The Impacts of Underenumeration and Age Estimation Error on the D0-14/D Ratio and Palaeodemographic Measures

Clare McFadden
Marc F Oxenham

School of Archaeology and Anthropology
Australian National University, Canberra, ACT 2601, Australia

Corresponding Author
Marc F Oxenham
Phone +61 2 61254418
Marc.oxenham@anu.edu.au

Text pages 10
Bibliography pages 3
Tables 1
Figures 0

Key Words
Palaeodemography
Fertility rate
Rate of natural increase
Infant underenumeration
Elderly underenumeration
ABSTRACT
The objectives of this study were to evaluate the impacts of infant and elderly underenumeration and age estimation error on previously reported measures derived from the D0-14/D ratio, specifically total fertility rate and the rate of natural increase. This study used data from the United Nations database for the year 1960. A two-step approach was taken: to test the stability of the relationship we examined the correlation between the D0-14/D ratio and population dynamics of interest with data omitted or misclassified to simulate a range of sample underrepresentation and age estimation error scenarios. To evaluate the practical implications, we used our existing equations to estimate total fertility and natural increase rates using the simulated differentially represented samples and calculated the standard error of the estimate. Correlations remained robust until a small number of infants and the elderly were represented. Where both infants and the elderly were underrepresented, as much as 75% of these age categories could be removed before accuracy of the equations was significantly compromised. Where either infant underenumeration or elderly underenumeration are suspected, our palaeodemographic measures maintain accuracy when up to 25% of the sample is missing. Age estimation error had a negligible impact. These measures demonstrated robusticity in a range of sample underenumeration scenarios, particularly for sources of bias that impact both infants and the elderly equally, and age estimation error. Where either infants or the elderly have been significantly underrepresented or omitted from the burial site, alternative measures may be required.

HIGHLIGHTS
• The applicability of the D0-14/D-based palaeodemographic methods to skeletal samples depends on the resilience of the methods to sources of bias
• This study has demonstrated the methods are robust when both infants and the elderly are underenumerated and that age estimation error has negligible impact.
• Alternative equations for fertility and the rate of natural increase are provided for samples with severe infant underenumeration.
1. INTRODUCTION

Underenumeration of infants and the elderly and age estimation error are known issues in bioarchaeology. For instance, differential burial practices can result in individuals and specific age groups being interred at a different location to the main burial site. In particular, children and infants have been known to be allocated to a separate cemetery (Guy, Masset, and Baud, 1997; Milner, Wood, and Boldsen, 2008). Preservation bias is also known to affect the representativeness of burial sites (Gordon and Buikstra, 1981; Djurić, Djukić, Milovanović, Janović, and Milenković, 2011; Lewis, 2007; Walker, Johnson, and Lambert, 1988; Weiss and Wobst, 1973). Age groups with lower bone density, specifically infants and the elderly, may not preserve as well as their more robust counterparts (Djurić et al., 2011; Gordon and Buikstra, 1981). Another concern with small and frail bones is recovery bias, where bones and indeed individuals may be missed or may remain unidentified in the excavation process (Pokines and De La Paz, 2016). With regards to age estimation, it has been well established that with increasing age there is also increasing error (Kemkes-Grottenthaler, 2002; Savall et al., 2016; Wittwer-Backofen et al., 2008). Some degree of error is to be expected at any age and is also highly dependent on the presence and preservation of skeletal elements and dentition, ancestry, and the method used to estimate age.

Such omission, underrepresentation or erroneous categorisation of particular age groups at burial sites may result in a skewed age-at-death distribution, which is highly problematic for palaeodemography. Paine and Harpending (1998) undertook modelling of the impacts of infant underenumeration and elderly age estimation bias on the age-at-death distribution and palaeodemographic measures such as crude birth rate and total fertility rate. They determined ageing-bias caused a 10-20% overestimation in calculations of crude birth rate, and infant underenumeration decreased birth and fertility estimates by 20-25%. As noted by Paine and Harpending (1998), while elderly age estimation bias can be predicted, underrepresentation is exceedingly difficult to quantify without the assistance of burial records, and as such the degree to which infants and the elderly are represented is often unknown. To avoid the bias introduced by infant underenumeration, palaeodemography has sought to exclude infants from the calculation of measures based on the age-at-death data (Bocquet-Appel and Masset, 1977; 1982; Buikstra, Konigsberg and Bullington, 1986; Milner et al., 2008; Seguy and Buchet, 2013).

