Estimation of mortality profiles from non-adult human skeletons in Edo-period Japan

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Abstract Reconstruction of the mortality profiles of non-adult human skeletons from an archeological site should greatly assist the interpretation of the sanitation, health, disease, and behavior of past human populations. The purposes of this study are to examine non-adult skeletons from the Sakai-kango-toshi 871 (SKT 871) site in Edo-period (17–19th centuries AD) Japan, to estimate their age-at-death distribution, and to discuss whether paleodemographic estimates can yield appropriate mortality patterns of this sample. The use of the Bayesian method for fetal age estimation, assuming uniform priors, yielded a peak of deaths at 10 months of gestation. The age-at-death distribution obtained from the whole population further indicated the peak of deaths being at the fetal stage and the number of deaths decreasing with age. The concentration on full-term of gestation implied deaths related to birth, which is consistent with natural mortality. Another important finding of this study is that individuals aged less than 7 years accounted for about 98% of the deaths and there was no burial for adults. An explanation for the lack of adults is preferential mortuary practices, in which the very young are buried separately from adults. It is concluded that this paleodemographic study of non-adults provides us with important information on mortality profiles and mortuary practices in Edo-period Japan.

Key words: paleodemography, non-adults, age-at-death estimation, Bayesian theorem, Edo period

Introduction

Reconstruction of the mortality profiles of non-adult human skeletons should greatly assist the interpretation of sanitation, health, disease, and behavior of past human populations (Lewis, 2007). The rapid increase in life expectancy in the 20th century was mainly attributed to the reduction of infant mortality (Wilmoth, 2000). However, little is known about infant mortality in pre-modern societies except for a few historical demographic and ethnological studies. Kobayashi (1956) examined historical documents of 19th-century Japan and demonstrated that 31% of the population had died before reaching 5 years of age. The ethnographic demographics of the hunter-gatherer Dobe !Kung in the mid-20th century exhibited a high mortality rate, accounting for 33% of deaths before the age of 5 (Howell, 1979). In model life tables constructed by Weiss (1973), the mortality proportion of non-adults is 20–60% in the first 5 years and 30–70% before reaching 15 years of age. Non-adults might afford the key to understanding the mortality profiles of past human populations.

However, the reconstruction of mortality profiles of non-adults from an archeological site is problematic. The proportion of deaths under the age of 5 years exhibits wide variations depending on the site: 8.8% for S’Illot des Poros, Spain (Alesan et al., 1999); 11.6% for Loisy-en Brie, France (Bocquet-Appel and Bacro, 1997); 13.8% for the Natufian period, Israel (Eshed et al., 2004); 16.4% for the Neolithic period, Israel (Eshed et al., 2004); 18.3% for Yugihamaminami, Japan (Nagaoka et al., 2006); 29.7% for Carlton Annis, USA (Mensforth, 1990); 30.7% for Libben, USA (Lovejoy et al., 1977); and 35.9% for Hitotsubashi, Japan (Nagaoka and Hirata, 2007). The proportion of deaths under the age of 5 years in archeological samples is often smaller than that in model life tables and historical demographic documents. Many previous studies have argued that infant human skeletons are underrepresented in archeological settings, which might cause a major potential bias in age distributions in these samples (Alesan et al., 1999; Angel, 1969; Bocquet-Appel and Masset, 1982, 1985; Chamberlain, 2006; Eshed et al., 2004; Gowland and Chamberlain, 2002; Jackes, 2000; Lewis, 2007; Lewis and Gowland, 2007; Mensforth, 1990; Weiss, 1973). Mensforth (1990: 89) summarized infant underrepresentation as due to “[s]elective cultural biases and mortuary practices at the time of death, differential postmortem preservation, selective recovery and curation practices, and variation in the degree to which age can accurately be inferred from fragmentary skeletal remains.”
Another problem regarding paleodemography of infants is the validity of age estimation techniques (Bocquet-Appel and Masset, 1982, 1985, 1996; Buikstra and Konigsberg, 1985; Horowitz et al., 1988; Mensforth, 1990; Konigsberg and Frankenberg, 1992). In general, in forensic medicine and paleodemography the age-at-death of infants regresses upon long-bone measurements (e.g. Scheuer et al., 1980; Sherwood et al., 2000). Bocquet-Appel and Masset (1982), however, criticized regression equations as systematically biasing the age-at-death of target samples (i.e. samples of unknown age), yielding a distribution similar to that of reference samples (i.e. samples of known age for which the age-at-death was estimated). Infant underrepresentation is related to unavoidable reasons, but this problem stems from a methodological fault.

