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Evaluating the Completeness of Death Registration for Developing Countries at Old ages

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Analytical evaluations of the completeness of death registration (DR) are based on assumptions that are often unrealistic, leading to error-prone results. These assumptions can hardly be empirically examined because they interact through complex population model relationships. Investigating the errors of these evaluations is necessary, but difficult if not impossible. This paper proposes a simple evaluation, of which the errors can be investigated analytically. Subtracting the number of population enumerated in a census at a given interval of old ages, at which migrants are negligible compared to deaths, by the number of survivors in the next census, the result is taken as the number of deaths between the two censuses. We assess the completeness of DR by comparing this number with that of DR. This procedure is called the intercensal cohort survival evaluation (ICSE); and the error of ICSE is analysed in this paper. Our analysis provides us with the conditions under which this approach can be used to evaluate DR at old ages, and to note that these conditions are more likely to hold in developing countries.

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Comments are welcome

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Background

The analytical evaluations of the completeness of death registration (DR) originate from stable population models. In stationary populations, the number of deaths over a given age is the number of persons in the population at the given age. Therefore, the number of registered deaths over a certain age could be evaluated by the number of persons at this age, if the population is stationary. In a stable population, the number of deaths over a given age is the number of persons in the population at the given age minus an additional term, which is the product of the number of persons in the population over the given age and the growth rate of the stable population. This relationship was first utilized by Brass (1975) to evaluate the completeness of DR. Using the growth rates by age obtained from two successive censuses, the evaluation was extended to non-stable populations by Bennett and Horiuchi (1981) and Hill (1987). These evaluations are sophisticated and require various assumptions, among which two are common and fundamental. The first fundamental assumption is no migration; and the second is no census error or that the errors in the two censuses obey special relationships. Since the two fundamental assumptions are unrealistic in most situations, the errors of analytical evaluation need investigations.

One of the purposes of this paper is to analyse the evaluation errors when the two fundamental assumptions do not stand; and the intercensal cohort survival evaluation (ICSE) below is proposed to reach the purposes. Subtracting the number of population in a certain old age group in the first census by the number of survivors in the second census gives the number of deaths computed by ICSE. On the other hand, the number of registered deaths that occurred along the surviving person-years can be counted using Lexis triangles, or estimated using assumptions such as evenly distributed over age and across time[3]. The completeness of DR is evaluated as the ratio of the corresponding number of DR deaths to the ICSE computed number of deaths. The ICSE is based on survival process, not on the balance og a growth process. The ICSE provides a simple comparison procedure to check the consistency based on two successive censuses and expected registered deaths (DR).

The first difference between ICSE and other methods, such as the General Growth Balance method (Hill, 1987) and the Variable-r method (Bennett and Horiuchi, 1981), is that that ICSE does not contain complex relationships, so that the effects of census error can be analysed, and therefore the assumption of zero census error (or that the errors in the two censuses obey special relationships) can be removed. The second difference is that ICSE focuses on old ages, so that the assumption of zero migration can be replaced by the knowledge that, at old ages, such as 60 years and over, migrants are negligible compared to deaths. This focus on older ages is particular convenient since 60% of deaths worldwide in 2010-2015 were estimated to be aged 60 years and older (United Nations 2015): 168 million out of a total of 279 million deaths occurred in 2010-2015 in that age group. And more than 60% of all deaths occur at age 60 or higher in nearly all developing regions, except in sub-Saharan Africa where only one fourth or less happen at those ages.

[3] For example, in the case of the deaths of Japanese males aged 60-64 between 2000-2004, the error of assuming even distribution is 0.25% when transforming deaths by 5-year period and 5-year age group into cohort deaths for the corresponding 5-year period (based on HMD data).

Thus, using ICSE is expected to provide reasonable results for countries of which the quality of census data are high. When applying ICSE to the countries included in Human Mortality Database (HMD), however, it turned out otherwise.

In HMD, populations by age on 1 January of year 2000 and 2010, for instance, are estimated from corresponding censuses, and can be used to conveniently match the period in which deaths are registered annually. Additionally, any conceptual or definitional issues between respective data sources have been already resolved through the HMD method protocol and country team. For example, the numbers of Japanese men aged 60-64 on 1 January 2000 and aged 70-74 on 1 January 2010 are estimated in HMD, using the data of the censuses in 2000 and 2010, and the numbers of deaths by age are collected annually between 2000 and 2010 by the DR of Japan. Applying ICSE to these data, however, would suggest that the DR over registered male deaths by 18%, which is implausible, and makes the evaluation meaningless.

Choosing Japan as an example is useful because Japan is one of the few countries that collected data not only on in-migration, but also on out-migration. At ages 60-74 years, the annual net international male migration was estimated to be less than 0.01% that of the population (National Institute of Population and Social Security Research, 2002), which, accumulated over the 10 years between 2000 and 2010, counts less than 0.1% of the population. In other words, the effect of migration is equivalent to less than 0.1% error in the population of one census. According to the PES of the 2010 census (Statistics Bureau of Japan, 2013), the census errors at ages 60-64, 65-69 and 70-74 are 1.44%, 1.14% and 0.92%, respectively. Thus, the effect of census error is 10 times bigger than that of migration. If the 2000 census errors under counted the population aged 60-64 by 1.44%, and the 2010 census over counted the population aged 70-74 by 0.92%, the result of ICSE would be that the DR over registered deaths by less than 1% if the completeness is close to 100%, or the result of ICSE would be explicable. In this explanation, the distribution of census error may seem too artificial. Nonetheless, this is perhaps the only explanation. Considering also the possible difference between the definitions of the enumerated population and that of registered deaths, and the procedure of estimating populations in 1 January from census dates, this explanation may look plausible.

How can so small census errors (such as 1.5%) cause so large error (such as 18%) of ICSE? The quality of census data of Japan is high. If the census errors make ICSE meaningless for Japan, what about other countries? An answer is offered below.

Moreover, in many indirect estimation methods, mortality levels are estimated using the numbers of populations in two successive censuses. Can such estimations be accurate and useful? An answer is provided in Appendix A.

The errors of ICSE

Let the number of persons in a given age interval enumerated in the first census be p_1 and the number of survivors in the next census be p_2. Further, let the net undercounting rates[4]

[4] The net undercounting rate represents the relative difference between the reported and the true numbers of population, which could be the result of miss-reporting of people or misreporting of age. A positive net

be u_1 and u_2 for the first and second censuses, respectively. Neglecting intercensal migration, the numbers of death (*d*) and estimated death ($\hat{d}$) by cohort are:

$$\begin{aligned} d &= p_1 - p_2, \\ \hat{d} &= \hat{p}_1 - \hat{p}_2 = p_1(1-u_1) - p_2(1-u_2) = d - (p_1u_1 - p_2u_2). \end{aligned} \qquad (1)$$

Furthermore, let the survival ratio be

$$s = p_2 / p_1. \qquad (2)$$

Then, the relative error in estimating the number of deaths is

$$E_d = \frac{\hat{d} - d}{d} = -\frac{p_1u_1 - p_2u_2}{d} = -\frac{p_1[u_1 - s \cdot u_2]}{p_1(1-s)} = -\frac{u_1 - s \cdot u_2}{(1-s)}. \qquad (3)$$

Now consider death registration (DR), and let the number of registered deaths be d_R. Then, the completeness of DR, namely *c*, and the evaluated completeness of DR, $\hat{c}$, are

$$\begin{aligned} c &= \frac{d_R}{d}, \\ \hat{c} &= \frac{d_R}{\hat{d}}. \end{aligned} \qquad (4)$$

And the relative error of evaluating the completeness of DR is

$$E_c(s, u_1, u_2) = \frac{\hat{c} - c}{c} = \frac{\hat{c}}{c} - 1 = \frac{d}{\hat{d}} - 1 = \frac{1}{1 + E_d} - 1 = \frac{-E_d}{1 + E_d} = \frac{u_1 - s \cdot u_2}{1 - s - u_1 + su_2}, \qquad (5)$$

which is a function of mortality level (s) and census errors.

Ideal census errors

Obviously, when $u_1 = u_2 = 0$ or $u_1 = s \cdot u_2$, (5) yields $E_c(s, u_1, u_2) = 0$. In other words, when census errors are zero or obey some exact relationships, the ICSE result would be perfect. But the $u_1 = u_2 = 0$ or $u_1 = s \cdot u_2$, or other similar requirements that are taken as assumptions for using various models to evaluate the completeness of DR, are unrealistic, and cannot explain evaluation errors in practice.

Situations beyond the ideal ones must be investigated, otherwise unreasonable of results of applying ICSE, such as the 18% ‘over registration’ of Japanese male deaths, could hardly be understood.

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undercounting rate indicates net under-counting or that the reported number is smaller than the true number. The net undercounting rate could also be negative to reflect net over-counting that may or may not be caused by misreporting of age.

Marginal effects of census errors

According to (5), there are

$$\frac{\partial E_c(s,u_1,u_2)}{\partial u_1} = \frac{1-s}{[1-s-u_1+s\cdot u_2]^2} > 0,$$
$$\frac{\partial E_c(s,u_1,u_2)}{\partial u_2} = \frac{-s(1-s)}{[1-s-u_1+s\cdot u_2]^2} < 0. \qquad (6)$$

Therefore, for $u_1, u_2 > 0$[5]

$$E_c(s,u_1,u_2) \approx E_c(s,0,u_2) + u_1 \left.\frac{\partial E_c(s,u_1,u_2)}{\partial u_1}\right|_{u_1=0} > E_c(s,0,u_2),$$
$$E_c(s,u_1,u_2) \approx E_c(s,u_1,0) + u_2 \left.\frac{\partial E_c(s,u_1,u_2)}{\partial u_2}\right|_{u_2=0} < E_c(s,u_1,0), \qquad (7)$$
$$E_c(s,0,u_2) < E_c(s,u_1,u_2) < E_c(s,u_1,0)$$

Thus, in general $E_c(s,u_1,u_2)$ lies between two marginal values, of which one of the net undercounting rates is zero:

$$E_c(s,u_1,0) = \frac{u_1}{1-s-u_1}, \qquad (8)$$

and

$$E_c(s,0,u_2) = \frac{-s\cdot u_2}{1-s+s\cdot u_2}. \qquad (9)$$

Given u_1 and u_2, $E_c(s,u_1,0)$ or $|E_c(s,0,u_2)|$ will increase with *s*, and could be quite large when *s* is large.

