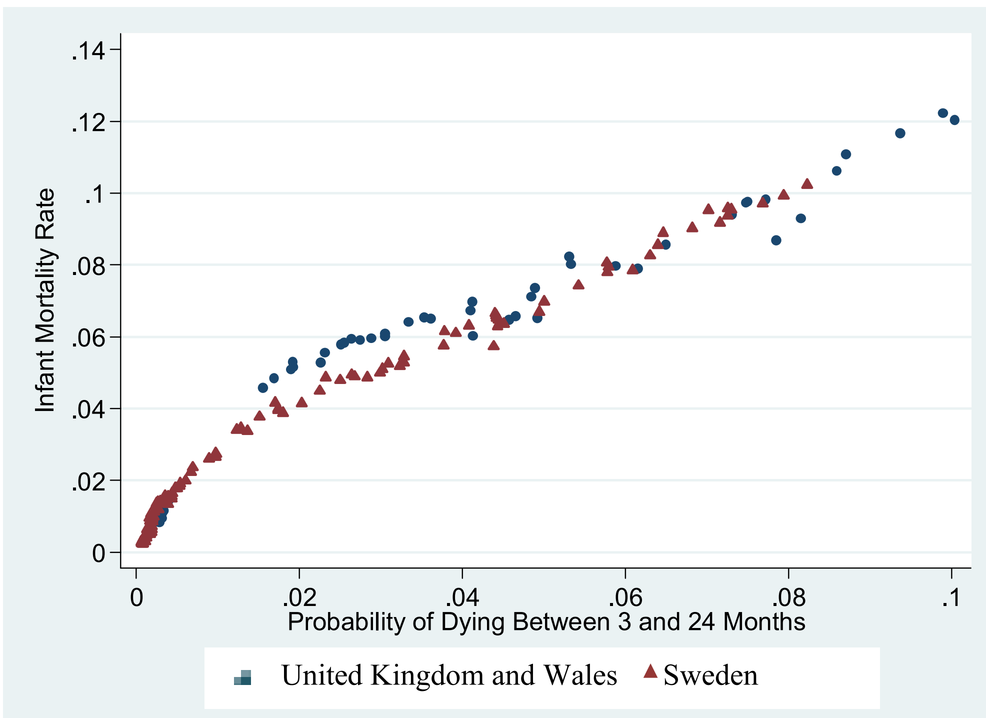
It is convenient to cover under the heading of "other estimates" a development over the last decade or so of not considering individual data sets or the application of a single methodology in isolation, but rather combining results from all available data sets and all available methods over long time periods. This approach has been applied most widely to the estimation of child mortality (for example, Rajaratnam and others, 2010; Alkema and others, 2013b). By utilizing estimates for different types of data and methods for overlapping time periods, the approach not only produces improved estimates for clearly-specified time points but also provides information about the relative performance of different methods and makes it possible to arrive at estimates of uncertainty around point estimates. Comparing CRVS estimates against such composite estimates provides the strongest basis for assessing registration completeness.

*4. A. 2. Comparisons with empirical regularities*

Historical data from countries with high-quality CRVS systems and contemporary data from prospective studies indicate (in the absence of epidemics such as HIV with abnormal age patterns of child mortality) robust relationships between age and sex patterns of child mortality and the overall level of under-five mortality. Regardless of data collection system, under-recording of child deaths appears to be most prevalent for deaths of very young children, and this appears to be particularly the case for data generated by CRVS systems. Calculation of ratios of (for example) early neonatal deaths to late neonatal deaths, neonatal deaths to post-neonatal deaths, or even death rates (or probabilities of dying) under one to those between the ages of one and five years, and comparison with the ratios calculated from accurate data can reveal CRVS omissions that are age-dependent. An additional ratio that may be informative is that of stillbirths to early neonatal deaths: where considerable energy is put into reducing early child deaths, with additional reporting requirements, early neonatal deaths may possibly be misclassified as stillbirths to avoid extra scrutiny. These comparisons are best made with data from high-quality CRVS systems; age patterns of child mortality from DHS or MICS surveys are often distorted by over-reporting of deaths at age 12 months and by possible under-reporting of deaths in the first month of life.

Unlike comparisons with other estimates, comparisons with empirical regularities can, given certain assumptions, be used for adjustment of CRVS estimates. Guillot (2013) applies this approach to CRVS data from Kyrgyzstan. The United Nations definition of a live birth includes any product of conception that breathes or shows any other evidence of life after delivery (United Nations, 2014). Prior to the breakup of the Soviet Union, formerly Soviet Republics used a definition of live birth that excluded a substantial proportion of early neonatal deaths. Most former Soviet Republics had adopted the United Nations definition after independence, but implementation of the new definition was slow, with the result that infant mortality was under-estimated even after independence. Guillot shows that the probability of dying between the beginning of the fourth month of life and second birthday, 21q3 (in months), is closely related to the infant mortality rate (IMR) in historical data from Sweden and the United Kingdom of Great Britain and Northern Ireland and Wales (figure 4.1), and calculates this measure from the CRVS data of the Kyrgyz Republic by single month of age. He then used the observed 21q3 combined with the historical relationship to estimate Kyrgyzstan's IMR; this estimate will be unaffected by either omission of child deaths prior to three months of age or misreporting of age at death around first birthday (a common problem with birth history data), though it will of course still be affected by any omission between 3 and 24 months of age. The time trend in the adjusted IMR closely follows that indicated by DHS data, but has the advantage of providing an annual sequence of estimates, not available from DHS because of sampling errors, thus allowing a much more detailed assessment of IMR trends.

**Figure 4.1: Relationship between IMR and 21q3: United Kingdom and Wales and Sweden**




Additional regularities in child mortality that could be used for evaluation are the difference by sex, education of mother, socio-economic status and type of place of residence. For example, male children almost always have higher mortality risks than female children, and the differences vary systematically by age range and with the overall level of child mortality (Hill and Upchurch, 1995; Alkema and others, 2014a). Similarly, children born to better-educated women almost always have lower mortality risks than those born to less-well educated mothers. However, real differences appear to exist in these relationships between populations, so they are less useful than age differences in the evaluation of CRVS data. Also, registration of events may also vary along these dimensions, so real differences could interact with recording errors to give the appearance of plausible patterns.