Fortunately, a consensus on procedures for estimating age-at-death from a skeletal sample, the "Rostock Manifesto," advocated the Bayesian theorem to provide a methodological basis for aging techniques (Hoppa, 2002). The pioneering work of Konigsberg and Frankenberg (1992) explored solutions to overcome systematic bias and improved on aging techniques from the Bayesian method. Konigsberg and Frankenberg (1992) further proposed three valid conditions for removing systematic bias in age-at-death estimation: (1) the age indicator must be perfectly correlated with chronological age; (2) the age distribution of the reference sample must be similar to that of the target sample; and (3) the reference sample must show a uniform age distribution. Gowland and Chamberlain (2002) applied the Bayesian theorem using long-bone measurements to fetal age-at-death estimation in Romano-British archeological sites. Tocheri et al. (2005) estimated the infant age distribution for a Roman-period Egyptian skeletal population, using the posterior probability of age by long-bone measurements given by Gowland and Chamberlain (2002), and found an expected peak of deaths at full-term of gestation. Lewis and Gowland (2007) applied the Bayesian method to infant skeletons in medieval and post-medieval England and obtained an appropriate age-at-death distribution which possibly reflected natural mortality profiles. The recent advancement in infant paleodemography has been due to the employment of the Bayesian theorem. However, only a few studies have employed the new technique or reconstructed paleodemographic features of infant skeletons (Gowland and Chamberlain, 2002; Tocheri et al., 2005; Lewis and Gowland, 2007), and no such study has involved a temporally and geographically different skeletal sample in Asia.

This study examined human skeletal remains from an Edo-period site in Sakai City, Japan. The Edo period is a segment of Japanese history that lasted from 1603 to 1867, marking the governance of the Tokugawa Shogunate that was established by Ieyasu Tokugawa. The Edo period was characterized by a stable and peaceful society and economic prosperity and Japan’s urbanization during this time may well have had no parallel anywhere in the world (Hanley, 1997). The feudal capital, Edo (now Tokyo), became a major city with a population of approximately one million under the Tokugawa Shogunate at an early stage of the era. Paleopathological studies have revealed that the Edo-period people suffered severely from cribra orbitalia, syphilis, dental caries, and lead contamination under the high population pressure (e.g. Suzuki, 1984; Hirata, 1990; Oyamada et al., 2010; Nakashima et al., 2011).

Historical demographers have studied the Buddhist temple census registers, shumon aratame cho, of the Edo period and consider that the birth and death rates were balanced, resulting in a low to zero rate of population growth (Hanley, 1997; Hayami, 2001; Kito, 2000). They speculated that a bias in the sex ratio was explained in terms of abortion and infanticide, which as a consequence had played an important role in the regulation of population growth. Although the mortality profiles of non-adults in Edo-period Japan were an interesting and important theme in historical demography, little is known about infant deaths due to a lack of historical documents. Paleodemographic points of view inferred from skeletal remains, however, provide information concerning the mortality profiles of non-adults in Edo-period Japan.

The purposes of this study are: (i) to examine non-adult human skeletal remains from an archeological site in Japan; (ii) to estimate their age-at-death distribution using new age indicators which can be applied to poorly preserved skeletons to maximize the sample size; (iii) to compare the skeletal age distributions obtained from different approaches; and (iv) to discuss whether paleodemographic estimates can yield an appropriate age-at-death distribution.

Materials

The target sample refers to groups of individuals whose age at death is unknown, while the reference sample refers to groups of individuals whose age-at-death is known and provides information on the age-at-death of the target sample (Konigsberg and Frankenberg, 1992).

The target sample used here comprised individuals from the Sakai-kango-toshi 871 (SKT 871) site in Sakai City, Osaka, Japan (34°34′20″N, 135°28′40″E) (Figure 1). The excavation was conducted by the third author and the Sakai City Board of Education in 2003. The archeological and historical evidence indicated that the SKT 871 site was located on the grounds of the Buddhist temple Kiunji, which had already appeared on an old map of Sakai, Sakai-oezu, drawn in the late 17th century (Sakai City Board of Education, 2005). The development of Sakai City stemmed from an autonomous city run by financial contributions from merchants since the medieval period and played an important role as a trade center. The chronology of excavated bronze coins indicated that the SKT 871 site dated back to the late 17–19th centuries of the Edo period (Sakai City Board of Education, 2005). The most interesting and important finding of the SKT 871 site is an unusual case of burials of more than one hundred human skeletons (Figure 2a). Preliminary examination by the second author implied that they consisted of non-adults (Sakai City Board of Education, 2005). The human skeletons were detected in 132 out of 154 ceramic urns, in which non-adults were housed with ceramic figures, shards, bronze coins, and other grave goods (Figure 2b). Most of them were individually buried but there are at least eight commingled burials containing multiple individuals. Because the ceramic urns were sometimes commingled, this study counted the numbers of each bone but not ceramic urns.
in order to quantify the number of individuals. The target sample is kept in the Department of Anatomy and Cell Biology, Osaka City University Graduate School of Medicine.