When $u_2 = 0$, (8) could explain the unreasonable 'over registrations' of Japanese male deaths. The *s* of Japanese men in the above example is about 0.866. Thus, plausibly taking $u_1 = 0.02$, (8) shows $E_c(s,u_1,0) = 0.18$, and explains why the unreasonable result of Japan occurs. On the other hand, if $u_1 = 0$, (9) could explain 'under registrations', which can also be quite large when *s* is large. Taking also the above example of Japanese women and assuming $u_2 = 0.02$, (9) shows $E_c(s,0,u_2) = -0.15$.

[5] For $u_1 < 0$ or $u_2 > 0$, the analysis can be done in the same way.

In general, the evaluation error described by (5) depends on u_1 and u_2, and will be between that of (8) and (9).

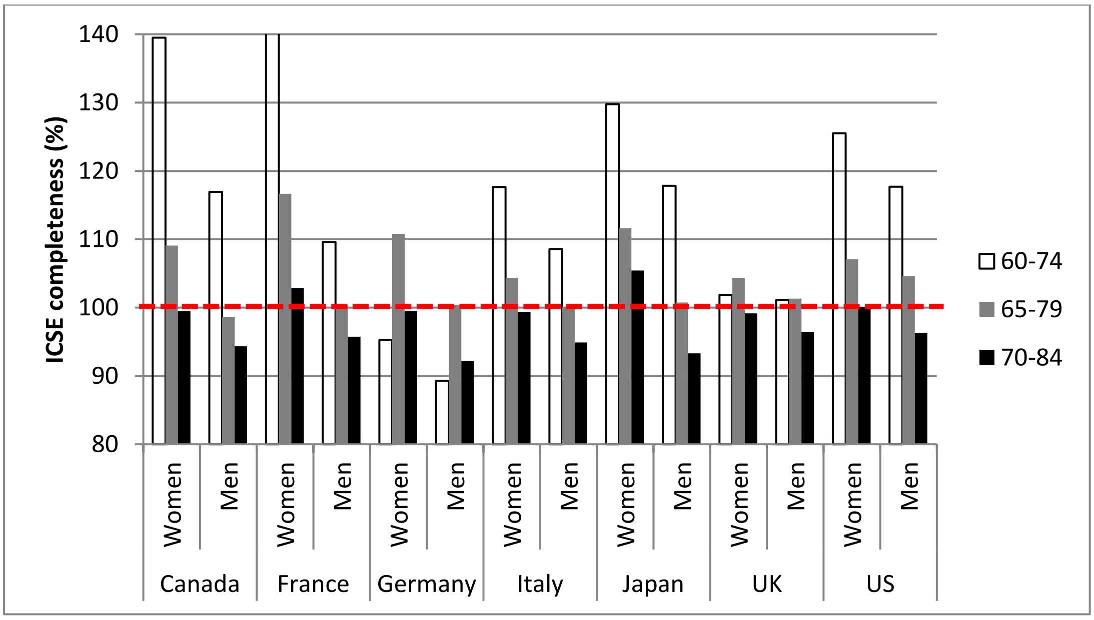
The effect of mortality level

The knowledge about what factors affect the evaluation of DR is limited. Studies have been carried out through simulations (Hill, et al, 2009; Murray, et al, 2010; Palloni et al., 2015). That mortality level affects the evaluation of DR completeness, which is obtained through analytical derivations above, is a new finding that has remained unidentified by previous works. How the level of mortality affects the evaluation of DR is described by equations (7)-(9), which indicate that when mortality level is lower (or the s is larger), the evaluation errors are larger, and vice versa. This conclusion is easy to understand. When mortality level is lower, the number of deaths is smaller and should therefore be harder to estimate accurately.

This conclusion is supported by the ICSE assessments in Figure 1, using data on population and death from HMD, and deeming that the completeness of DR is close to 100% for different old age intervals (e.g., 60-74, 65-79, 70-84). Female mortality in general is lower than that of male at those ages. Subsequently the ICSE errors for female are larger than that for male. Mortality levels at old ages are higher than that at younger ages. Consequently, the ICSE errors at older ages are smaller than that at younger ages.

Figure 1 also indicates that ICSE is unable to provide reasonable evaluations for all the G7 countries for ages 60-74 (surviving from 60-64 to 70-74), or even older ages. Then, can ICSE work at all? The conditions for ICSE to work are illustrated below.

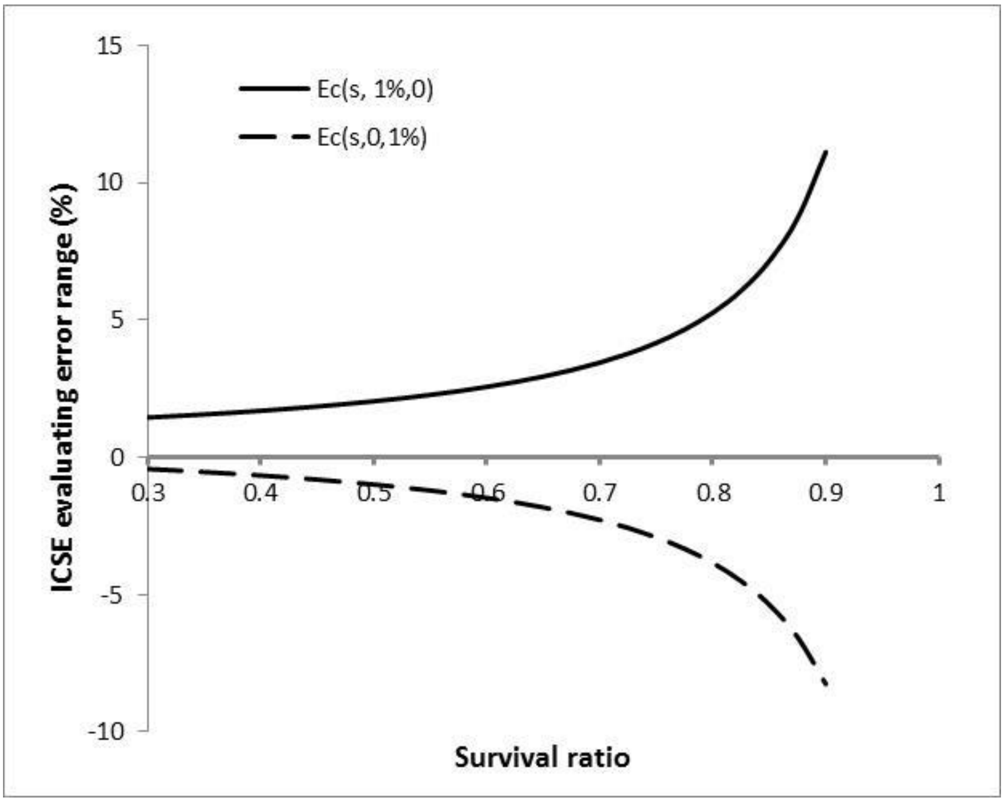
Figure 1. ICSE evaluated completeness, G7 countries 2000-2010



The conditions of using ICSE to evaluate DR at old ages

The census errors (at ages older than 60 in the 2010 census of Japan) are slightly bigger than 1% on average. If the quality of Japanese census is higher than the average of other countries, it is optimistic to assume that in general census errors at ages older than 60 to be 1%. Using $u_1 = u_2 = 0.01$, the ranges of ICSE assessment error are described by (8)-(9) as functions of survival ratio and depicted in Figure 2.

Figure 2. The range of ICSE assessment error with census error 1%



When the completeness is high so that only very small evaluation errors are acceptable, or when the level of mortality is low so that the evaluation errors are large, ICSE could not provide reasonable result for old ages, because the incompleteness is significantly smaller than the error range. This is an explanation for the problems of applying the ICSE to the HMD countries in recent years. Consequently, ICSE is not recommended to apply to developed countries, at least for recent years.

When the completeness is not high so that moderate evaluation errors are acceptable, and when the level of mortality is not low so that the evaluation errors are not large, ICSE could provide reasonable result for old ages such as 60 and over, because the incompleteness is remarkably larger than the error range. This is the situation of many developing countries in recent and past years. Consequently, ICSE is recommended to be applied in developing countries.

The two curves in Figure 2 are not symmetric to level 0; and the marginal errors of over evaluation (positive) are larger than the absolute value of the marginal errors of under evaluation. This feature indicates that when the errors in the two censuses are similar, over evaluating effect would be bigger than under evaluating effect. Because of the cancelation of the two effects, over-evaluation errors would tend to appear more often than under-evaluation errors. This feature is supported by the evaluations in Figure 1, in which there are indeed more over evaluation errors (>100).

Applications

We apply the *intercensal cohort survival evaluation (*ICSE) method on five developing countries with multiple censuses spaced by about 5 to 10 years apart, and death counts from vital registration available annually over several intercensal periods. The five countries are Brazil for 1980-1991, 1991-2000, and 2000-2010 intercensal periods; Egypt for 1947-1960, 1960-1976, 1976-1986, 1986-1996, and 1996-2006 intercensal periods; Maldives for 1985-1990, 1990-1995, 1995-2000, 2000-2006 and 2006-2014 intercensal periods; Malaysia for 1991-2000, and 2000-2010 intercensal periods; and Thailand for 1960-1970, 1970-1980, 1980-1990-2000, 2000-2010 intercensal periods.