The implications of elderly underenumeration on palaeodemographic measures have been less thoroughly considered. Walker et al. (1988) evaluated the impacts of preservation bias on
the age-at-death distribution using a 19th century cemetery sample with associated cemetery records. They found that whilst infants and elderly represented approximately 30% and 35% of the cemetery records, they each represented less than 5% of the burial sample. As noted by Cave and Oxenham (2014) the elderly have been neglected in bioarchaeological studies, largely due to the complexities associated with estimating age from skeletal degeneration and the presumption that people in the past experienced a much younger maximum age-at-death. In palaeodemography as well, the elderly have received minimal attention.

In two recent papers (McFadden and Oxenham, 2018a; 2018b), we provided new palaeodemographic tools for estimating the total fertility rate and rate of natural population increase from the ratio of deaths 0-14 years to total deaths (D0-14/D). Both tools were developed with samples with good preservation in mind, particularly those in Southeast Asia. However, as infant and elderly underenumeration are widespread issues, it is essential to evaluate the impacts of removing or underenumerating these age categories on our palaeodemographic measures if they are to be used more broadly. Further, it is beneficial to estimate the impact of age estimation error as this affects all skeletal samples to varying degrees. The applicability of the measures relies on their resilience against such biases.

2. MATERIALS AND METHODS

We utilised the data as used in McFadden and Oxenham (2018a; 2018b) for this study, specifically: age-at-death data, fertility rates, birth rates and mortality rates from the United Nations Database (United Nations, 2017) for the year 1960. There were 48 countries with sufficient records for inclusion. Infants were defined as individuals aged 0-4 years and the elderly as those aged 45 years or over, for consistency with previous work including Bocquet-Appel and Masset (1977; 1982), Paine and Harpending (1998), and Walker et al. (1988). In order to simulate the effects of differential burial, preservation and recovery, a number of scenarios were evaluated: the omission and underrepresentation of infants only; the omission and underrepresentation of the elderly only; and the omission and underrepresentation of both infants and the elderly.

Based on average error rates from recent studies of dental and skeletal methods (AlQahtani, Hector and Liversidge, 2014; Rissech, Márquez-Grant, and Turbón, 2013), individuals aged 12-14 years may be estimated to be over 14 years of age, and individuals aged 15-17 years may be estimated to be 14 years or younger. In order to encapsulate these ages, and due to
practicalities of the available data, we used age categories 10-14 years and 15-19 years. If anything, this should overestimate the impact of ageing bias. To evaluate the effects of age-estimation bias, we developed scenarios of under-ageing (where a proportion of individuals aged 15-19 years were erroneously placed in the 10-14 years category) and over-ageing (where a proportion of individuals aged 10-14 years were erroneously placed in the 15-19 years category). For the purposes of our palaeodemographic methods, under-ageing would overestimate the number of individuals categorised as 0-14 years, and over-ageing would underestimate the number of individuals in the 0-14 years category.

To test the practical value of the original equations when applied to differentially represented samples, the D0-14/D ratios for the omission, underrepresentation and incorrectly aged scenarios were calculated, and then the total fertility rate and the rate of natural increase were estimated using our standard equations (McFadden and Oxenham, 2018a; 2018b). For underrepresentation, the impacts of removing 75%, 50% and 25% of the relevant sub-samples were evaluated. For age estimation error, the impacts of misclassifying 75%, 50% and 25% of individuals for both positive age bias (over-ageing) and negative age bias (under-ageing) were evaluated. For positive age bias, the rates were applied to individuals aged 10-14 years, simulating the impact of these individuals being over-aged and excluded from the 0-14 years component of the D0-14/D ratio. For negative age bias, the rates were applied to individuals aged 15-19 to simulate the impact of these individuals being under-aged and included in the 0-14 years group.