To estimate the age of non-adults from the target sample, we used the reference sample information. Table 1 lists the skeletal collections of Japanese individuals of known age whose death years were in the former half of 20th century. Although the reference sample is temporally different from the target one, there is a genetic continuity between the Edo-period and modern Japanese (e.g. Dodo and Ishida, 1990, 1992; Hanihara, 1991). The use of Japanese skeletons as a reference sample allows us to reduce inaccuracy when estimating the age-at-death of the target sample, because age-related indicators exhibit too much variation across different populations to serve as a reference (Loth and Işcan, 1989; Kemkes-Grottenthaler, 1996; Galea et al., 1998; Hoppa, 2000; Jackes, 2000). The reference sample is composed of 342 individuals from Tohoku University (145 individuals), Nippon Dental University (25 individuals), and Saga University (172 individuals). The collection from Saga University included aborted fetal specimens (Matsushita et al., 1995). The gestational ages were recorded in months from gestations of 3–11 months. The age categories of 3, 4, 5, 6, 7, 8, 9, 10, and 11 months respectively correspond to 9–12, 13–16, 17–20, 21–24, 25–28, 29–32, 33–36, 37–40, and 41–44 weeks. The target-sample individuals estimated at 10 months or less were classified as fetuses, and those of 11 months as neonates.

Methods

Uniformitarian hypothesis

Demographic estimates of the sample require the uniformitarian assumption that the biological processes related to aging were the same in the past as in the present (Weiss, 1973; Howell, 1976; Hoppa, 2002; Chamberlain, 2006). Although Huxley (1998) demonstrated the shrinkage of fetal skeletons from fresh to dry bone, the proportion of shrinkage of each bone was assumed to be the same in the target and reference samples.

Quantifying the number of individuals

The number of individuals is fundamental information for estimating age-at-death structure from an archeological site and it is necessary that researchers avoid counting the same individual twice. This study counted the numbers of each bone, quantified the number of individuals, and finally estimated age-at-death for the individuals associated with the most preserved skeletal part.

The minimum number of individuals ($MNI$) and the most likely number of individuals ($MLNI$) were calculated using the method of Adams and Konigsberg (2004, 2008). The $MNI$ was calculated by:

$$\text{Max} \ (R_t, L_t),$$

where $R_t$ and $L_t$ are respectively the number of right and left bones. The Max ($R_t, L_t$) signifies the number of better-preserved sides of skeletons. The lowest quantity of the $MNI$ is the average of paired parts of skeletons:

$$\frac{(R_t + L_t)}{2}.$$

Another estimator of the $MNI$ is:

$$R_t + L_t - P,$$

where $P$ is the number of pairs. This estimator assumes that the unpaired elements are derived from different individuals.

However, these $MNI$ estimators represent the recovered number of individuals, not the original number of individu-
those from the other side are analogous to the secondly recaptured ones in the capture–recapture method, and the pairs which were possibly derived from the same individuals are analogous to the recaptured individuals of initially caught individuals (Adams and Konigsberg, 2004). The MLNI is calculated as:

\[ MLNI = \frac{(R_t + 1)(L_t + 1)}{(P + 1)} - 1. \]

The probability of the MLNI equation is calculated using the hypergeometric function as:

\[ Pr(N|R_t, L_t, P) = Pr(P|R_t, L_t, N) \times \frac{P}{(N + 1)}, \]

where \( N \) is the estimated number of individuals from an archaeological assemblage, \( Pr(N|R_t, L_t, P) \) is the probability of being \( N \) conditional on being \( R_t, L_t \), and \( P \). \( Pr(P|R_t, L_t, N) \) is the probability from the hypergeometric distribution of being \( P \) conditional on being \( R_t, L_t \), and \( N \) (Adams and Konigsberg, 2004). Following Adams and Konigsberg (2008), an approximate 95\% confidence interval for \( MLNI \) can be calculated as:

\[ MLNI \pm 1.96 \times \left[ \frac{(R_t + 1)(L_t + 1)(R_t - P)(L_t - P)}{(P + 1)^2(P + 2)} \right]^{1/2}. \]

In a capture–recapture study, the recovery probability (\( r \)) of each skeletal part is defined as the probability of capture (Adams and Konigsberg, 2004). The maximum likelihood estimate of \( r \) is:

\[ \hat{r} = \frac{2P}{R_t + L_t}, \]

and the standard error of \( \hat{r} \) (SE) is:

\[ SE = \left[ \frac{(\hat{r} - 1)^2(\hat{r} - 2)^2}{2(\hat{r} + L_t)(3 - 2\hat{r}) + 2P(2 - 6\hat{r} + 3\hat{r}^2)} \right]^{1/2}. \]

The calculations of \( MLNI \), \( \hat{r} \), and \( SE \) were processed by an Excel spreadsheet written by Konigsberg (http://konig.la.utk.edu/MLN.html).