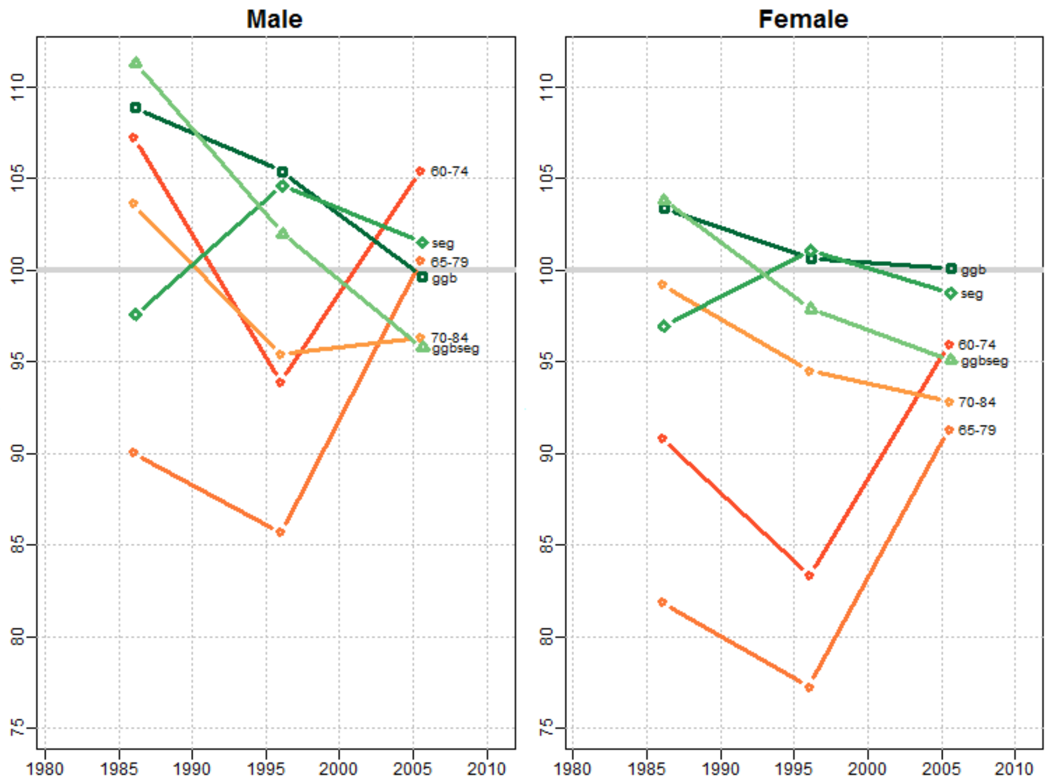
Summary results are provided in Table 1 for selected age groups from age 60 onward, as well as for corresponding open age groups. Appendix B provides further details about data sources and an illustrative example of the steps involved in the computations. Figures 3A to 3E provide for each of these respective countries a summary plot by sex showing the trend over time of the intercensal completeness in death registration based on the application of the ICSE method for selected age groups from age 60 onward (see also Appendix C for results with open age groups), and on the application of three of the most well-established death distribution methods (Generalized Growth Balance, ggb (Hill, 1987); Synthetic Extinct Generation, seg (Bennett and Horiuchi, 1981 and 1984) and the extended method using ggb first to adjust census completeness before to apply seg, denoted here as ggbseg (Hill et al., 2009)).

Estimates of completeness for these three death distribution methods (DDM) are based on the same input data as for the ICSE method, and were computed using the “R implementations of three growth balance methods for estimating adult mortality coverage by Everton Lima, Bernardo Queiroz, and Timothy L. M. Riffe[6]. Table 2 provides a summary of these DDM results. The age range used for each DDM varies for each country, period, sex and method, and was chosen automatically by the DDM R package by minimizing the square of the average squared residual and finding the best-fitting linear relationship by “picking ages that follows the advice typically given for doing so visually”.

[6] https://github.com/timriffe/AdultCoverage

Results from the application of the ICSE method to Brazil for the 1980-2010 period (orange-red lines on Figure 3A for age 60-74, 65-79, 70-84) suggests that the completeness of death registration for male is better than for female, and has improved in the most recent intercensal decade to about 95% for male and 90-95% for female. Overall results, especially for the most recent decade, are reasonably consistent with those from the three DDMs. Differences in ICSE results by specific age groups indicate a greater challenge with completeness or data quality reporting in earlier periods, especially under age 70, and affecting more females.

Figure 3A. Brazil 1980-2010 intercensal completeness of death registration by sex based on ICSE for selected age groups and death distribution methods



In Egypt (Figure 3B), due to data availability only with a lower open age group (75+), the ICSE method can only be computed over the 1947-2006 period for the age group 60-74. While the overall trend suggests some improvement over time, the ICSE results suggest a rather low completeness (with female lower than male), far lower than the results from the application of the three DDMs (in green on Figure 3B) which are more consistent with the consensus from national authorities about the completeness of death registration in Egypt in recent decades. This discrepancy between ICSE and DDM results is related to the sensitivity of the age reporting and data quality used for the ICSE with a specific age group. If instead the ICSE method is computed on the open age group 60+ (see Appendix C Figure C2), the results are more consistent with the DDM evaluation. However, the use of the open age group 65+ in this case shows some completeness results implausibly too high, and suggests that the use of data at older ages in Egypt is problematic.

Figure 3B. Egypt 1947-2006 intercensal completeness of death registration by sex based on ICSE for selected age groups and death distribution methods

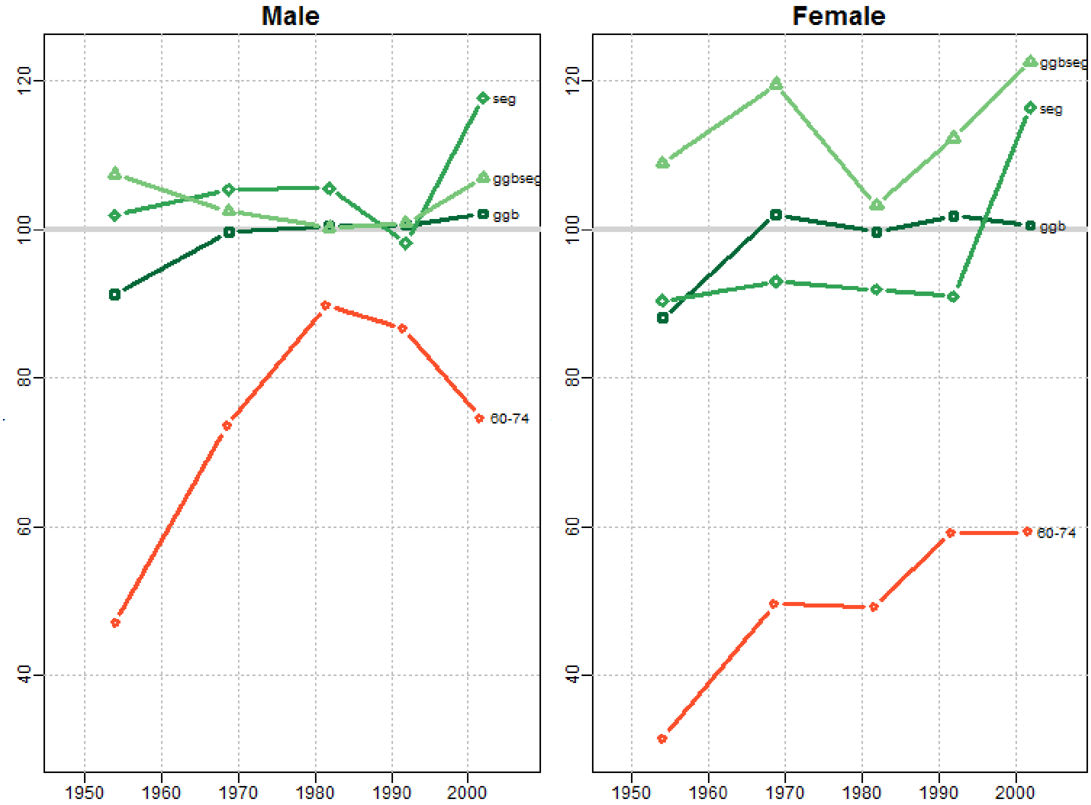
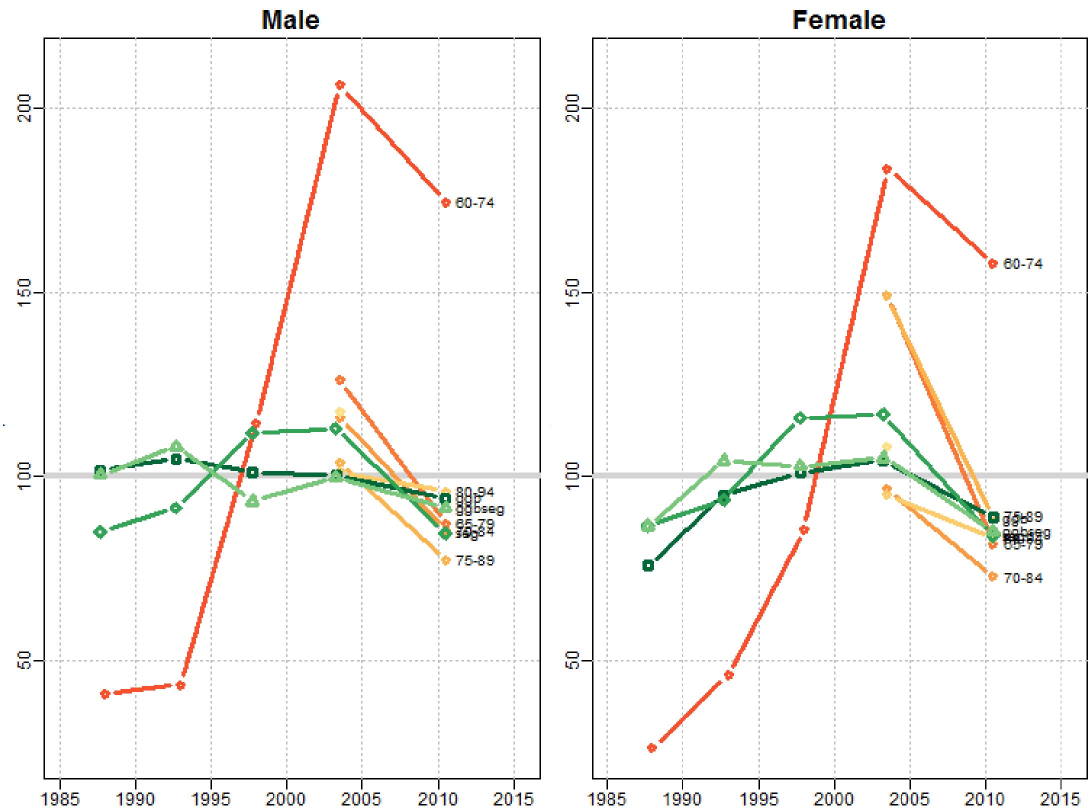