*4.B. Methods for assessing the quality of child death registration*

In the case of child deaths, determination of accuracy in terms of age and sex reporting overlaps with methods for assessing completeness, and has therefore been covered in section 4. A. 2.

## 5. ADULT DEATH REGISTRATION

Following the discussion at the beginning of Section 4, for the purposes of this paper adult deaths are those that occur from age 15 years and onwards.

*5. A. Methods for assessing the completeness of adult death registration*

Most of the methods described in the following sub-sections are illustrated by application to a single data set, the female population of the Republic of Korea as recorded by the censuses of 1975 and 1980 and deaths as registered in 1978, approximately the mid-point of the census interval. These illustrative applications are not presented as evidence of what works and what doesn't, since a single data set cannot incorporate a wide range of possible errors, but the applications are nonetheless revealing. This is an interesting case study since death registration was improving rapidly, but had not yet reached 100 per cent for female deaths. It should be noted, however, that in one respect the Republic of Korean data are not typical of most low and middle-income countries (LMICs), since the quality of age reporting is unusually good, and results may therefore be abnormally positive. More rigorous tests of the methods using simulations and applications to data presumed to be accurate are discussed in section 6.

*5. A. 1. Comparisons with other estimates*

The strongest estimates of adult mortality not making use of age patterns of deaths are derived from some form or other of intercensal survival using two census age distributions (Age Distribution Methods (ADMs)). These methods have a very long history (United Nations, 1949; 1967; 1983), and are based on the truism that, with accurate recording and in the absence of migration, the ratio of the population of a cohort at a second census to the population of the cohort at the first census is equal to the intercensal survival ratio of the cohort. With an intercensal interval of 10 years, and data arranged in five-year groups, calculations are simple and the resulting survival ratios easy to turn into a standard live table survivorship function which can then be compared to life table measures derived from CRVS data to estimate the completeness of the CRVS system. This simple approach has a number of pitfalls however: a change in completeness of enumeration from one census to the next can have a huge effect on the estimates; migration may not be negligible and is usually less well recorded than deaths; the intercensal interval may not be exactly 10 years; and age reporting may not be accurate, to name a few.

The history of these methods has essentially consisted of an evolution of ways for circumventing these pitfalls. Early methods used model life tables (Courbage and Fargues, 1979), cumulation and often an assumption that the underlying population was demographically stable (United Nations, 1967).

In the late 1970s, methods were introduced that replaced the direct use of cohorts by the use of population age structure and growth rates, initially assuming stability (Preston and Hill, 1980; Preston and others, 1980) and subsequently using age-specific growth rates for generalized closed populations (Preston and Bennett, 1983; Preston, 1983). The use of growth rates was seen as advantageous, first, because they are unaffected by age reporting errors that are proportionately constant in both censuses (though of course the age distributions to which they are applied remain distorted), and second, because it simplifies applications to censuses that are not exact multiples of five years apart. Since few, if any, populations can be regarded as stable today, this paper will only review methods that do not require the assumption of stability.

The essence of the Preston-Bennett method is to use cumulated intercensal age-specific growth rates to reduce an average of the two census age distributions to a stationary, life table age distribution from which all required summary measures can be derived. The basic relationship is

$$ {}_5L_x \approx {}_5N_x * \exp\left( \sum_{y=0}^{x-5} \left(5 * {}_5r_y\right) + 2.5 * {}_5r_x \right) * \frac{\ell(0)}{B} \qquad (1) $$

where ${}_5N_x$ is the average population aged x,x+5 and ${}_5r_x$ is the intercensal growth rate for that age group. $B$ is the average annual number of births, $\ell(0)$ is the radix of the life table of which ${}_5L_x$ is the person-years lived between exact ages x and x+5.

From Equation (1), the connection to conventional intercensal survival is clear: survivorship ratios such as ${}_5L_{x+10}/{}_5L_x$ can be calculated from the average intercensal age distribution ${}_5N_{x+10}$ *and* ${}_5N_x$ plus cumulated age-specific growth rates, since the constant term $\ell(0)/B$ cancels out. Preston and Bennett originally proposed using equation (1) to estimate a series of life expectancies at ages $x$ (for $x$ 5 and over) by cumulating ${}_5L_y$ terms for all ages older than $x$ to obtain $T_x$, and then divide by an estimate of $\ell(x)$ obtained by averaging ${}_5L_{x-5}$ and ${}_5L_x$. The (minor) problem with this procedure versus estimating survivorship ratios is that it requires a term for the open age interval, the width of which will not be five years, and the mid-point of which (for cumulating growth rates) will not be 2.5. Individual survivorship ratios are far too unstable because of data errors to be used to estimate coverage, but such ratios can be used to calculate survivorship over a much larger age range while still excluding the open interval. There are several ways to implement this, for example, fitting a parametric or non-parametric curve to the $T_x$ function and then recovering ${}_5L_x$ terms from it, or to compute the partial life expectancy between age 15 and 65 years; a third option, which is applied here, is to approximate $\ell(15)$ and $\ell(65)$ by averaging the adjacent ${}_5L_{x-5}$ and ${}_5L_x$. values. All three approaches add some smoothing to the results, but are still affected by errors around ages 15 and 65 years; the third approach is chosen here because it provides an estimate more immediately comparable to other methods to be applied in this section.

Table 5.1 compares the probability of surviving between 15 and 65 years using data for the female population from the Republic of Korea for the intercensal period 1975 to 1980 with the observed life table calculated using registered deaths for 1978; probabilities of surviving to exact ages x are estimated by averaging the 5Ly on either side of x. The probabilities of surviving from the Preston-Bennett method are somewhat lower than those in the life table based on registered deaths, suggesting that death registration was approximately 85 per cent complete. As further analysis will show, this is probably an over-estimation of true completeness: migration, age exaggeration or census coverage change have biased upwards the survival estimates from the Preston-Bennett method.