### Methods for estimating age-at-death for non-adults

In order to maximize the sample size of the non-adults from an archaeological site, this study examined the age-at-death for the individuals associated with the most preserved skeletal part and developed a new aging technique for it. The age-at-death of individuals which had both dentition and the most preserved skeletal part was estimated based on dental development, which is the most accurate method of estimating subadult age-at-death. Aspects examined included the formation of all crowns and roots, and the eruption of each tooth (Figure 71 in Ubelaker, 1989). Unfortunately, calcifying teeth are small and poorly preserved in particular in fetuses and neonates (Tocheri et al., 2005) and the age-at-death estimation of fetuses and neonates which have no teeth is usually based on the diaphysis of long bones (e.g. Balthazard and Dervieux, 1921; Fazekas and Kósa, 1978; Scheuer et al., 1980; Sherwood et al., 2000; Gowland and Chamberlain, 2002; Lewis and Gowland, 2007). However, fetal and neonatal skeletons from an archeological site are not always associated with long bones due to poor preservation. This
study measured the petrous part of temporal bones and the basilar part of occipital bones, both of which were relatively resistant to decay in subadult skeletons, and obtained a new method to estimate the age-at-death of fetal and neonatal skeletons by using the regression and Bayesian methods. The first author will report on the validity of new age indicators elsewhere (Nagaoka et al., in preparation).

**Measurements**

This study measured four items using modified definitions of Fazekas and Kósa (1978) (Figure 3). The definitions of the items are:

1. **Length of petrous part of temporal bone (LPT):** “[T]he greatest distance between the apex of the petrous part and the superior–posterior end of the mastoid part” (Fazekas and Kósa, 1978: 46). The measurements are taken along the superior border of the anterior and posterior surfaces of the petrous part, which is almost identical to the groove for the superior petrous sinus.

2. **Width of petrous part of temporal bone (WPT):** the distance measured in a vertical plane from the arcuate eminence to the jugular notch.

3. **Length of basilar part of occipital bone (LBO):** “[T]he distance measured in the midline between the foramen magnum and synchondrosis sphenoccipitalis” (Fazekas and Kósa, 1978: 46).

4. **Width of basilar part of occipital bone (WBO):** “the greatest distance measured in the line of the lateral tubercles” (Fazekas and Kósa, 1978: 46).

Specimens with abnormalities and pathological changes were excluded. Both the right and left sides of the petrous parts of temporal bones were measured and the averages were used in this study. There is no significant difference due to sex in these measurement items in each age group from 5 to 10 months (t-test, P > 0.05) with the exception of the WPT at the 5% level (t-test, P = 0.04). Since the sex of subadult human skeletons from an archeological site cannot be determined, both sexes of the reference sample were pooled. To avoid inter-observer errors, the first author alone recorded the target and reference age indicators. Measurements were taken by the first author using a digital caliper (Mitutoyo NTD12P-15C).

In order to test intra-observer errors in the measurement items, measurements were taken twice for 24 individuals of the reference sample with an interval of six months by the first author. The technical error of measurement (TEM) and the coefficient of reliability (Rl) were calculated following Ulijaszek and Lourie (1994) and Goto and Mascie-Taylor (2007). The reliability of the measurement is expressed as the degree of Rl which ranges from 0 (poor reliability) to 1 (high reliability).

**Linear regression analysis**

This study conducted the linear regression analysis using one or two variables. Linear regression equations based on the reference sample can be used for estimating age-at-death for each target-sample individual.

**Bayesian estimation**

Another method for estimating age-at-death of the target sample is the Bayesian estimation. Konigsberg and Frankenberg (1992) expressed the Bayesian theorem as:

\[
p(a|i) = \frac{p(i|a) \cdot p(a)}{\sum_{a=1}^{w} p(i|a) \cdot p(a)},
\]

where \(p(a|i)\) is the posterior probability of being a particular age, \(a\), conditional on being in a particular state of an age indicator, \(i\), and \(p(i|a)\) is the probability of being in a particular state of an age indicator, \(i\), conditional on being a particular age, \(a\). \(p(a)\) is the prior probability of age \(a\). \(a\) is a discontinuous age interval indexed from 1 to \(w\) (1 ≤ \(a\) ≤ \(w\)), while \(i\) is a discontinuous age indicator state indexed from 1 to \(n\) (1 ≤ \(i\) ≤ \(n\)). The calculation of the posterior probability from known-age human skeletal collections and an appropriate prior probability is fundamental information to obtain the age distribution of human skeletal remains from an archeological site. There are two alternative prior probabilities which we can apply to the present case: uniform and reference prior probabilities. In uniform priors an equal prior probability is assigned to each age category, while reference ones were calculated from the age distribution of the
reference sample (Chamberlain, 2006). However, the assumption of the reference priors yielded the age distribution of the target sample showing the similar distribution of the reference sample. Bocquet-Appel and Masset (1982) have criticized reference priors as systematically biasing the age-at-death of target samples, yielding a distribution similar to that of reference samples. This study analyzed the age distribution of the target sample based on the assumption that the age distribution of the reference sample is uniform. The posterior probability obtained by using a uniform prior probability is independent of the age distribution of the reference sample (Gowland and Chamberlain, 2002). When \( d(a) \) is assumed to be uniform in all age categories \( (d(a) = 1/w) \), the Bayesian theorem is expressed as:

\[
p(a|d) = \frac{p(d|a)}{\sum_{a=1}^{n} p(d|a)}.
\]

When the frequency of an archeological sample individual in age indicator state \( i \) is expressed as \( f(i) \), the age distribution for this sample, \( d^*(a) \), is expressed as:

\[
d^*(a) = \sum_{i=1}^{n} f(i)p(a|i).
\]

**Statistics**

The basic statistical analyses were performed using SPSS for Windows 16.0J and Microsoft Excel 2003.