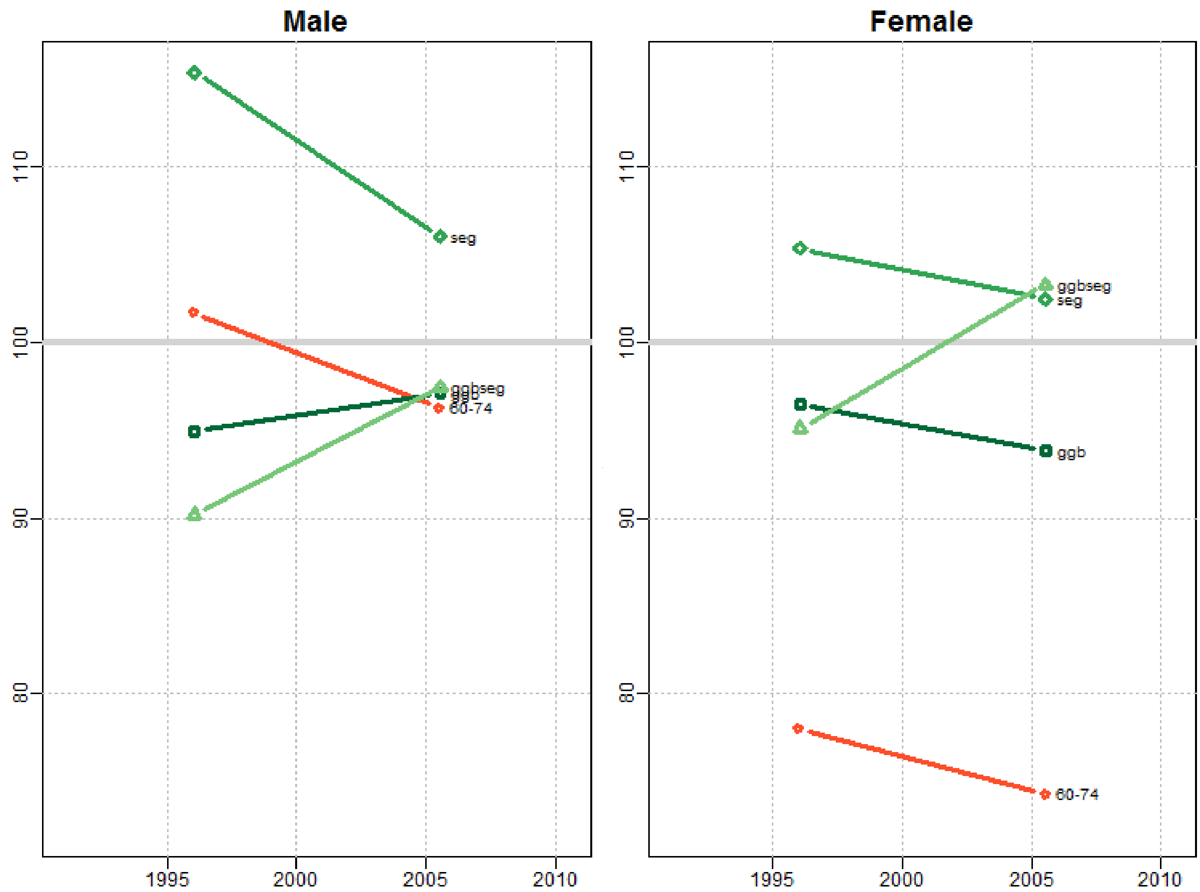
Figure 3C. Maldives 1985-2014 intercensal completeness of death registration by sex based on ICSE for selected age groups and death distribution methods



The application of the ICSE method in 2000-2014 in the Maldives (Figure 3C) shows for age groups starting at age 65 some reasonably consistent results with the application of the three DDMs which suggest overall a very high level of completeness. The ICSE results for the age group 60-74, however, are far more erratic and implausible that are indicative of migration perturbations, especially below age 65. But the inclusion of data at higher ages for the open age group 60+ onward shows that before 2000 data on older ages in the Maldives were probably too unreliable to provide meaningful assessment of completeness (see Appendix C Figure C3).

In the case of Malaysia for the 1991-2010 period (Figure 3D), the ICSE results for male are overall consistent with DDMs results and indicative of high completeness. For female, the ICSE results are far more discordant, and indicate an implausibility too low level of completeness based on the age group 60-74. Like for Egypt, if the ICSE method is computed on the open age group 60+ (see Appendix C Figure C4), the results are more consistent with the DDM evaluation, and with a very high level of completeness. This situation suggests that data at older ages, especially for female, in Malaysia are more affected by age reporting and data quality issues.

Figure 3D. Malaysia 1991-2010 intercensal completeness of death registration by sex based on ICSE for selected age groups and death distribution methods



Finally, the application of the ICSE method to Thailand for the period 1960-2010 (Figure 3E) provides a reasonable consistency with the DDMs results, including the fluctuations over time related to migration issues, especially in the mid-1990s. Results for specific age groups are overall consistent irrespective of the age group used, including if open age groups are included (see Appendix C Figure C5). ICSE results for 1970-1990 and 2000-2010 indicate a high completeness of 90% or more for both sexes, with a higher completeness in the 1970-1990 period for male than female, and since 2000 slightly higher for female than male.

Figure 3E. Thailand 1960-2010 intercensal completeness of death registration by sex based on ICSE for selected age groups and death distribution methods

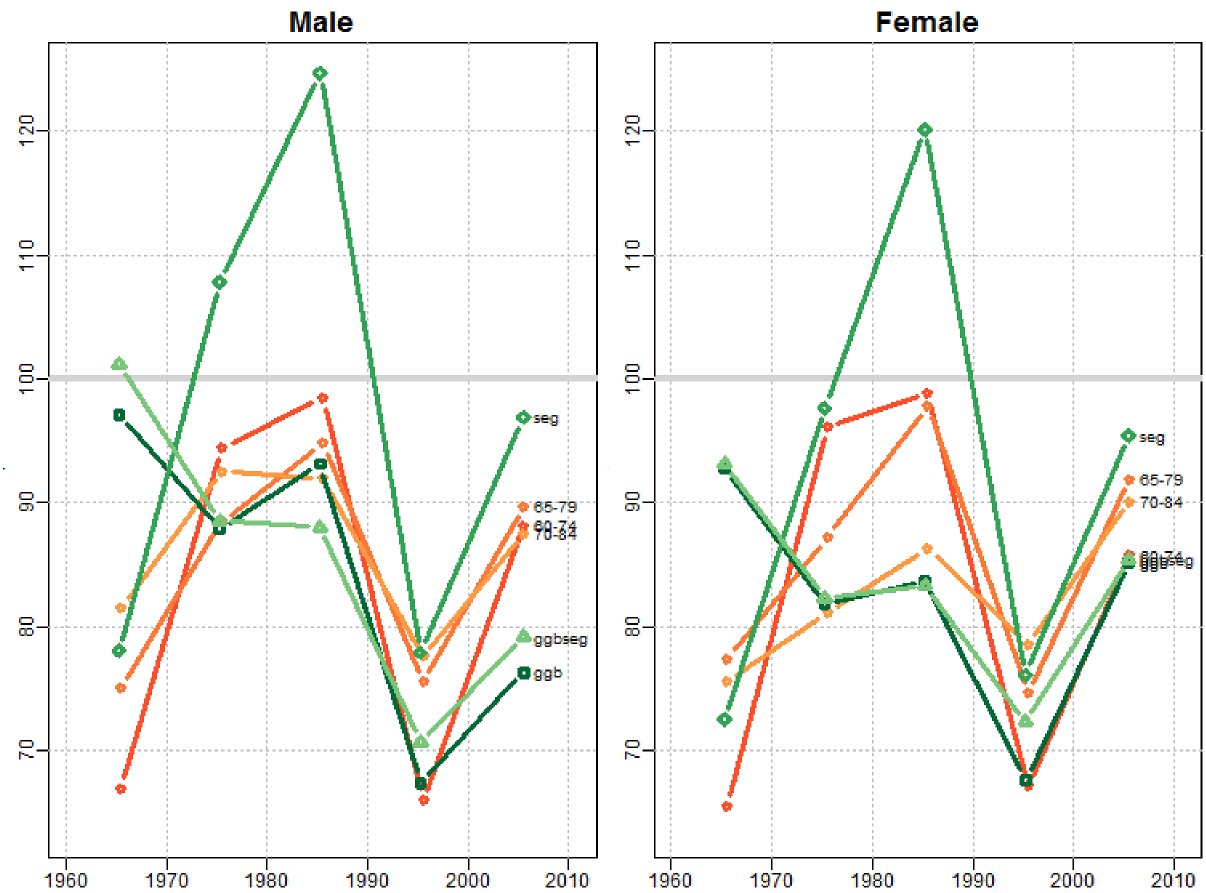


__Table 1. Intercensal completeness of death registration by sex based on ICSE for selected age groups and by open age groups for five selected countries__