TABLE 5.1: ESTIMATES OF COMPLETENESS OF DEATH REGISTRATION; REPUBLIC OF KOREA, FEMALES, 1975-1980

| | | *Method* | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | *Preston Integrated* | | | | | |
| *Measure* | *Observed* | *Preston-Bennett* | *From Birth* | *From Age 5* | *SEG* | *SEG Adjusted* | *GGB 40-70* | *GGB 15-65* |
| l(65)/l(15) | 0.7748 | 0.7420 | 0.7336 | 0.7332 | 0.7107 | 0.6899 | 0.6763 | 0.6921 |
| Completeness (%) | na | 85.5 | 82.3 | 82.2 | 74.7 | 68.7 | 65.2 | 69.3 |
| k1/k2 | na | na | na | na | na | 0.988 | 0.972 | 0.988 |

The Preston Integrated Method (Preston, 1983) provides a second approach for estimating a life table from two census age distributions. This approach requires in addition to two age distributions an approximate representation of the population probability of surviving from birth, $p^s(x)$, function (using a one parameter logit transformation) and, if available, an independent estimate of the probability of surviving to age 5 years, $p(5)$. The basic expression is derived from the equation for the age structure of a general population closed to migration in terms of survivorship ratios and growth rates, and is a generalization of the cumulative variant of the Ogive method (Coale and Demeny, 1967; Palloni and others, 2016). By rearranging the equation and expressing survivorship in terms of the logit of a standard life table multiplied by a constant, Preston arrived at

$$\frac{\exp\left(-\int_0^x r(y)dy\right)}{c(x)} = \frac{1}{b} + \frac{\tau}{b} * \left(\frac{1-p^s(x)}{p^s(x)}\right) \qquad (2)$$

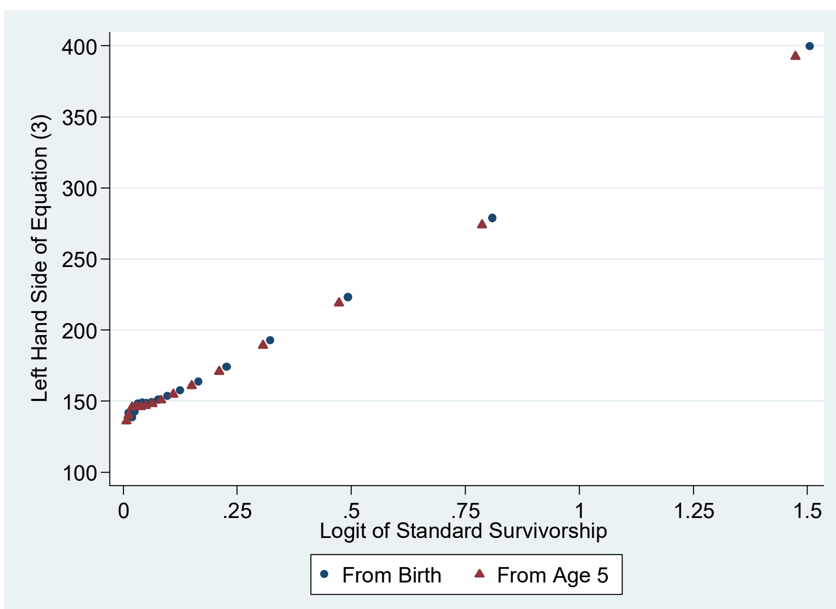
where $r(y)$ is the population growth rate at age $y$, $c(x)$ is the proportion of the population at age $x$, $b$ is the population birth rate, $\tau$ is the level of mortality relative to the standard survivorship function $p^s(x)$. Equation (2) is the equation of a straight line with intercept $1/b$ and slope $\tau/b$; calculating terms for a range of values $x$ and fitting a straight line to the points will thus estimate both the population birth rate (potentially useful for estimating the completeness of birth registration) and the adjustment factor that needs to be applied to bring the standard survivorship function into agreement with the population age structure.

Considering the elegance of the method, the Preston Integrated Method has not been widely applied, though Chen (2016) had recently applied it to estimate the completeness of birth registration in China. Equation (2) is fairly straightforward to apply, and unlike the Preston-Bennett method, does not require any special treatment of the open age interval. This requirement means that the method can be used even with very limited or no vital statistics. The immediate question, however, is what to use as the standard survivorship function $p^s(x)$, which should represent the true age pattern of mortality as closely as possible. In a population with death registration that is 80 per cent or so complete, one possibility is to use a life table derived from observed registered deaths and population; as long as death registration does not vary much by age, the resulting survivorship function will not be greatly distorted in age pattern. An alternative suggested by Preston is to use a model life table with an expectation of life close to that believed to be appropriate for the population in question. Preston also notes that much of the variation in age patterns of survivorship arises from different mortality patterns in childhood versus adulthood; this variation can be eliminated if an independent estimate of *p(5)* is available by modifying equation (2) to reflect only mortality after age 5:

$$\frac{\exp\left(-\int_0^x r(y)dy\right) * p(5)}{c(x)} = \frac{1}{b} + \frac{\tau}{b} * \left(\frac{p^s(5) - p^s(x)}{p^s(x)}\right) \qquad (2a)$$

Table 5.1 shows results of an application of this method to data for the same population as the Preston-Bennett method was applied to, and figure 5.1 plots the resulting points for both equation (2) and equation (2a). In this application, the life table computed from registered deaths has been used as the standard survivorship pattern, and *p(5)* is taken as the average of the United Nations estimates for 1975 and 1980 (United Nations, 2015). Straight lines have been fitted to the points using ordinary least squares (OLS) to estimate the slope and intercept. As can be seen, the use of the version starting from age 5 years gives almost exactly the same results as the method starting from birth. The graph suggests some small irregularity in the relationships at early ages (points close to the origin); however, fitting only to points from age 40 to age 75 years, produces almost identical results as fitting to all points. The estimated slope indicates that the "level" of mortality shown by the observed survivorship function, calculated from registered deaths, needs upward adjustment by about 25 per cent, indicating that about 82 per cent of female adult deaths were registered, not very different from the Preston-Bennett estimate of 85 per cent.