**Results**

Table 2 shows the number of each type of bone from the SKT 871 site. The best-preserved parts of skeletons were the cranium, followed by femur, tibia, and pelvis. The estimated number of individuals from the SKT 871 site represented by temporal bone, humerus, radius, ulna, ilium, femur, andibia is shown in Table 3. The recovery probability suggests that the temporal bones are the best preserved and are good indicators for calculating the number of individuals from the SKT 871 site (Table 3). The MNI calculated from the number of temporal bones ranged from 107 to 127. The probability of the MNI from the temporal bones showed a peak at 131 with an approximate 95% confidence interval from 126 to 136 (Figure 4; Table 3). The estimated number of individuals using the formation of all crowns and roots, and the eruption of each tooth. In order to test intra-observer errors of diagnosis, the first author observed the 59 target-sample individuals twice, in 2008 and 2010, and compared the first and second observations. The estimated bias caused by two observations was small and statistically insignificant (\( U \)-test, \( P > 0.05 \)). The age-at-death distribution of the 59 individuals was, in order, 14, 12, 11, 10, 6, 1, 3, 0, 1, 0, and 1 in each age group from 0 to 10 years old with an interval of one year. The number of deaths decreases with age and the proportion less than 7 years old accounted for 96.6% out of one year. The number of deaths decreases with age and the proportion less than 7 years old accounted for 96.6% out of one year. The number of deaths decreases with age and the proportion less than 7 years old accounted for 96.6% out of one year.

The age-at-death of the remaining 34 individuals which had no dentition was estimated by using osteometric data of the temporal and occipital bones. Before the analyses, intra-observer TEMs and RIs were calculated for the reference

<table>
<thead>
<tr>
<th>Bone</th>
<th>Side</th>
<th>Number of bones</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cranium, petrous part of the temporal bone</td>
<td>Right</td>
<td>107</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>107</td>
</tr>
<tr>
<td>Basilar part of the occipital bone</td>
<td>Right</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>25</td>
</tr>
<tr>
<td>Zygomatic bone</td>
<td>Right</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>20</td>
</tr>
<tr>
<td>Maxilla</td>
<td>Right</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>19</td>
</tr>
<tr>
<td>Mandible</td>
<td>Right</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>49</td>
</tr>
<tr>
<td>Humerus</td>
<td>Right</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>49</td>
</tr>
<tr>
<td>Radius</td>
<td>Right</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>33</td>
</tr>
<tr>
<td>Ulna</td>
<td>Right</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>40</td>
</tr>
<tr>
<td>Pelvis, ilium</td>
<td>Right</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>49</td>
</tr>
<tr>
<td>Ischiun</td>
<td>Right</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>12</td>
</tr>
<tr>
<td>Pubis</td>
<td>Right</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>19</td>
</tr>
<tr>
<td>Femur</td>
<td>Right</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>60</td>
</tr>
<tr>
<td>Tibia</td>
<td>Right</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>56</td>
</tr>
</tbody>
</table>

Table 2. Number of each type of bone from the SKT 871 site

<table>
<thead>
<tr>
<th>Skeletal element</th>
<th>Rt</th>
<th>Lt</th>
<th>P</th>
<th>Max (Rt, Lt)</th>
<th>(Rt + Lt)/2</th>
<th>Rt + Lt - P</th>
<th>MLNI (an approximate 95% confidence interval)</th>
<th>r</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cranium (temporal bone)</td>
<td>107</td>
<td>107</td>
<td>87</td>
<td>107</td>
<td>107</td>
<td>127</td>
<td>131 (126–136)</td>
<td>0.81</td>
<td>0.03</td>
</tr>
<tr>
<td>Humerus</td>
<td>49</td>
<td>49</td>
<td>32</td>
<td>49</td>
<td>49</td>
<td>66</td>
<td>74 (66–82)</td>
<td>0.65</td>
<td>0.06</td>
</tr>
<tr>
<td>Radius</td>
<td>37</td>
<td>33</td>
<td>20</td>
<td>37</td>
<td>35</td>
<td>50</td>
<td>60 (50–70)</td>
<td>0.57</td>
<td>0.07</td>
</tr>
<tr>
<td>Ulna</td>
<td>47</td>
<td>40</td>
<td>23</td>
<td>47</td>
<td>43</td>
<td>64</td>
<td>80 (66–94)</td>
<td>0.53</td>
<td>0.06</td>
</tr>
<tr>
<td>Pelvis (ilium)</td>
<td>51</td>
<td>49</td>
<td>33</td>
<td>51</td>
<td>50</td>
<td>67</td>
<td>75 (67–83)</td>
<td>0.66</td>
<td>0.05</td>
</tr>
<tr>
<td>Femur</td>
<td>69</td>
<td>60</td>
<td>46</td>
<td>69</td>
<td>64</td>
<td>83</td>
<td>89 (82–96)</td>
<td>0.71</td>
<td>0.05</td>
</tr>
<tr>
<td>Tibia</td>
<td>48</td>
<td>56</td>
<td>28</td>
<td>56</td>
<td>52</td>
<td>76</td>
<td>95 (80–110)</td>
<td>0.54</td>
<td>0.06</td>
</tr>
</tbody>
</table>