Location & intercensal period	age	Specific age group: Male sx	Male Complete-ness	Female sx	Female Complete-ness	Age	Open age group: Male sx	Male Complete-ness	Female sx	Female Complete-ness
A. Brazil										
1980-1991	60-74	0.71	107.2	0.78	90.8	60+	0.54	104.2	0.61	97.6
	65-79	0.57	90.0	0.66	81.9	65+	0.45	103.3	0.52	99.1
	70-84	0.45	103.6	0.55	99.2	70+	0.35	110.3	0.42	106.3
						75+	0.25	115.3	0.32	110.3
1991-2000	60-74	0.74	93.9	0.82	83.3	60+	0.58	94.1	0.65	90.2
	65-79	0.62	85.7	0.71	77.3	65+	0.49	94.1	0.57	91.6
	70-84	0.51	95.4	0.63	94.5	70+	0.40	97.9	0.48	96.6
						75+	0.31	99.4	0.38	97.6
2000-2010	60-74	0.77	105.4	0.84	96.0	60+	0.59	100.3	0.67	96.6
	65-79	0.66	100.5	0.75	91.3	65+	0.50	99.2	0.59	96.7
	70-84	0.54	96.3	0.65	92.8	70+	0.41	98.8	0.50	98.1
						75+	0.31	100.1	0.38	100.3
B. Egypt										
1947-1960	60-74	0.49	47.1	0.54	31.5	60+	0.44	113.7	0.46	106.3
						65+	0.39	161.2	0.39	151.4
1960-1976	60-74	0.54	73.5	0.58	49.5	60+	0.43	106.2	0.45	117.0
						65+	0.35	123.9	0.36	149.0
1976-1986	60-74	0.61	89.8	0.49	49.2	60+	0.44	102.2	0.37	94.6
						65+	0.31	107.5	0.29	118.3
1986-1996	60-74	0.57	86.8	0.52	59.1	60+	0.40	94.5	0.39	103.9
						65+	0.28	97.6	0.30	127.3
1996-2006	60-74	0.57	74.6	0.56	59.3	60+	0.44	103.2	0.45	114.4
						65+	0.35	115.8	0.38	143.3
C. Malaysia										
1991-2000	60-74	0.73	101.7	0.75	78.0	60+	0.54	97.9	0.57	89.1
						65+	0.44	96.8	0.48	92.1
2000-2010	60-74	0.73	96.3	0.75	74.3	60+	0.60	112.1	0.62	104.5
						65+	0.52	117.9	0.54	113.9
D. Maldives										
1985-1990	60-74	0.70	41.2	0.57	26.3	60+	0.71	86.3	0.67	70.7
						65+	0.72	122.1	0.76	154.1
1990-1995	60-74	0.72	43.5	0.72	46.1	60+	0.74	96.2	0.74	95.2
						65+	0.76	144.8	0.76	143.8
1995-2000	60-74	0.89	114.3	0.87	85.7	60+	0.79	105.5	0.78	108.4
						65+	0.72	105.6	0.72	116.4
2000-2006	60-74	0.92	206.1	0.91	183.5	60+	0.83	127.5	0.84	127.2
	65-79	0.87	126.3	0.90	149.1	65+	0.78	128.2	0.80	133.3
	70-84	0.80	116.0	0.76	96.4	70+	0.71	132.6	0.71	131.5
	75-89	0.67	103.7	0.75	148.9	75+	0.62	136.9	0.65	155.8
	80-94	0.56	101.2	0.54	94.8	80+	0.55	149.1	0.54	139.1
	85-99	0.52	117.3	0.55	107.9	85+	0.54	170.1	0.54	157.4
						90+	0.57	185.8	0.53	166.9
2006-2014	60-74	0.86	174.4	0.88	157.7	60+	0.59	92.5	0.62	87.6
	65-79	0.64	87.1	0.68	81.7	65+	0.49	84.2	0.50	80.4
	70-84	0.51	85.3	0.45	72.7	70+	0.39	83.2	0.36	80.2
	75-89	0.32	77.3	0.33	89.0	75+	0.27	81.9	0.26	86.6
	80-94	0.24	95.9	0.20	83.2	80+	0.19	87.5	0.17	84.2
						85+	0.11	77.0	0.13	85.6
E. Thailand										
1960-1970	60-74	0.57	67.0	0.69	65.5	60+	0.45	79.4	0.54	78.3
	65-79	0.47	75.1	0.60	77.4	65+	0.37	85.4	0.46	82.6
	70-84	0.34	81.5	0.44	75.6	70+	0.29	91.7	0.36	84.8
						75+	0.24	100.5	0.29	90.7

Location & intercensal period		Specific age group					Open age group				
		Male		Female			Male		Female		
	age	sx	Complete-ness	sx	Complete-ness	Age	sx	Complete-ness	sx	Complete-ness	
1970-1980	60-74	0.68	94.4	0.79	96.1	60+	0.54	96.1	0.60	89.6	
	65-79	0.55	88.5	0.66	87.2	65+	0.44	96.7	0.50	88.1	
	70-84	0.42	92.6	0.51	81.2	70+	0.34	101.4	0.40	88.5	
						75+	0.26	108.8	0.30	93.0	
1980-1990	60-74	0.73	98.5	0.82	98.8	60+	0.58	99.1	0.65	96.0	
	65-79	0.62	94.8	0.73	97.8	65+	0.50	99.4	0.57	95.5	
	70-84	0.49	92.0	0.59	86.3	70+	0.41	101.5	0.47	94.8	
						75+	0.33	108.8	0.37	99.6	
1990-2000	60-74	0.69	66.0	0.78	67.2	60+	0.54	75.8	0.61	78.3	
	65-79	0.59	75.6	0.68	74.6	65+	0.45	79.4	0.52	81.1	
	70-84	0.45	77.6	0.56	78.5	70+	0.35	81.1	0.41	83.2	
						75+	0.25	83.3	0.31	85.4	
2000-2010	60-74	0.77	88.2	0.83	85.8	60+	0.61	89.9	0.67	92.7	
	65-79	0.67	89.7	0.76	91.9	65+	0.53	90.3	0.59	94.1	
	70-84	0.55	87.5	0.64	90.1	70+	0.43	90.6	0.48	94.8	
						75+	0.31	92.6	0.35	97.0	

Table 2. Intercensal completeness of death registration by sex based on three death distribution methods (ggb, seg, ggbseg) for five selected countries

	Male completeness by method			Age range		Female completeness by method			Age range	
Location	**ggb**	**seg**	**ggbseg**	**Lower**	**Upper**	**ggb**	**seg**	**ggbseg**	**Lower**	**Upper**
A. Brazil										
1980-1991	108.9	97.6	111.3	15	50	103.4	97.0	103.8	30	70
1991-2000	105.4	104.6	102.0	25	65	100.6	101.1	97.9	30	65
2000-2010	99.7	101.5	95.8	25	70	100.1	98.7	95.1	20	60
B. Egypt										
1947-1960	91.3	101.9	107.5	15	55	88.1	90.4	108.9	20	55
1960-1976	99.7	105.3	102.5	20	55	102.0	93.0	119.6	15	55
1976-1986	100.5	105.6	100.3	25	60	99.7	91.9	103.3	15	65
1986-1996	100.6	98.1	100.9	20	55	101.8	91.0	112.4	15	60
1996-2006	102.1	117.7	107.0	30	65	100.6	116.4	122.6	15	55
C. Maldives										
1985-1990	101.7	85.0	100.5	25	60	75.9	86.6	86.5	15	55
1990-1995	104.8	91.5	108.0	25	60	94.9	93.7	104.2	15	50
1995-2000	101.2	111.9	93.2	20	60	101.0	115.9	102.7	25	65
2000-2006	100.2	113.0	99.8	40	75	104.3	116.8	105.1	20	55
2006-2014	94.1	84.6	91.4	15	50	88.8	83.8	85.2	30	65
D. Malaysia										
1991-2000	95.0	115.4	90.2	35	70	96.5	105.4	95.1	35	70
2000-2010	97.1	106.0	97.4	20	55	93.8	102.5	103.3	15	50
E. Thailand										
1960-1970	97.1	78.1	101.2	40	75	92.8	72.5	93.2	35	70
1970-1980	87.9	107.8	88.5	15	50	81.9	97.7	82.3	15	50
1980-1990	93.2	124.6	88.0	15	50	83.7	120.1	83.3	15	50
1990-2000	67.4	77.9	70.7	15	50	67.7	76.1	72.3	15	50
2000-2010	76.4	96.9	79.2	15	50	85.2	95.4	85.4	15	55

Summary

In the evaluation of the completeness of DR using census data on populations by age, previous methods are based mainly on two assumptions. The first is zero migration; and the second is that the errors of the two successive censuses are zero or obey special relationships. These assumptions are unrealistic and therefore produce errors. Investigating the errors of these evaluations is necessary, but difficult if not impossible. The purposes of this paper are to analyse the errors of the evaluation and to provide the conditions under which census population can be used to evaluate the completeness of DR.

To achieve these goals, this paper proposed a simple evaluation, namely the intercensal cohort survival evaluation (ICSE). ICSE focuses on old ages so that the assumption of zero migration is replaced by the knowledge that, migrants are negligible comparing to deaths at old ages. ICSE involves only the process of intercensal cohort survival, which can be used to analyse the effect of census error. Consequently, the assumption that census errors are zero or obey special relationships is removed.

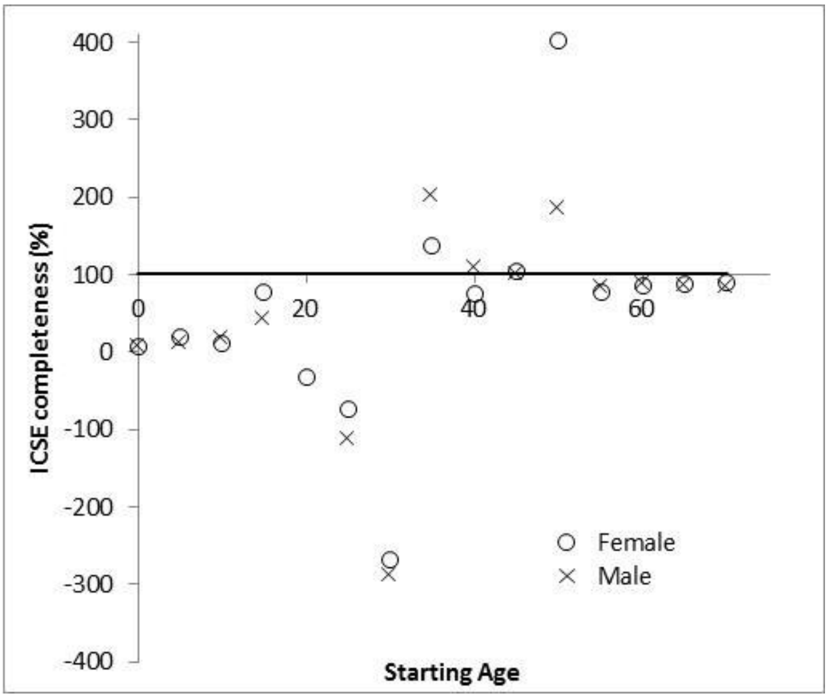
The basic finding of this paper is that given the levels of census error, the lower the mortality level, the larger the evaluation error. This finding is not identified by previous simulation studies, and leads to two conditions of applying ICSE.