**Figure 5.1. Application of Preston Integrated Method to Republic of Korea Females 1975-1980**




Additional information on adult mortality has been derived from survey information on survival of relatives, particularly parents (Brass and Hill, 1973; Timæus, 2013a) and siblings (Rutenberg and Sullivan, 1991; Masquelier, 2013). As with the use of summary birth histories for estimating child mortality, the use of parental survival data requires numerous assumptions and cannot produce period-specific estimates. The direct analysis of sibling histories, in contrast, closely resembles that of birth histories, and period-specific estimates of mortality rates between the ages of 15 and 50 years can be made (although large samples are required). Doubts remain however, about possible reporting errors in sibling histories. Neither parental nor sibling survival methods are generally regarded as being as accurate as are birth history methods for estimating child mortality, and estimates based on them should be treated as lower bounds of plausible adult mortality ranges rather than as valid point estimates.

Analytical approaches to combining all estimates from all data and methods have not been as widely used in the area of adult mortality as for child mortality, with the exception of estimation of maternal mortality (Alkema and others, 2015). However, substantial improvements in the assessment of CRVS completeness of registration of adult deaths can be expected from a wider use of the strategy.

*5.A.2. Analytical methods based on mathematical relationships between age patterns of populations and age patterns of deaths*

One reason why the Preston Integrated Method has not been more widely used to assess completeness of registered deaths may be that its development coincided with the development of a range of methods for assessing completeness directly through mathematical expressions of population dynamics relating age distributions of populations and age distributions of deaths (Death Distribution Methods (DDMs)). These methods start from the recognition of a link between the age pattern of deaths in a population and the level of mortality; indeed, in a stationary population, the age pattern of deaths is simply the *d(x)* column of a life table with radix equal to the annual number of births. Attractively, DDMs estimate completeness of registered deaths directly.

The first methods extending this idea beyond stationary populations assumed stability (Brass, 1975; Preston and others, 1980; Preston and Hill, 1980), but methods extending to generalized closed populations, using age-specific as opposed to constant growth rates, followed rapidly (Preston and Hill, 1980; Bennett and Horiuchi, 1981, 1984; Hill, 1987). As noted before, methods that assume stability are of little practical value today, so this paper will focus on the non-stable methods.

Preston and Hill (1980), combined information on intercensal cohort changes and numbers of cohort deaths, while also addressing the issue of change in census completeness, on the assumption that such completeness was proportionately constant by age. They derived the following relationship:

$$\frac{{}_5N_x^1}{{}_5N_{x+10}^2} = \frac{k_1}{k_2} + \frac{k_1}{c} * \frac{{}_5D_x^c}{{}_5N_{x+10}^2} \qquad (3)$$

where $N^1$ and $N^2$ refer to enumerated cohort populations at a first and second census (separated in this instance by 10 years), $D^c$ is intercensal cohort deaths, $k_1$ is the (true) completeness of the first census, $k_2$ is the (true) completeness of the second census, and $c$ is the (true) completeness of intercensal registered deaths. Preston and Hill note that equation (3) is identified primarily because the errors in observed values for younger ages are primarily due to change in census completeness, whereas those for older ages are primarily determined by under-recording of deaths. The method was never widely applied because of the sensitivity of the estimates of registration completeness to age reporting errors (note the similarity to later measures of age misreporting among the elderly such as those proposed by Dechter and Preston (1991) and Preston and others (1999)), whether of deaths or population, though estimates of relative census coverage are more robust.

Palloni and Kominski (1984), proposed an extension of the Preston-Hill method, using forward and backward projection to reduce the effects of age reporting errors. Forward and backward projection are used to arrive at estimated level of mortality in a system of model life tables, and a set of survivorship ratios from the model are used in equation (1); the estimated intercept is then used to adjust the survivorship ratios, and forward and backward projection is used with the revised data. This iterative procedure is continued until convergence is reached. Palloni and Kominski note that forward and backward projection can never give the same mortality estimates if there are data errors, and that backward projection will usually provide an estimate closer to true survivorship.

The problems posed by net migration can be addressed by limiting analysis to ages little affected by migration (at least at the national level), such as the population aged 60 years and over. Li and Gerland (2017), show algebraically that evaluation error in cohort survival is larger when mortality is lower and that evaluations are likely to over-estimate completeness rather than underestimate it. The authors use these findings to argue that evaluation via cohort survival is most appropriate for older ages (higher mortality, lower migration) and higher mortality populations such as those of developing countries, though they note that results are still sensitive to the quality of census data.

Palloni and others (2016), used errors in cohort survivorship ratios to quantify age reporting errors in both enumerated populations and registered deaths, with applications to populations of Latin America. Using a model of age misreporting (assumed to be the same for population and deaths) derived from a matching study in Costa Rica, they reconstructed the population matrix by adjusting the quantum of age misreporting. The reconstructed data are then used to evaluate other methods.