\( R_t \): number of right bones; \( L_t \): number of left bones; \( P \): number of pairs; \( MLNI \): most likely number of individuals; \( r \): recovery probability; \( SE \): standard error of recovery probability.
sample (Table 4). Although the WPT was a less reliable measurement than any other item ($R_l = 0.934$), other measurement items of the $R_l$s were greater than 0.99. If an acceptable level of reliability can be assumed to be 0.90 or more (Ulasiak and Lourie, 1994), most of the measurements used here are judged not to be affected by intra-observer errors. All four measurement items were positively correlated with the gestational age ($P < 0.01$) (Figure 5; Table 5). The regression equations of gestational age in months of the temporal and occipital measurements were calculated (Table 6). In terms of the determination of coefficient ($R^2$), the WPT ($R^2 = 0.14$) was less reliable than any other measurement item ($R^2 = 0.75–0.82$). When the regression equations calculated for the LPT and also for the LPT, WPT, LBO, and WBO were applied to the target sample for estimating gestational ages (Table 7), the age-at-death distribution obtained by the regression method showed a peak of mortality at 9 months with 40–44% of the fetuses in the regression analyses (Figure 6).

The contingency table of the number of known-age individuals in each category of the LPT (Table 8) was used for calculating the posterior probability of age, assuming uniform prior probability of age (Table 9). The age-at-death distribution obtained by the Bayesian method had a mortality peak at 10 months with 34.1% of the fetuses, which was more gradual and later than the peak observed in the regression analyses (Figure 6). The Bayesian estimation increased the proportion of individuals dying after 11 months from 0% to 16.1% (Figure 6).

The age-at-death distribution of the SKT 871 series,
including the age distribution of 0–10 years estimated by dental formation and eruption and that of fetuses and neonates estimated by the Bayesian method, indicated a peak of deaths at the fetal stage, and the number of deaths decreased with age (Figure 7). In the cumulative age distribution demonstrated in Figure 8, individuals aged less than 7 years old accounted for about 98% of the deaths of the SKT 871 site.

**Discussion**

**Bone preservation**
The *MLNI* represented by temporal bones was estimated to be 131 ± 5, which is almost identical to the number of excavated ceramic urns housing human skeletons, and which indicated that the SKT 871 site originally included about 130 individuals. The recovery probability showed that the SKT 871 series exhibited various degrees of preservation and the best-preserved part was the cranium. This finding is consistent with previous studies by Merbs (1997) and Stojanowski et al. (2002). Merbs (1997) demonstrated that the cranial and leg bones were the best preserved in the fetal human skeletons from the Inuit sites of Hudson Bay. Stojanowski et al. (2002) examined the skeletal preservation of the Windover Pond series and revealed variability in preservation with an apparent lack of age-specific differences in preservation. The cranium was the best preserved, followed by...
by the femur, radius, ulna, and tibia, while the least-preserved parts were the scapula and sternum (Stojanowski et al., 2002). The use of well-preserved parts of skeletons for age-at-death estimation allows us to maximize the sample size of the non-adults derived from an archeological site and to know the mortality pattern that otherwise could not be discerned.

Estimation of fetal age-at-death distribution

All measurement items of the temporal and occipital bones were positively correlated with gestational ages, which demonstrated that both the petrous part of the temporal bone and the basilar part of the occipital bone were good indicators for estimating infant age-at-death. This strengthens earlier findings by Scheuer and Black (2000), Scheuer and McLaughlin-Black (1994), and Tocheri and Molto (2002), who implied that the petrous part of temporal bones and the basilar part of occipital bones changed with gestational age and are likely to be a useful index for fetal age-at-death estimation.

To reconstruct the age-at-death distribution of the SKT 871 series from osteometric data, this study employed the regression and Bayesian methods. The application of the two methods led to different results: the regression method using these measurement items yielded a peak of deaths at a gestation of 9 months, whereas the Bayesian method yielded a peak at 10 months.