The first condition is that ICSE cannot provide reasonable results for situations where mortality is low and completeness is high, which include typically developed countries. This condition explained the failure of applying ICSE to the G7 countries in 2000-2010.

The second condition is that ICSE could provide reasonable results for situations where mortality is not low and completeness is not high, which include typically developing countries. Guided by this condition, ICSE provides a reasonably easy way to check the consistency and usability of mortality data from vital registration at older ages. Like for other analytical methods, ICSE depends on the reliability of the census data. The evaluation using several different age groups, including data for open age group, provides further insights on the sensitivity and robustness of these results, and potential issues with the reliability of data at older ages in some countries or periods.

An important inference of this research is that ICSE cannot provide reasonable results to young ages, at which the level of mortality is the low, and the number of migrants can matter more than deaths. An example of applying ICSE to all the ages of Thailand is shown in Figure 4. How to evaluate the completeness of DR at young ages is the question to be answered in future studies, which should include Record Linkage Methods.

Figure 4. ICSE completeness of Thailand, 2000-2010



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Appendix A. The errors of indirectly estimating mortality level using census population

To see the fundamental difference between the errors of ICSE and that of indirect estimation of mortality levels using populations in two successive censuses, the error of estimating the survival ratio between the two censuses are analysed below.

The estimated survival ratio can be written as

$$\hat{s} = \hat{p}_2 / \hat{p}_1 = \frac{p_2(1-u_2)}{p_1(1-u_1)} = s\frac{(1-u_2)}{(1-u_1)}. \qquad \text{(a.1)}$$

Using (2), the relative errors of estimating *s* is

$$E_s(s,u_1,u_2) = \frac{\hat{s}-s}{s} = \frac{1-u_2}{1-u_1} - 1 = \frac{u_1-u_2}{1-u_1}. \qquad \text{(a.2)}$$

It can be seen that the estimating error is independent from *s*, which is an exceptionally good property. Further, (6) still stands

$$\begin{aligned} \frac{\partial E_c(s,u_1,u_2)}{\partial u_1} &= \frac{1-u_2}{(1-u_1)^2} > 0, \\ \frac{\partial E_c(s,u_1,u_2)}{\partial u_2} &= \frac{-1}{(1-u_1)} < 0. \end{aligned} \qquad \text{(a.3)}$$

So that the marginal situations are still useful:

$$-u_2 < E_s(s,0,u_2) < E_s(s,u_1,u_2) < E_s(s,u_1,0) = \frac{u_1}{1-u_1}. \qquad \text{(a.4)}$$

Furthermore, as (a.4) shows, the marginal relative errors in estimating *s* are just the census net undercounting rates, which are usually small. The principle difference between (a.4) and (7)-(9) is that, (a.4) excludes survival ratio but (7)-(9) include survival ratio. The above analysis indicates that indirect estimations using census population, such as the Census Method (Li and Gerland, 2013) or the Variable-r Method (Bennett and Horiuchi,1981), are entirely different from ICSE, and are able to provide reasonable results.

Taking also Japanese men between 2000 and 2010 as an example, the ratio of surviving from 60-64 to 70-74 is estimated as 0.866 using populations in 2000 and 2010 censuses, which is only 2.4% higher than the corresponding survival ratio in HMD, and can be explained by (a.4) and the Japanese 2010 PES.

Appendix B. Example of country application of intercensal cohort survival evaluation (ICSE)

Census population counts from censuses and death counts from vital registration were compiled from the UN Statistics Division Demographic Yearbook online database[7], and data gaps were filled-in using auxiliary sources such as census reports from national authorities and death counts from the WHO Mortality Database.[8]

When multiple versions of data existed, the official final published results (eventually adjusted by national statistical authorities based on post-enumeration survey or other methods) rather than provisional values were selected, for population the *de-facto* rather than *de-jure* concept was favoured, and for vital events the year of occurrence rather than year of registration was selected. For each intercensal period, age group distributions were harmonized using the highest common open age group between population and death counts, and unknown age counts were proportionately redistributed.

For each country and each intercensal period, a standardized tabular dataset was prepared with the following structure using Brazil 2000-2010 period as an example:

Table B1: 2000 and 2010 census population and intercensal vital registration deaths by age and sex for Brazil

(col.1) **Location**	(col.2) **sex**	(col.3) **age**	(col.4) **pop1**	(col.5) **pop2**	(col.6) **date1dec**	(col.7) **date2dec**	(col.8) **deaths10first**	(col.9) **deaths10last**
Brazil 2000-2010	m	0	1635916	1378532	2000.59	2010.71	233613	221178
Brazil 2000-2010	m	1	6691010	5638455	2000.59	2010.71	45767	43550
Brazil 2000-2010	m	5	8402353	7624144	2000.59	2010.71	28040	27012
Brazil 2000-2010	m	10	8777639	8725413	2000.59	2010.71	35481	35052
Brazil 2000-2010	m	15	9019130	8558868	2000.59	2010.71	144795	144819
Brazil 2000-2010	m	20	8048218	8630229	2000.59	2010.71	216836	217937
Brazil 2000-2010	m	25	6814328	8460995	2000.59	2010.71	206348	208949
Brazil 2000-2010	m	30	6363983	7717658	2000.59	2010.71	203757	204557
Brazil 2000-2010	m	35	5955875	6766664	2000.59	2010.71	227387	226030
Brazil 2000-2010	m	40	5116439	6320568	2000.59	2010.71	271023	271289
Brazil 2000-2010	m	45	4216418	5692014	2000.59	2010.71	321243	325171
Brazil 2000-2010	m	50	3415678	4834995	2000.59	2010.71	370692	379097
Brazil 2000-2010	m	55	2585244	3902344	2000.59	2010.71	407219	418604
Brazil 2000-2010	m	60	2153209	3041035	2000.59	2010.71	455018	463413
Brazil 2000-2010	m	65	1639325	2224065	2000.59	2010.71	515731	523569
Brazil 2000-2010	m	70	1229329	1667372	2000.59	2010.71	562363	572508
Brazil 2000-2010	m	75	780571	1090517	2000.59	2010.71	558317	571517
Brazil 2000-2010	m	80	428501	668623	2000.59	2010.71	465744	482973
Brazil 2000-2010	m	85	302849	464499	2000.59	2010.71	537077	564077
Brazil 2000-2010	f	0	1577394	1334712	2000.59	2010.71	179230	170168
Brazil 2000-2010	f	1	6471408	5444459	2000.59	2010.71	37535	35501
Brazil 2000-2010	f	5	8139974	7345231	2000.59	2010.71	19911	19368
Brazil 2000-2010	f	10	8570428	8441348	2000.59	2010.71	22015	21743
Brazil 2000-2010	f	15	8920685	8432004	2000.59	2010.71	39392	39064
Brazil 2000-2010	f	20	8093297	8614963	2000.59	2010.71	49834	49644
Brazil 2000-2010	f	25	7035337	8643419	2000.59	2010.71	58969	59415
Brazil 2000-2010	f	30	6664961	8026854	2000.59	2010.71	71111	71594
Brazil 2000-2010	f	35	6305654	7121915	2000.59	2010.71	94973	94344
Brazil 2000-2010	f	40	5430255	6688796	2000.59	2010.71	130160	130283
Brazil 2000-2010	f	45	4505123	6141338	2000.59	2010.71	170287	172765
Brazil 2000-2010	f	50	3646923	5305407	2000.59	2010.71	207158	211456

[7] UNSD Demographic Yearbook: http://unstats.un.org/unsd/demographic/products/dyb/dyb2.htm and online database http://data.un.org/Browse.aspx?d=POP
[8] WHO mortality database: http://www.who.int/healthinfo/mortality_data/en/

(col.1) Location	(col.2) sex	(col.3) age	(col.4) pop1	(col.5) pop2	(col.6) date1dec	(col.7) date2dec	(col.8) deaths10first	(col.9) deaths10last
Brazil 2000-2010	f	55	2859471	4373877	2000.59	2010.71	242462	248901
Brazil 2000-2010	f	60	2447720	3468085	2000.59	2010.71	293377	297775
Brazil 2000-2010	f	65	1941781	2616745	2000.59	2010.71	359134	364220
Brazil 2000-2010	f	70	1512973	2074264	2000.59	2010.71	434682	442452
Brazil 2000-2010	f	75	999016	1472930	2000.59	2010.71	491864	504896
Brazil 2000-2010	f	80	607533	998349	2000.59	2010.71	487915	507552
Brazil 2000-2010	f	85	493222	804113	2000.59	2010.71	779926	823633

In this table, the respective columns correspond to the following information:

- Column 1 is simply a label describing the series.
- Columns 2 and 3 provide descriptors for sex and age with “m” and “f” respectively for male and female as sex, and for age only the start of the age group (e.g., 60 means 60-64) up to the last open age group. Here age 85 means 85 and over. Note that for this application data under age 5, or age 50 or 60 are not used and could be ignored or only provided in 5-year age group for under age 5.
- Columns 4 and 5 contain the population enumerated respectively in 2000 and 2010 censuses
- Columns 6 and 7 provide respectively the date for the oldest and most recent census in decimal year. Knowing these two dates, we can compute the length of the intercensal period, here equal to 10.12 years
- Columns 8 and 9 are based on the length of the intercensal period as the closest multiple of either 5 or 10 years (to remain consistent with the 5-year age groups distribution and to follow intercensal cohorts). Column 8 corresponds here to the sum of the first 10 years of annual deaths starting from the year of the first census (2000) up to the end of 2009 (see Table B2 for annual deaths used as input). Column 9 corresponds to the sum of the last 10 years of annual deaths ending with the year of the second census (2010), thus covering the period 2001 up to the end of 2010.