Vincent (1951), proposed the method of extinct generations as a way of estimating the population of a specific age at some point in the past by cumulating all the subsequent deaths to that cohort until it became extinct. Bennett and Horiuchi (1981), proposed using the equation for a nonstable population to adjust current deaths above age *x* using population growth rates above age *x* to estimate the current population age *x*; the relative completeness of recording of deaths above age *x* could then be estimated as the ratio of the estimated to the observed populations. The form of the equation derived by Bennett and Horiuchi for the Synthetic Extinct Generations (SEG) method is deceptively simple:

$$N(x) = \int_x^{\omega} D(y) \exp\left(\int_x^y r(z)dz\right)dy \tag{4}$$

where *N(x)* is the population age *x*, *D(y)* are deaths at all ages *y* above *x*, and *r(z)* are the population growth rates between *x* and *y* (see Dorrington (2013) for details of implementation). Assuming that growth rates and point populations are accurately measured from successive census enumerations, and that deaths are recorded with a completeness *c* that does not vary with age, *c* can be estimated as the ratio of the *N(x)* calculated from equation (4) to that observed. Note that deaths and growth rates at all ages above *x* are required to estimate *N(x)*, making the method sensitive to systematic age reporting errors. In addition, all growth rates will be distorted by any systematic change in census enumeration completeness; Bennett and Horiuchi suggest an iterative procedure for estimating a correction delta to the growth rates to account for the relative completeness of one census to the other that makes the age sequence of estimates of $c$ as horizontal as possible.

**Figure 5.2. Application of Synthetic Extinct Generations Method to Republic of Korea, females, 1975-1980**

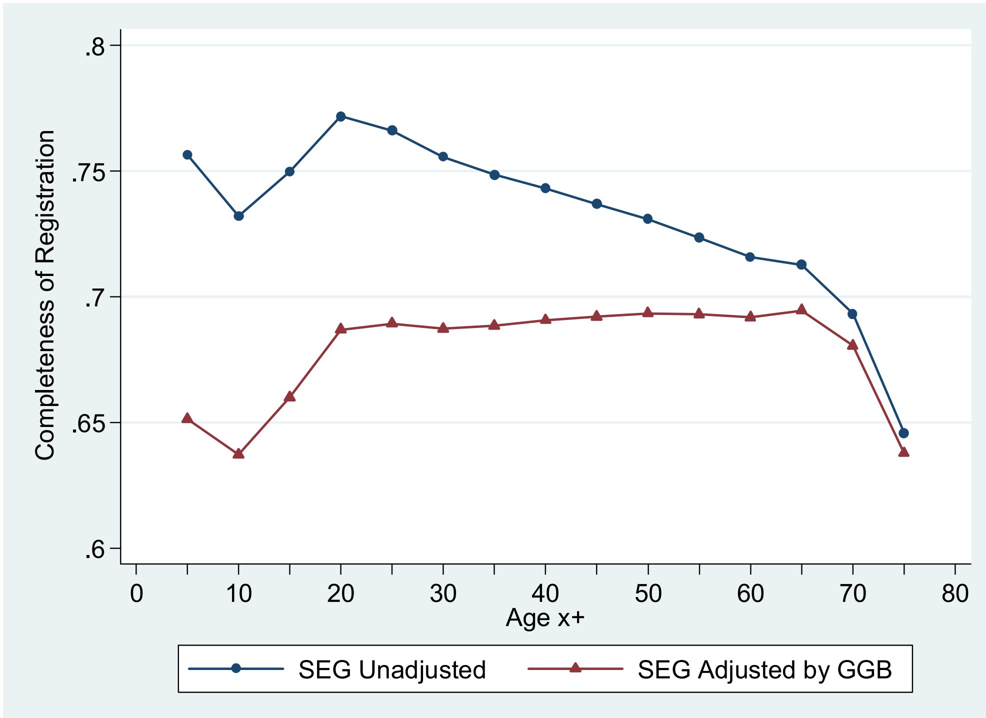



Table 5.1 summarizes the application of the method to data for the female population of the Republic of Korea from 1975 to 1980. Without adjustment for possible change in census completeness, the estimated completeness of death registration is approximately 75 per cent. Figure 5.2 shows the sequence of completeness estimates by age; although overall the pattern by age looks like an inverted "U", from age 20 to 65 years the coverage estimates decline monotonically, a pattern consistent with bias in the growth rates arising from an increase in census coverage from 1975 to 1980. Given the overall "U" shape, however, it is hard to know how to make the pattern more horizontal.[1]

Hill (1987), proposed a non-stable extension of the Brass (1975) growth-balance method called the generalized growth balance (GGB) method. Noting that the entry rate into the population age $x$ and over less the growth rate of that population segment is, in a closed population, equal to the exit (death) rate of the segment, Hill (1987), used approximations of entry, growth and death rates to derive the expression

$$b(x+) - r^o(x+) = \frac{1}{t}\ln\left(\frac{k_1}{k_2}\right) + \frac{\sqrt{k_1 * k_2}}{c} * d^o(x+) \qquad (5)$$

where $b(x+)$ is the entry rate into the population age $x+$, $r^o(x+)$ and $d^o(x+)$ are the observed growth and death rates $x+$ (given completeness errors), $t$ is the intercensal interval, $k_1$ and $k_2$

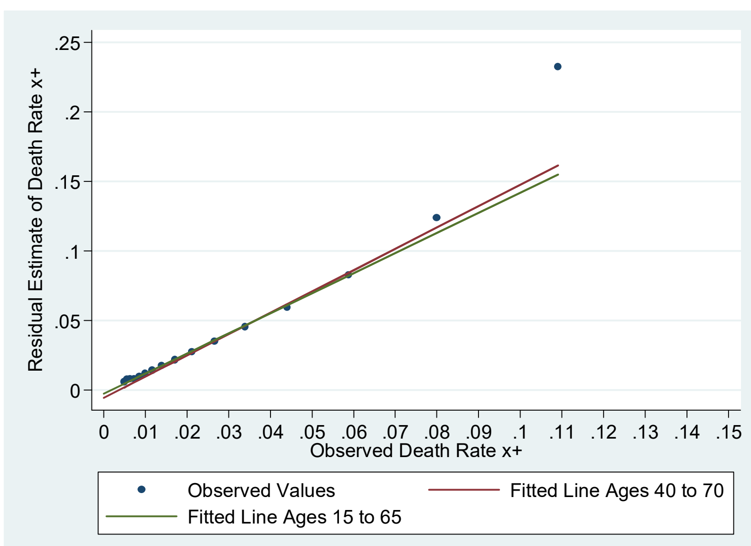
[1] Note that the right leg of the "n" shape suggests that one should use an open interval starting at a lower age, and thus that the range 20 to the open interval could be used to set Delta, and the "u/n" shape is also reflected in the Generalized Growth Balance (GGB) plot, and hence the problem becomes what range of ages should be used to determine Delta using the GGB method.

are the (true) completeness of the first and second censuses respectively, and $c$ is the (true) completeness of intercensal registered deaths. Equation (5) represents a linear relationship, with the intercept estimating change in census completeness and the slope the completeness of death registration relative to an average of census completeness. The parallel to equation (3), for cohorts, is striking.