To quantify the actual impact of differential representation and incorrect age-estimation on estimated fertility rates and rates of natural growth, the standard error of the estimate (SEE) was calculated using the estimated rates for each scenario, where the original regression equations and the differentially represented D0-14/D ratios were used to calculate an estimated rate (Y’), and the actual rates of fertility and growth (Y). The correlations between the estimates derived from underenumerated and incorrectly aged D0-14/D ratios, the wholly represented estimates, and the actual fertility and natural increase rates were also evaluated to determine whether the relationships were significant. This alone does not indicate practical value, but in combination with the evaluation of SEE indicates the robusticity of the measures in various contexts. All statistics were performed in Microsoft Excel (2016).

3. RESULTS
3.1. Applying the Total Fertility Rate and Natural Population Increase Measures to Differently Represented Samples
The SEE provides an overall measure of the accuracy of predictions. Lower error estimates indicate observations that are more closely fitted to the regression line. Table 1 provides the SEEs for all underenumeration and age misclassification scenarios in this study. Based on a wholly represented sample, the SEE for the D0-14/D ratio and total fertility rate is 0.742. Where infants were underrepresented by up to 25%, the SEE increased by approximately 9% to 0.810. With the elderly underrepresented by up to 25%, the SEE also increased by 9%. Beyond this, the error exceeded practical value. In contrast, where the infants and elderly were both underrepresented, the equations remained relatively accurate with up to 75% underrepresentation of infants and the elderly, with the SEE increasing by a maximum of 12%. For age estimation, the SEE was negligibly impacted.

For the wholly represented D0-14/D ratio and the rate of natural increase, the SEE was 1.491. Where infants were underrepresented by up to 25%, the SEE increased by approximately 11% to 1.653. With the elderly underrepresented by up to 50%, SEE decreased by 9% to 1.360. Where both were underrepresented, SEE decreased insignificantly to 1.466, or an approximately 2% decrease. Again, for age estimation error, the impact on SEE was insignificant.

3.2. Correlations with Total Fertility Rate and Rate of Natural Increase

Descriptive statistics for the ratios and total fertility rate, and the rate of natural increase, are provided in Table 1. For this sample, the correlation between the D0-14/D ratio and the total fertility rate was $r=0.897$. Reducing the representativeness of the 0-4 years age category by 25%, 50% and 75% had a negligible impact on the correlation with total fertility rate. In fact, the correlation remained above $r=0.800$ until only 2% of the 0-4 years age category were represented. When the 0-4 years age category were excluded, the correlation was reduced to $r=0.747$. Similar results were obtained for elderly underenumeration, where the correlation remained strong until only 5% of the elderly sample was represented. Omission of the elderly resulted in a correlation of $r=0.731$. For the underenumeration of both infants and the elderly, representativeness of 75%, 50%, and 25% produced very nearly equivalent correlations. Representation of only 1% of the infants and elderly resulted in a correlation of $r=0.791$, and exclusion of both infants and the elderly reduced this to $r=0.733$. For age estimation bias all correlations remained robust, even where 75% of individuals in the 10-14 year (over-ageing) or individuals in the 15-19 year (under-ageing) age groups were misclassified.
For the rate of natural increase, the correlation with the D0-14/D ratio was $r=0.864$. Infant underenumeration had a minor impact on the correlation with the rate of natural increase, with 75%, 50% and 25% underenumeration producing correlations of $r=0.857$, $r=0.847$, and $r=0.834$ respectively. The correlation remained above 0.800 until only 7.5% of infants were left. With infants omitted the relationship ceased to be of practical value ($r=0.683$). For elderly underenumeration, there was no statistically significant difference between the wholly represented sample and the 50% and 25% underenumerated samples. With the elderly omitted, the correlation was $r=0.750$. For both the infants and the elderly, there was no statistically significant difference between the whole sample, and the 75%, 50%, and 25% underrepresented samples. With only 2% of the elderly and infants represented, the correlation was $r=0.798$ and with both omitted the correlation was $r=0.707$. For the age estimation bias scenarios, the correlations with rate of natural increase were consistently strong.