Table B2. Supplementary 2000-2010 annual vital registration deaths by age and sex for Brazil

age	sex	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
0	m	30287	26699	25651	25075	23819	22256	21420	20062	19286	19061	17851
1	m	5769	5403	4977	5018	4605	4269	4223	3969	3852	3683	3552
5	m	3360	2884	2993	2889	2734	2672	2774	2660	2577	2498	2331
10	m	3729	3747	3678	3559	3643	3561	3441	3450	3337	3335	3300
15	m	14291	14587	15213	14666	14406	14284	14444	14439	14410	14055	14315
20	m	20990	20763	22462	22572	21828	20844	21421	21646	21892	22418	22092
25	m	19645	19654	20482	20460	20288	19892	20593	21317	21778	22239	22245
30	m	20747	20763	20749	20380	20010	19483	19845	20254	20360	21166	21547
35	m	23660	23240	23376	23155	23095	22062	22254	22140	22168	22238	22303
40	m	26881	26544	26960	27099	27477	26638	27352	27094	27611	27367	27146
45	m	30082	30551	30979	31845	32427	32250	32926	32985	33630	33568	34010
50	m	33239	34155	34851	35459	37240	37011	38336	39089	40436	40876	41644
55	m	36428	36478	37804	38831	40375	40434	42749	43388	44664	46067	47813
60	m	43401	43569	43486	44846	45575	43962	45637	46741	48735	49066	51796
65	m	47917	48239	49427	50570	52365	51540	53455	53179	54524	54515	55755
70	m	52601	53970	54462	55913	56700	54889	57104	57231	58891	60601	62745
75	m	49309	50085	52591	54887	57011	55788	58996	58958	60018	60672	62509
80	m	39557	40577	42315	44018	46123	45949	49417	50533	52903	54352	56786
85	m	43938	45533	48336	51379	53784	52614	56784	59032	61311	64367	70938
0	f	23061	20676	19439	19075	18141	17157	16409	15240	15240	14793	13999
1	f	4871	4571	4153	3984	3665	3485	3460	3246	3073	3029	2837
5	f	2239	2041	2154	1983	1973	1962	1946	1901	1933	1778	1697
10	f	2403	2199	2363	2144	2167	2120	2195	2145	2158	2122	2131
15	f	4152	4125	4070	4099	4012	3804	3881	3744	3715	3792	3823
20	f	5092	4859	5174	5018	5099	4842	4920	4780	4871	5180	4902

age	sex	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
25	f	5799	5608	5845	5833	5653	5812	5832	6160	6052	6375	6245
30	f	7302	7274	7114	7008	6891	6773	6854	7167	7140	7588	7785
35	f	10032	9503	9742	9469	9325	9236	9385	9266	9407	9608	9403
40	f	12807	12836	12816	12942	12801	12708	13005	13193	13483	13569	12930
45	f	15811	15995	16742	16734	16989	16888	17452	17539	17995	18141	18289
50	f	18927	19145	19668	19709	20631	20503	21268	21418	22641	23247	23225
55	f	21640	22063	22719	23327	23935	23646	25333	26087	26499	27212	28079
60	f	28736	28034	28237	28486	29183	27828	29430	30294	31674	31475	33134
65	f	33666	33568	34661	35305	36698	36010	36989	36809	37489	37939	38753
70	f	40793	41495	42268	42914	43582	41904	44202	44802	45586	47136	48563
75	f	41986	43204	46537	47754	49720	49277	52810	53314	53158	54104	55018
80	f	41799	42139	44151	45539	47601	47606	51097	53915	55565	58502	61437
85	f	60836	64241	69832	73771	76821	77892	83906	86894	90304	95430	104543

Using the dataset in Table B1, and similar ones for other countries, all computations have been implemented in R with the supporting datasets for public replication and documentation (see "Li-Gerland_2016_Evaluating the Completeness of DR-Supplement.zip" with R source code "VR-Dx-completeness-ICSE.r" and input datasets which also include as default number of "deaths" the number occurring between census dates for the computation of DDMs). A simple text file called "filelist.txt" provides a list of the various datasets to be processed, with each dataset being analysed one at the time and the results pooled into an overall summary text output.

In an effort to use the information available with the least amount of additional interference introduced by the evaluation method, the annual deaths are used as reported for a fixed 5 or 10-year period either from the year of the first census or ending in the year of the second census. Death counts are for civil calendar year from January 1 to 31 December, and the population enumerated at the two censuses are shifted accordingly to the start and end of the closest 5 or 10-year period. In general censuses are not conducted on 1 January, therefore to estimate the corresponding population at this date we first compute the intercensal growth rate (r) by age for each sex, and shift accordingly the population to this new reference time (also used in the variable-r approach). Practically censuses are often not exactly 5 or 10 years apart but a variable number of years either closer to 5 or 10. Shifting the population using intercensal growth rates by age provides a reasonable approximation only within a couple of years from each census, not for longer intercensal period of 15 or more years.

In the example given in Table B1 for the 2000-2010 intercensal period in Brazil, we estimate completeness for two 10-year periods: 2000-2009 and 2001-2010 corresponding to the 10-year period either starting from the year of the first census or ending in the year of the second census. We use as final estimate the average of the two estimates.

In the first case, we use deaths10first which is the cumulated number of deaths for the first 10 years starting from the year of the first census (2000) up to the end of 2009 (see column 8). We then compute the population on 1 January 2000 (as pop1estimate) using pop1 * exp(r * (2000-date1dec)) where r = log(pop2 / pop1) / (date2dec - date1dec), and we compute the population on 1 January 2010 (as pop2estimate) using pop2 * exp(r * (2010-date2dec)). In the second case, we compute deaths10last (Column 9) as the sum of the last 10 years of annual deaths ending with the year of the second census (2010), thus covering the period 2001 up to the end of 2010. In this case for the rest of the evaluation we compute the population on 1 January 2001 using Pop1 * exp(r * (2001-date1dec)), and the population on 1 January 2011 using pop2 * exp(r * (2011-date2dec)).

Table B3 provides these intermediate values for female by 5-year age groups from age 60 onward for the first case using deaths10first as deaths. Death completeness (DxCompleteness) in this case is computed for each age group summing up the deaths over the 10-year period by cohort and dividing them by the population change by cohort within this period[9]. For example, for the first age 60, the sum of deaths by cohort over this 10-year period corresponds to ((0.25* deaths(60-64)) + (0.5*deaths(65-69)) + (0.25*deaths(70-74))) = ((0.25*293377) + (0.5*359134) + (0.25*434682)) = 361582. The population change by cohort within this period corresponds to: pop1estimate(60-64) – pop2estimate(70-74) = 2398842-2028870 = 369971. Thus, the ratio of deaths on surviving population for age 60-74 = 100 * (361582 / 369971) = 97.7.

Table B3. Computation of death completeness for 2000-2010 female in Brazil for age groups

age	sex	DateStart	DateEnd	deaths	r	pop1estimate	pop2estimate	DxCompleteness
60	f	2000	2010	293377	0.034418	2398842	3384368	97.7
65	f	2000	2010	359134	0.029467	1908535	2562569	90.5
70	f	2000	2010	434682	0.031167	1485589	2028870	91.4
75	f	2000	2010	491864	0.038349	976814	1433369	
80	f	2000	2010	487915	0.049062	590313	964173	
85	f	2000	2010	779926	0.048280	479462	777018	

The same computations can be performed for open age groups using the population and death distributions cumulated downwards from older ages to younger ones as seen in Table B4.

Table B4. Computation of death completeness for 2000-2010 female in Brazil from open age group

age	sex	DateStart	DateEnd	deaths. CumSum	pop1estimate. CumSum	pop2estimate. CumSum	DxCompletenessOpenAge
60	f	2000	2010	2846898	7839554	11150367	96.2
65	f	2000	2010	2553521	5440713	7766000	96.0
70	f	2000	2010	2194387	3532178	5203430	97.5
75	f	2000	2010	1759705	2046589	3174560	99.9
80	f	2000	2010	1267841	1069775	1741191	
85	f	2000	2010	779926	479462	777018	

The computations performed using the deaths and population estimates for the first 5 or 10 years can be repeated in similar fashion for the last 5 or 10-years. Final estimates in this case can be computed as the average of the two, and Table 1 in this paper presents those.

[9] Note that for other situations with a 5-year period, the sum of deaths by cohort at age 60-64 over a 5-year period corresponds to ((0.5* deaths(60-64)) + (0.5*deaths(65-69)) and the population change by cohort within this period corresponds to: pop1estimate(60-64) – pop2estimate(65-69).