Summary results of the application to the Republic of Korea data are shown in table 5.1. The plot of entry minus observed growth rates against observed death rates is shown in figure 5.3. Given that both the left and right hand sides of equation (4) are subject to error, the slope and intercept are estimated by orthogonal regression. Two lines are fitted: to points for ages 15 years or over to 65 years or over, and to those for ages 40 years and over to 70 years and over. As can be seen in figure 5.3, the differences are small. The registration of adult female deaths is estimated to be 65 per cent to 69 per cent complete, and the 1980 census is estimated to be about 2 per cent more complete than the 1975 census, a finding consistent with the results of the SEG method. It is notable however, how sensitive the slope estimates are to the range of points fitted, given the almost imperceptible differences between the fitted lines in figure 5.3.

In the process of reviewing the performance of these methods, Hill and others (2009), suggested combining them, using GGB to estimate any change in census coverage, adjusting the population data for that change, and then applying the SEG to the adjusted data. This approach estimates completeness as 69 per cent, the same as GGB applied to points 15+ to 65+ (table 1), and results in a series of completeness estimates by age that is pretty much flat from age 20 to 70 years. This combined approach (SEG adjusted using GGB) takes advantage of the fact that the GGB intercept term is much less sensitive to choice of fitting age range than the GGB slope term.

**Figure 5.3. Application of Generalized Growth Balance Method to Republic of Korea Females 1975-1980**




The SEG and GGB methods address systematic errors in completeness of death registration and changes in census coverage. The populations are assumed to be closed to migration, the errors are assumed to be invariant by age and age reporting is assumed to be accurate. In principle, migration can be introduced into the methods quite simply (Bhat, 2002; Hill and Queiroz, 2010), but migration is often less well-measured than adult mortality.

Efforts to adapt the methods to migration when its level is not known, for example by Hill and Queiroz (2010) using a standard age pattern of net migration and attempting to quantify the level iteratively, have not been uniformly successful. Since migration increases in relative magnitude the greater the level of population disaggregation (for example, by region or socio-economic characteristics) these DDM methods are of limited value below the national level without strong assumptions.[2] Both methods are sensitive to completeness patterns (of population or deaths) that vary with age and to systematic age misreporting such as age exaggeration (Hill and Choi, 2004). It should also be noted that the methods assess average registration completeness over an intercensal interval and do not provide a point estimate. This limits their value for monitoring short-term changes in death registration completeness.

The DDM methods can be applied to a further source of information on adult mortality that in many ways has been intended as a substitute for CRVS data when the latter are clearly incomplete, namely questions on recent household deaths included in a population census or other very large household survey (sample sizes need to be in the hundreds of thousands in order to yield estimates with acceptable confidence intervals because of the rarity of adult deaths). The use of such questions in censuses dates back to at least the mid-twentieth century; as a result of concern about the quality of the data collected, the necessary data were rarely collected in censuses in the 1970s and 1980s, but has become more frequent since with the recognition of its potential use in the measurement of maternal mortality (Stanton and others, 2001; Hill and others, 2011), and is included as an option in the third revision of the *United Nations Principles and Recommendations for Population and Housing Censuses* (United Nations, 2015). If the census data on deaths by age and sex were free of error or can be satisfactorily adjusted for data errors, the completeness of registered deaths can be assessed by comparison with the adjusted series, an assessment potentially applicable at the sub-national level. Although in practice, adjustment of the census data is usually insufficiently precise to support such a direct approach, particularly at the sub-national level, it may be argued that the census data will in general under-estimate adult mortality (since deaths of single person households will not be reported and the dissolution of households following the death of a member may also result in omission), and can therefore be regarded as a plausible lower bound for mortality against which the CRVS data can be compared. To mitigate the limitations of any direct comparison, Dorrington and Timaeus (2015), proposed to apply first the DDM methods at the national level (eventually disaggregated by population characteristics) and to compute age-sex-specific correction factors based on the ratio of census household deaths by the expected registered deaths (adjusted using DDM). In a second step, they suggested to apply these national age-sex-specific correction factors to census household deaths at the subnational level, and to compute completeness for each subnational area as the ratio of adjusted census household deaths by registered deaths.

*5.A.3. Comparisons with empirical regularities*

Studies of age patterns of mortality uniformly show a strong relationship between levels of mortality in childhood and adulthood. This regularity underlies model life table systems and their use in overall mortality estimation (Coale and Demeny, 1983; United Nations, 1982; Murray and others, 2003; Wilmoth and others, 2012). The relationships are not tight enough to provide point estimates of mortality, but can, by employing a variety of model life tables, provide ranges for plausible mortality levels in adulthood if child mortality is well-

[2] Dorrington and Timaeus (2015), propose a work around combining the two sources of data (vital registration deaths and deaths reported by households in the census) that makes use of the respective strengths of each to produce reliable estimates of sub-national mortality.

measured. Similarly, strong relationships exist between male and female mortality patterns by age. Once again, the relationships are not tight enough to provide point estimates of mortality, but can be used to assess plausibility of observed age-sex-specific mortality rates (for example, Coale and Kisker, 1986) or life expectancy by age (Anderson and Silver, 1997). Weaker regularities are that mortality tends to decline over time and to vary negatively with socio-economic indicators. If rates calculated from CRVS data show a rising trend over time, or a positive association with socio-economic indicators, registration may be improving or there may be differential completeness of registration.