As for the reliability of the age-at-death estimation, Gowland and Chamberlain (2002) compared the age distributions obtained by applying the traditional regression method and the newly employed Bayesian method to a Romano-British archeological sample (43–597 AD), and found that the Bayesian method improved the accuracy of age estimation for infant individuals. The difference in the distributions produced by the two methods was also detected in medieval and post-medieval England (850–1859 AD) (Lewis and Gowland, 2007) and in the East cemetery of Kellis in Egypt (250–400 AD) (Tocheri et al., 2005) and these studies also emphasized that the Bayesian estimation yielded appropriate age distributions which reflected natural mortality profiles. In spite of the differences in times, places, and historical backgrounds of the sites, we can see a peak of younger gestational ages in the regression statistics than in the Bayesian estimations. It is reasonable to consider that the difference in the peaks produced by the regression method and the Bayesian method can be attributed to the influence
The difference in the age-at-death distributions produced by the two methods caused an interesting controversy on infanticide in Romano-Britain (Mays, 1993, 2003; Mays and Eyers, 2011). Mays (1993) pointed out the possibility of infanticide by citing the infant age-at-death distribution in Romano-British archeological sites on the grounds that the age structure, which was estimated by the regression method for long-bone measurements, exhibited far more pronounced neonatal peaks than natural mortality data. Re-examination of the age structure using the Bayesian method by Gowland and Chamberlain (2002), however, revealed the absence of pronounced peaks and negated the possibility of infanticide. Nevertheless, Mays (2003) and Mays and Eyers (2011) criticized the discussion of Gowland and Chamberlain (2002) and provided empirical evidence that there is no systematic bias in their regression-based age structure. Because the age indicators used in the study by Mays and Eyers (2011) have high correlation coefficients (0.95 or higher), the systematic bias is remarkably reduced in the age-at-death structure. In general, in the case that the correlation coefficient between age and age indicators is low, the estimated age-at-death
distribution of the target sample produced by the regression method becomes a reproduction of the age structure of the reference sample (Konigsberg and Frankenberg, 1992).

Although it is difficult to answer the question which estimation approximates the actual age distribution of infants from the target sample, the age distribution by the Bayesian method is likely to be more plausible than that by the regression method. This is because the methodological fault in the regression method has been pointed out since the pioneering work by Bocquet-Appel and Masset (1982), who criticized that the regression equations systematically biased the age-at-death of target samples and yielded a distribution similar to that of reference samples. The estimated age-at-death distribution of the target sample produced by the regression method is only a reproduction of the age structure of the reference sample, while the Bayesian method allows one to remove the systematic bias and to obtain a more reliable estimation of the age-at-death distribution of the target sample (Bocquet-Appel and Masset, 1982; Konigsberg and Frankenberg, 1992; Chamberlain, 2000, 2006; Gowland and Chamberlain, 2002; Hoppa, 2002; Lewis and Gowland, 2007). Because the reference sample used in this study...
concentrated on 5–7 months with a peak at 7 months, the age-at-death distribution of the target sample derived from the regression method possibly exhibited a younger distribution. In this study, furthermore, the peak at 9 months in the regression method cannot be empirically explained, but rather the peak at 10 months in the Bayesian method is consistent with the natural mortality profiles observed in modern human populations (Gowland and Chamberlain, 2002; Tocheri et al., 2005) and the concentration on full-term of gestation indicates deaths related to birth.

Mortality profiles
The mortality profiles obtained from the SKT 871 series indicated that the peak of deaths was at the fetal stage and that the number of deaths decreased with age. These profiles are consistent with the natural mortality patterns documented in ethnographic and historical demographic records or model life tables, according to which, in pre-industrial societies, age-specific mortality followed a high mortality rate at birth but decreased with age (Howell, 1979; Kito, 2000; Kobayashi, 1956; Weiss, 1973).

The age-at-death distribution detected in the SKT 871 series showed a clear contrast with the general patterns observed in another archeological sample. Table 10 compares the age structure of SKT 871 with that of Hitotsubashi, which is a contemporary archeological site located in Tokyo (1657–1683 AD) (Nagaoka and Hirata, 2007). It represented townsmen, based on the fact that the largest proportion of the graves contained wooden coffins (hayaoke) that were often used for the lower social classes (Nagaoka and Hirata, 2007). Most of the SKT 871 cases were fetal individuals and the number of deaths monotonously decreased with age from the fetal stage, while the Hitotsubashi showed a peak of deaths at 1 year of age with an apparent underrepresentation of fetuses. The previous studies have considered infant underrepresentation as a major source of census errors in age distributions (Angel, 1969; Weiss, 1973; Bocquet-Appel and Masset, 1982, 1985; Mensforth, 1990; Jackes, 2000; Alesan et al., 1999; Eshed et al., 2004) and the variability in the proportion of non-adults in archeological sites can be explained by assuming different taphonomic processes. The fortunate situation that the SKT 871 series contained well-preserved infant skeletons is possibly because the human remains were housed in ceramic urns, which prevented post-mortem physical and chemical deterioration, and because the excavation was carefully performed by a skillful archeologist. It is concluded that the age-at-death distribution in SKT 871 contrasts with that in other archeological cases but it is likely to represent the natural mortality patterns in pre-industrial societies.