4. DISCUSSION

4.1. Preservation Bias: Robusticity of Palaeodemographic Measures

In any scenario it is difficult to quantify the representativeness of the age-at-death distribution of a skeletal sample. The results presented here demonstrate that our palaeodemographic equations for total fertility rate and rate of natural population increase can be confidently used for samples where up to 25% of infants or the elderly (that is, one or the other) are missing. But how accurately can we ‘eyeball’ good preservation? Skeletal completeness is one means by which the degree of preservation is estimated and, whilst it falls short of a percentage, it may be used as an indication of the sample representation (Domett and Oxenham, 2011). These results provide assurance that if good preservation equates to representation somewhere between 75% and 100% for either infants or the elderly, then these methods remain accurate and applicable without adjustment.

If one were to assume that preservation bias impacts infants and the elderly to a similar extent, as indicated by work by Walker et al. (1988), then the total fertility rate and rate of natural population increase equations can be applied to samples where as many as 75% of the infants and elderly are missing with only a minimal impact on the accuracy of the methods. This is the result of the reduction affecting both the numerator and denominator of the ratio. As previously noted, it is nearly impossible to quantify the degree of underenumeration without cemetery records, however, the accurate applicability of these methods on samples
with just 25% representation should give bioarchaeologists confidence that these equations
can be used where overall poor preservation (as opposed to complete omission via, for
example, differential burial) is indicated, with no adjustments to the equations or estimation
of underrepresentation necessary. This produces a far more accurate result than the tradition
of deliberate omission of infants from palaeodemographic methods.

For the total fertility rate, 25% underenumeration of infants or the elderly, and 75%
underenumeration of infants and the elderly, increased the SEE by between 9-11%. For the
rate of natural increase, the error increased by 11% with 25% underenumeration of infants,
decreased by 9% with up to 50% underenumeration of the elderly, but subsequently increased
by 10% with 75% underenumeration. For both infants and the elderly, SEE decreased by 2%
with 75% underenumeration. These error rates suggest that not only does the relationship
between palaeodemographic measures and the D0-14/D ratio remain robust, but that the ratio
remains stable enough for use in our existing equations in a range of sample-bias scenarios.
The acceptable rate of error should be evaluated on a case by case basis and it is necessary
with all methods to calculate standard error based on sample size. Paine and Harpending
(1998) argued that error of 10-20% was unacceptable. Whilst in isolation these rates seem
high, to outright reject such error contradicts the accuracy one can hope to achieve with
palaeodemographic measures even in the best-case scenarios. As observed by Wood,
Holman, O’Connor, and Ferrell (2002), there are limits to the detail researchers may
credibly obtain from the age-at-death distribution. Further, even modern demographic
predictions experience significant error rates despite being based on large volumes of data,
living populations, and often complex calculations (for example, Khan and Lutz, 2007;
Office for National Statistics, 2015). We suggest that the acceptability of such error should
be evaluated on a case by case basis, in the context of the sample, interpretive framework,
and research aims.