The only established empirical regularity specifically for adult deaths is that the overall pattern, from age 30 to age 80 years or over, closely follows a Gompertz function, whereby the log of the force of mortality is linearly related to age (this pattern does not apply in populations with high prevalence of HIV). This regularity is of little use in assessing completeness of death reporting, however, since a proportional omission of deaths at all ages will not affect the linear relationship. This comparison will be more useful for assessing quality, as discussed below, than completeness.

### *5.B. Methods for assessing the quality of adult death registration*

The quality of adult death registration has many dimensions, but this paper will only consider the issue of age reporting.

#### *5.B.1. Comparisons with empirical regularities*

Many single year distributions of deaths by age exhibit some degree of digital preference, usually for ages ending in zero or 5 years. The extent of such digital preference can be measured by Whipple's Index (Whipple, 1919), which measures the number of deaths reported at selected ages in some age range relative to total deaths in that age range. For example, the sum of deaths reported at ages ending in 0 and 5 between 20 and 60, multiplied by 5, would be divided by total deaths at all ages from 18 to 62 years; values of the index over one would indicate digital preference for ages 0 and 5 years, and the index also provides a reasonable assessment of overall reporting quality of age at death, though precise interpretation of the index is not possible.

Though useful to provide some quantification of the magnitude of age misreporting, an indicator of digital preference is of limited value since digital preference itself is a minor problem by comparison with systematic over- or under-reporting of age. Even proportionately symmetric misstatement of age at death creates some bias, however, since transfers up and down will depend on the numbers of deaths in neighbouring age groups (Preston and others, 1999). The problem is smaller for deaths than for population, however, since the age distribution of deaths has a less pronounced slope with age than that of a population.

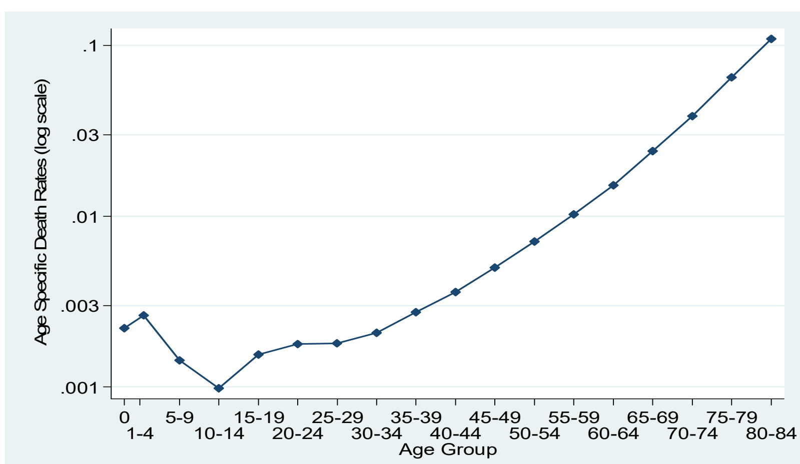
Dechter and Preston (1991), used simulated cohort survival ratios in the form of ratios of the predicted population at a second census age (x+t) and over (initial cohort population less cohort deaths) to the observed population at the second census to explore effects of different patterns of age misstatement. They found that such ratios increasingly rise above one by age, if age exaggeration is limited to the population data, but fall below one if proportionately similar age errors affect both populations and deaths. Such ratios thus provide useful diagnostics of potential age reporting problems beyond simple digital preference.

The methods outlined above are useful as diagnostic tools to identify problems of age misstatement and to provide some approximate quantification of likely errors. However, given the interactions of misstatement of ages of the living, of the dead, and of omission of events, all of which may be age variant, there is no definitive way of quantifying errors in reporting age at death beyond record linkage studies where one set of records is error free (see, for example, Elo and Preston, 1994).

As noted earlier, the primary empirical regularity in the age pattern of mortality is that from, say, age 30 to 80 years, the increase in mortality with age should be exponential, except in populations affected by diseases such as HIV with abnormal epidemiological patterns. Although the Gompertz model is defined in terms of the force of mortality $\mu(x)$, age-specific mortality rates will behave in approximately the same way, so a set of age-specific mortality rates should increase exponentially with age (in the absence of any abnormal mortality conditions). The data for registered female deaths in the Republic of Korea are tested in figure 5.4 by plotting the logarithm of the death rates against age. The pattern from age group 30-34 to 80-84 years is approximately linear, though it seems to curve up slightly with age. As Dechter and Preston (1991) showed, this curvature would be consistent with exaggeration of age in the reported populations and in deaths or to symmetrical random error, which would result in some net exaggeration. It is also interesting to note the abnormally low level of mortality in the first year of life versus at ages 1 to 4 years. If ${}_4q_1$ were plotted against IMR in combination with typical historical patterns, this point would lie way above any historical data points. The large under-recording of under-five deaths is confirmed by comparison with the only birth history data available for the Republic of Korea, from the *1975 World Fertility Survey*. This survey estimated the U5MR for 1972 at 51 per 1,000, whereas registered deaths in 1978 combined with the 1975 and 1980 census populations give an estimate of around 12 per 1,000.

**Figure 5.4. Age-specific death rates (log scale) by age, Republic of Korea, females, 1975-80**

Age-specific death rates (log scale)




Concern about errors in reporting age at death are of particular importance in the analysis of patterns and trends of mortality at age 80 years and over in low mortality populations. The extent of digit preference can be assessed by applying Whipple's Index to deaths of the oldest old by limiting to the age range (for example) 83 to 107 (Jdanov and others, 2008). There is an extensive literature on other indicators of age at death reporting errors, such as the ratio of deaths at ages 105 years and over to deaths at 100 years and over (which should not exceed 5 per cent (Bourbeau and Lebel, 2000). Alternatively, the ratio can be compared to that for Sweden (Jdanov and others, 2008)). Similarly, ratios of the probability of dying at age 101 years to that at age 100 years, or of $T_{100}$ to $T_{80}$ can be compared to those for a "gold standard", for example, Sweden. Thatcher and others (1998), applied a number of evaluation metrics in developing mortality estimates for the oldest old in low mortality countries. Assessments of the quality of age reporting at older ages generally conclude that the problem is more pronounced for the living (population) than for deaths; methods for identifying errors in population data by age and adjusting for them generally rely on extinct generation and survival ratio methods (Bourbeau and Lebel, 2000).