Appendix C. ICSE results for open age groups

Figure C1. Brazil 1980-2010 intercensal completeness of death registration by sex based on ICSE for open age groups and death distribution methods

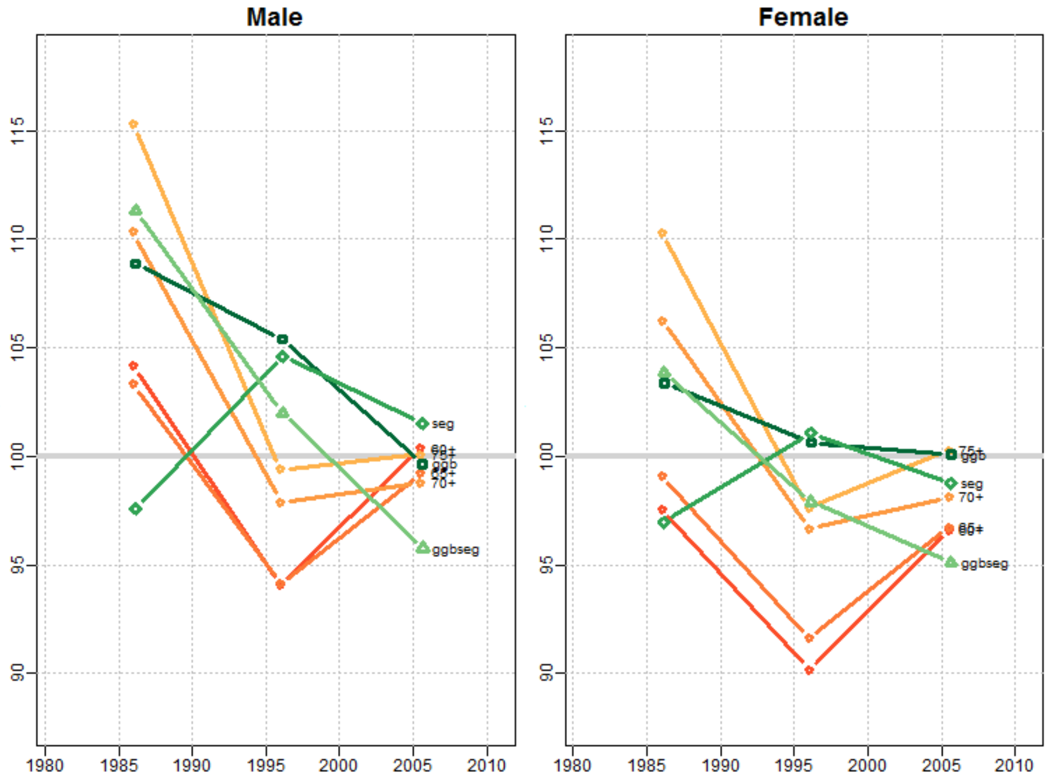

Figure C2. Egypt 1947-2006 intercensal completeness of death registration by sex based on ICSE for open age groups and death distribution methods

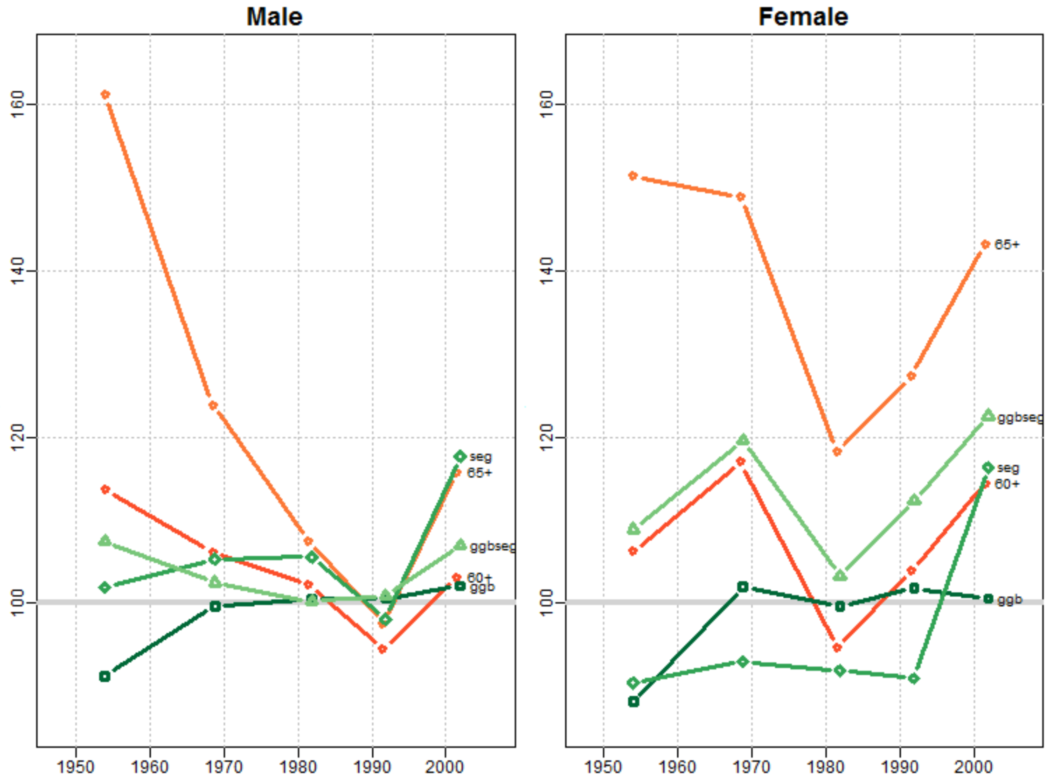

Figure C3. Maldives 1985-2014 intercensal completeness of death registration by sex based on ICSE for open age groups and death distribution methods

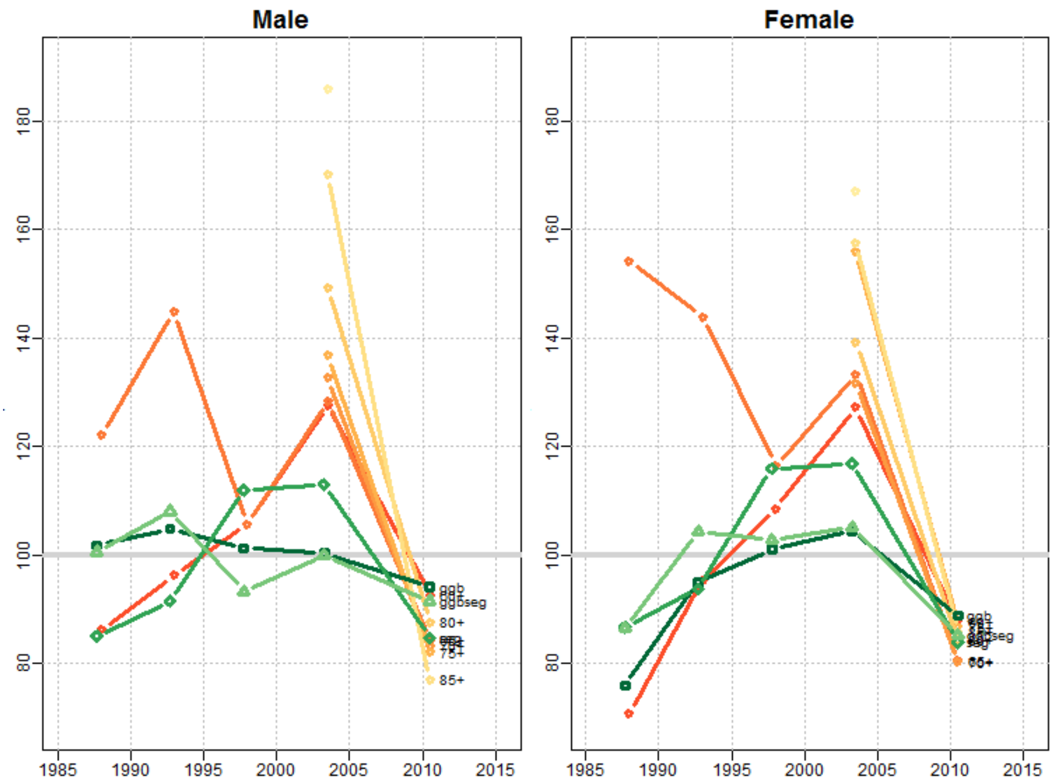

Figure C4. Malaysia 1991-2010 intercensal completeness of death registration by sex based on ICSE for open age groups and death distribution methods

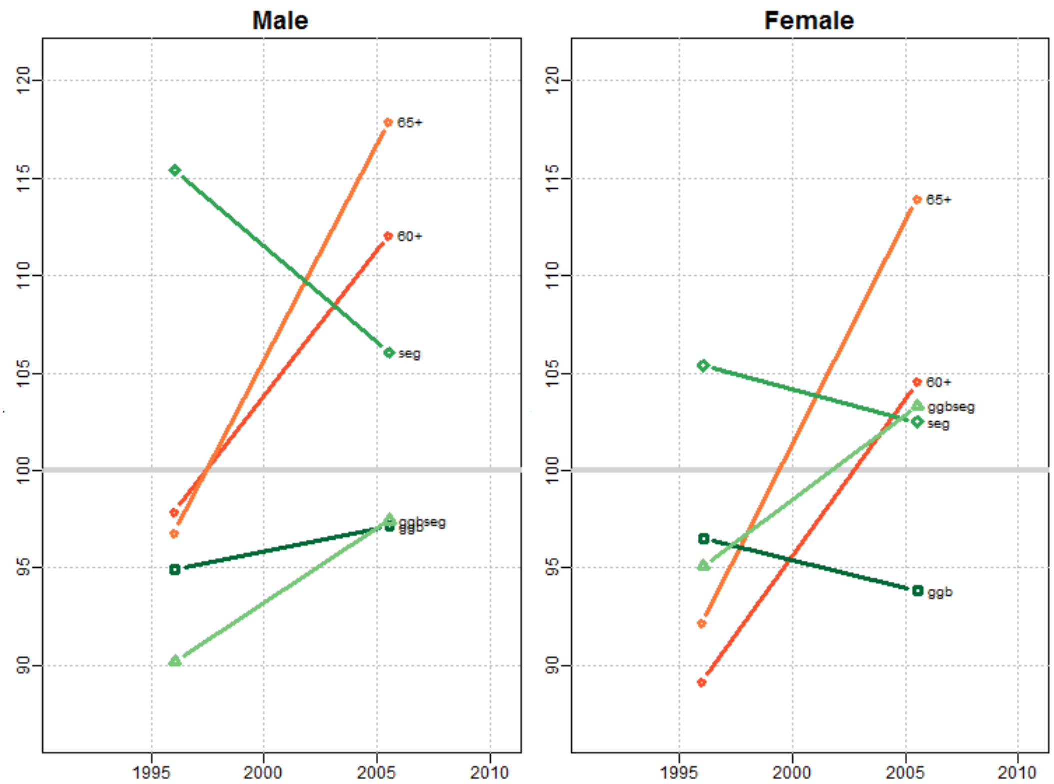

Figure C5. Thailand 1960-2010 intercensal completeness of death registration by sex based on ICSE for open age groups and death distribution methods