### Table 10. Comparison of the age-at-death structure between SKT 871 and Hitotsubashi

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Number of individuals</th>
<th>Proportion (%)</th>
<th>Number of individuals</th>
<th>Proportion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fetus</td>
<td>21</td>
<td>25.0</td>
<td>2</td>
<td>0.9</td>
</tr>
<tr>
<td>0–4</td>
<td>57</td>
<td>67.9</td>
<td>75</td>
<td>35.9</td>
</tr>
<tr>
<td>(0)</td>
<td>(18)</td>
<td>(21.4)</td>
<td>(16)</td>
<td>(7.7)</td>
</tr>
<tr>
<td>(1)</td>
<td>(12)</td>
<td>(14.3)</td>
<td>(27)</td>
<td>(12.9)</td>
</tr>
<tr>
<td>(2)</td>
<td>(11)</td>
<td>(13.1)</td>
<td>(8)</td>
<td>(3.8)</td>
</tr>
<tr>
<td>(3)</td>
<td>(10)</td>
<td>(11.9)</td>
<td>(7)</td>
<td>(3.3)</td>
</tr>
<tr>
<td>(4)</td>
<td>(6)</td>
<td>(7.1)</td>
<td>(1)</td>
<td>(0.5)</td>
</tr>
<tr>
<td>(Indeterminable)</td>
<td>(0)</td>
<td>(0.0)</td>
<td>(16)</td>
<td>(7.7)</td>
</tr>
<tr>
<td>5–9</td>
<td>5</td>
<td>6.0</td>
<td>20</td>
<td>9.6</td>
</tr>
<tr>
<td>10–14</td>
<td>1</td>
<td>1.1</td>
<td>13</td>
<td>6.2</td>
</tr>
<tr>
<td>15–19</td>
<td>0</td>
<td>0.0</td>
<td>8</td>
<td>3.8</td>
</tr>
<tr>
<td>20+</td>
<td>0</td>
<td>0.0</td>
<td>91</td>
<td>43.5</td>
</tr>
<tr>
<td>Total</td>
<td>84</td>
<td>100</td>
<td>209</td>
<td>100</td>
</tr>
</tbody>
</table>

1 Nagaoka and Hirata (2007).

Implication for mortuary practices
The SKT 871 series consisted of individuals aged less than 7 years, accounting for about 98% of the deaths, and there was no burial for adults. The lack of adults in the SKT 871 series, however, cannot be explained by assuming taphonomic factors. This is because adult human skeletons are more resistant to decomposition than non-adults. One explanation for the lack of adults is preferential mortuary practices, by which the very young are buried separately from adults (Mensforth, 1990). Ethnographic records indicate a great deal of variability for burial of infants. For example, the prehistoric Iroquoians of Southern Ontario buried infants under pathways and believed their souls influenced the fertility of passing women (Lewis, 2007). In modern East and Southeast Asia infants were buried under the floor, entrance, and kiln of settlements or in gardens, while in 20th century Japan they were often buried under the floors of settlements or under pathways (Nakamura, 1999). The folklorist Kunio Yanagita introduced a specific type of burial for non-adults, which was called kobaka (Yanagita, 1946). The kobaka, where non-adults aged 7 years or less were buried, was prevalent all over Japan, in particular, in the Kinki and Chugoku Districts (Yanagita, 1946). Yanagita (1946) stated that non-adults aged 7 years or less were regarded as god-like beings and that the parents believed in their reincarnation by burying their bodies in kobaka. It is interesting that the age structure seen in the SKT 871 site is consistent with Yanagita’s (1946) description. The results of this study imply special treatment for non-adult deaths and strengthen the discussion of Yanagita from the viewpoint of paleodemography. The presence of individuals aged under gestation of 7 months, which were “less likely to survive the extraterine environment due to the immaturity of their vital internal structures” (Lewis and Gowland, 2007: 118), further indicates deaths by miscarriage. The individuals who are assumed to have been from kobaka include not only postnatal children but also stillbirths and aborted fetuses. All non-adults buried in kobaka were likely to have received equal and respectful treatment regardless of their age because of a rich assortment of burial goods was equally offered to them (Sakai City Board of Education, 2005).

Conclusions
The use of the Bayesian method for estimating non-adult age at death yielded an appropriate age structure of the archeological sample. The mortality profiles obtained from the SKT 871 series suggested a peak of deaths at the fetal stage,
the number of deaths decreasing with age, and a lack of adult individuals. It is plausible to conclude that, due to the age structure, the non-adults observed in SKT 871 died of natural causes (e.g., traumas, congenital anomaly, and pneumonia), and that the lack of adults is related to preferential mortuary practices for non-adults, which is possible evidence for kobaka. This paleodemographic study of non-adults from the archeological sample provides us with important information on the mortality profiles of a past human population and refines our understanding of mortuary practices, which we cannot see in ethnological or historical documents.

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References