## 6. Discussion

As noted in the introduction, it is important to monitor the completeness and internal quality of CRVS data on deaths for two main reasons: to adjust the data if necessary and in combination with population estimates, to measure mortality levels and trends; and to monitor the overall quality of CRVS systems. A variety of methods have been presented above for assessing the completeness and quality of death registration, but the measures of completeness are all essentially in comparison to the completeness of population data. Quality in terms of assessing the age recording of deaths alternatively, includes both measures that involve only data on deaths (for example, indicators of digital preference) and measures that also involve population denominators (for example, patterns of death rates by age).

What was observed about the performance of the methods for assessing completeness? The methods for child deaths rely primarily on comparisons with empirical regularities or with other types of data deemed more accurate. The approach through empirical regularities will be useful only if errors are highly age-specific: they essentially depend on some age ranges (and ideally only one) suffering errors, and other age ranges being accurate. Under such circumstances, errors can both be detected and adjustments can be made (Guillot, 2013). The adjusted estimates may permit more detailed analysis of time trends and differentials than would be available using survey data alone, because CRVS measures are available for each year and sampling errors would not be an issue. The approach through comparisons with other types of data, specifically estimates from birth histories, is useful for assessing completeness and for monitoring improvement, but not for making estimates since there is no additional information content in the CRVS data without making strong assumptions about completeness trends. That said, evaluations of birth history data pertaining to child mortality indicate that they are generally of good quality in terms of overall level (though not necessarily in terms of age detail), and such data are available for multiple time points for most countries with suspect CRVS data on child mortality, so a strong basis exists for monitoring the completeness of registration of child deaths over time.

The methods for assessing completeness of registration of adult deaths rely primarily on comparisons with other types of data, specifically census age distributions (ADMs), and on mathematical relationships between deaths and population by age, (DDMs). There has been a number of systematic evaluations of the performance of the various DDMs, but only one that included evaluation of ADMs.

The DDM evaluations (Hill and Choi, 2004; Dorrington and Timæus, 2008; Hill and others, 2009; Murray and others, 2010; Palloni and others, 2016) have all included applications to data with simulated errors (omission of population or deaths, misreporting of ages) or deviations from assumptions (non-proportionate completeness by age, migration), although numbers of simulations included have varied from 20 (Hill and Choi, 2004) to over 20,000 (Palloni and others, 2016). Murray and others, also evaluated the methods by application to populations (national and sub-national) presumed to have complete death registration.

The evaluations all conclude that DDMs work very well when applied to data that conform to their assumptions, but find them sensitive to migration and errors that are not proportional by age. Given the quite strong assumptions underlying the methods, specific analyses often involve subjective decisions on implementation. Murray and others (2010), used their evaluation base to develop a standardized approach that would not be analyst-specific. They examined method-specific choices of age trims, that is, optimal age ranges for starting and finishing analysis. They recommended limiting analysis to age ranges of 40 to 70 years for GGB, 55 to 80 years for SEG and 50 to 80 years for the GGB-SEG combination. Using such age ranges are likely to minimize migration effects since migration is usually low above age 40 years. This conclusion differed from that of Hill and Choi (2004), who recommended use of the age range 5 to 65 years over 15 to 55 years, but did not explore narrower and older trim limits. Different studies also recommend different combinations of methods: Hill and Choi (2009), proposed the combined approach, using GGB to estimate coverage change and then the application of SEG to adjusted census data. Palloni and others (2016), also recommended this approach, noting that GGB is remarkably effective at estimating census completeness change, though they do not explicitly address age ranges for fitting. Dorrington and Timæus (2008), recommended using SEG with a Delta adjustment for census completeness change. Murray and others (2010), recommended the median of all three methods, GGB, SEG and GGB-SEG combined. What has not been addressed in systematic evaluations is a GGB-SEG combination using different age trims for the two applications. Estimate census completeness change by applying GGB to the wide age range 5 to 65 years, adjust the populations accordingly, and then apply SEG, estimating coverage for the age range 50 to 70 years. This approach should maximize the effectiveness of GGB for estimating completeness change, while minimizing SEG errors from migration.[3]

Only one evaluation (Palloni and others, 2016) has included ADMs as well as DDMs and even that did not evaluate the Preston Integrated Method. This evaluation found that DDMs in general out-performed ADMs as ways of estimating mortality (in agreement with the single case evaluation presented in this paper), and should similarly be regarded as preferable as ways of assessing completeness of death registration. However, Murray and others (2010), cautioned that the uncertainty range around DDM estimates of completeness should be taken as ± 20 per cent, and therefore provide only a very rough basis for adult mortality estimation and an even rougher basis for monitoring trends in death registration completeness. Despite a spate of evaluations in the last decade or so, very little in the way of new methodology has emerged, except for new ways to evaluate the quality of data on mortality of the oldest old.

An important development over the last decade or so, for both child and adult mortality estimation, has been in analytical strategy. There has been substantial progress in the application of statistical models to multiple data sources and estimation methods, in the process providing insights into the accuracy of different data sources and estimation methods (see, for example, Alkema and others, 2013b). These strategies have improved our estimates

[3] These age ranges can easily be used in the implementation of the GGB-SEG combined approach in the form of the SEG method with Delta adjustment (Dorrington, 2013) available online as part of the IUSSP *Tools for Demographic Estimation* (Moultrie and others, 2013).

of time trends of mortality, with uncertainty intervals, and thus our ability to monitor the completeness of death registration.  There remains scope for additional application of this approach to adult mortality in particular.

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