Where representation for either age group (but not both) is below 75%, the correlations with
total fertility rate and rate of natural increase remained significant, but the SEE was too high,
in our opinion, for the existing equations to be used. In order to overcome this issue, we
would need to be able to confidently estimate the percentage of representation we are dealing
with in order to create a bespoke predictor, however, this is a highly unlikely scenario. We
do not recommend our measures be applied to samples where infants appear to be
significantly underrepresented, or the elderly appear to be significantly underrepresented. Scenarios where one of these age groups may be misrepresented, but not the other, include differential burial practices and recovery bias. In both cases, infants and juveniles are the more likely candidates, due to the known occurrence of child cemeteries (Milner et al., 2008) and small bones being more susceptible to recovery bias (Pokines and De La Paz, 2016). Where infants are seemingly well represented and there are low numbers of elderly individuals, it would be necessary to consider all potential explanations before pursuing a methodology. One such scenario that should be considered is lower overall life expectancy, which could mean the apparently low representation of elderly is a true reflection of the age-at-death distribution. Notwithstanding, the potential impacts of age-estimation bias against the elderly should not be ignored (see Cave and Oxenham, 2014).

Where infants, the elderly, or both are entirely omitted from the burial samples, the proposed palaeodemographic equations are not suitably accurate for use. For infant omission or significant underenumeration (a commonly seen phenomenon), we recommend the use of the following equations, noting the correlation is reduced to $r=0.747$ for total fertility rate and $r=0.683$ for the rate of natural increase:

\[
\text{Total Fertility Rate} = (32.225 \times D_{5-14}/D_{5+}) + 3.028
\]

\[
\text{Rate of Natural Increase} = (17.708 \times D_{5-14}/D_{5+}) + 1.259
\]

These equations were developed using the dataset of the present study and the same methodology as McFadden and Oxenham (2018a, 2018b), and where $D_{5-14}$ is the number of individuals age 5-14 years at death and $D_{5+}$ is the number of individuals aged 5 years or over at death. For elderly omission or severe underenumeration, or dual infant and elderly omission, linear regression may similarly be used to develop alternative equations which exclude these age categories, though accuracy of such equations will also be reduced.

4.3. **Age-Estimation Error**

In all age-estimation scenarios evaluated, the impact on accuracy was negligible. Both over-ageing and under-ageing of individuals within the range of error for the 14 years of age demarcation point does not appear to adversely impact upon the methods for estimating total
fertility rate or rate of natural increase. This should provide researchers with confidence that the methods can be applied to samples of diverse origins and using a variety of age-estimation approaches.

5. CONCLUSION
Infant and elderly underrepresentation and age-estimation have historically been problematic for palaeodemography, with the traditional approach being to intentionally omit infants from palaeodemographic measures. The results reported here show that correlations between the total fertility rate, rate of natural increase and the D0-14/D ratio remain robust even with minimal representation of each age category, however, this alone does not mean our methods (McFadden and Oxenham, 2018a; 2018b) are suitable for underrepresented samples. In terms of practical application, where infant underenumeration or elderly underenumeration is suspected our palaeodemographic equations maintain accuracy when up to 25% of the sample is missing, based on the results of the standard error estimates. This may be applicable for samples where good, but not complete, preservation is indicated. Age estimation error for the relevant demarcation point (14 years of age) was found to have a negligible impact on palaeodemographic methods. An anomaly was observed where SEE was reduced by underenumerating the elderly by 25-50%, and it is suggested the theoretical cause of this be explored in further research. If both infants and the elderly are underrepresented, the D0-14/D ratio remains relatively stable when as many as 75% of individuals are missing from the sample, and as a result our equations remain sufficiently accurate for use. A potential application of this is where preservational bias against those with low bone density is suspected. Where either infants or the elderly have been omitted from the burial site via differential burial rites, or where they have been significantly underrepresented due to factors such as recovery bias, alternative measures may be required. This study has highlighted the need for further experimental research into differential preservation of infants and, particularly, the elderly. Infant underenumeration has been a concern for palaeodemographers for some time, however, our results indicate that elderly underenumeration should be of equal concern. Ultimately, this study has shown palaeodemographic methods derived from the D0-14/D ratio to be robust and stable in a variety of sample bias scenarios.

ACKNOWLEDGEMENTS
This research was supported by an Australian Government Research Training Program (RTP)
Scholarship and Australian Research Council; Grant number: FT 120100299.
REFERENCES


*Microsoft Excel* (2016) [computer program]. Microsoft.


