Prediction Models for Age-at-Death Estimates for Calves, Using Unfused Epiphyses and Diaphyses

R. GILLIS,* R-M. ARBOGAST, J-F. PININGRE, K. DEBUE AND J-D. VIGNE

a Département Ecologie et Gestion de la Biodiversité, UMR 7209, Archéozoologie, Archéobotanique: Sociétés, Pratiques et Environments, CNRS—Muséum National d’Histoire Naturelle, Paris, France
b Etude des Civilisations de l’Antiquité: de la préhistoire à Byzance, UMR 7044, Université Marc Bloch Strasbourg 2, CNRS, Strasbourg, France
c Archéologie, Terre, Histoire, Sociétés, Services Régionaux de l’Archéologie de Franche Comté, Université de Bourgogne, CNRS, UMR 6298, Dijon, France

ABSTRACT
For cattle (Bos taurus), age estimations using dental criteria before the eruption of the first molar (3–8 months) have large error margins. This hampers archaeozoological investigation into perinatal mortality or the putative slaughtering of very young calves for milk exploitation. Previous ageing methods for subjuveniles have focused on the length of unfused bones, but it is rarely possible to use them because they are restricted to foetuses and because of the fragmentation of bones. This paper presents new age prediction models based on length, breadth and depth of post cranial bones produced from a dataset of modern calves (n = 27). This reference collection was compiled from material of known age at death, sex and breed from collections in Britain, France, Germany and Switzerland. Linear regression models were constructed using the modern data for age prediction, and these models were then successfully tested and assessed using a Middle Neolithic assemblage of complete calves’ skeletons from Bourguignon-Lès-Morey, France. From the assessment, the astragalus and metapodials were determined to be the most reliable bones, and the femur was the worst. Measurements of the epiphyseal and distal elements and depth measurements were the most reliable. For ages before 12 months, these models can provide ±1 month age estimates. Copyright © 2013 John Wiley & Sons, Ltd.

Key words: archaeozoology; calf age-at-death estimation prediction models; unfused post cranial bones; Middle Neolithic

Introduction

The presence of very young ungulate remains at archaeological sites can provide direct and indirect evidence for hunting practices (Munro, 2004; Atici, 2009), the seasonality or status of sites (Helmer & Vigne, 2004; Rowley-Conwy, 2004; Zeder, 2006), early domestication events (Wheeler, 1984; Mengoni Goñalons & Yacobaccio, 2006; Zeder, 2006) or specialised husbandry practices (Payne, 1973; Arbuckle et al., 2009). In addition, determining the age of young animals is important for understanding herd health (Mengoni Goñalons & Yacobaccio, 2006), herd structure (Cribb, 1987) and the development of stock rearing techniques for specific products such as milk (Payne, 1973; Vigne & Helmer, 2007). More specifically, determining the character of calf mortality is important for understanding the evolution and development of husbandry practices such as dairying. For traditional breeds, the presence of the calf during milking is necessary to initiate milk ejection. This has been suggested to have been the situation in the past, particularly during the Neolithic (Clutton-Brock, 1981; Peske, 1994; Balasse & Tresset, 2002; Balasse, 2003). In the absence of the calf, there are many methods that are practiced to stimulate milk ejection such as creating a dummy using the dead calf skin, sharing a calf between cows and blowing into the uterus (Balasse, 2003; Tani, 2005). Prehistoric evidence of these practices (Amoroso & Jewell, 1963; Lucas, 1989) supports the possibility that calves could have been slaughtered prior to weaning to increase milk production using artificial means and adoption (Vigne & Helmer, 2007). Archaeozoological mortality patterns are constructed from dental eruption and wear, and bone fusion timings.

e-mail: gillis@mnhn.fr

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On the basis of tooth eruption and replacement, and also on the—though admittedly less precise—dental wear, dental age estimates are more commonly used than the former (Grant 1982; Halstead, 1998; Helmer, 2000; Greenfield & Fowler 2005; Vigne & Helmer 2007). However, there are limitations in using dental age estimates particularly in ageing young calves because there is no eruption/replacement of other teeth between the first molar (M1: 1–6 months) and the second molar (M2: 6–15 months). The upper and lower limits are from Higham (1967) and Legge (1992), respectively. The second problem of using dental ageing for precisely ageing calves is that young mandibles are fragile and are subject to fragmentation and dissociation of teeth (Munson, 2000); consequently, estimated ages can be imprecise. Finally, discrepancies exist for eruption timings between dental age estimation methods (for a review, see Bull & Payne, 1982, Legge, 1992).

In cattle, there are three main groups of epiphyseal fusion ages (Silver, 1963; Schmid, 1972; Habermehl, 1975): early (7–20 months), middle (24–36 months) and late (42–48 months). The earliest epiphyseal events occur too late to be useful to discuss the question of prenatal or post-natal mortality and are too imprecise and variable due to nutrition, health, geography and climate (Bull & Payne, 1982; Reitz & Wing, 2008) to be used for the precise ageing of young post-natal calves. Regli (1963) and Bünger-Marek (1972) proposed sigmoid models for predicting the age of cattle foetuses using the length of the diaphyses. Regli’s models (1963) were based on Simmental and Fribourg breeds and those of Bünger-Marek (1972) on German Black and Lowland foetuses and can hardly be extrapolated to perinatal animals. However, at most archaeological sites, unfused long bones are often broken because of the following:

(i) their porosity/fragility, (ii) cooking practices, (iii) carnivore gnawing, and (iv) post-depositional fragmentation (Munson, 2000). For young as well as for adult bones, length measurements are much rarer than breadths and depths. Therefore, bone age prediction methods are only used rarely and do not provide precise and sufficient amount of age data for perinatal/yearling calves.

Because neither dental eruption, long bone fusion or length growth are accurate for young calves, we explore here the possibility of using the breadth and depth measurements of post-cranial elements. In young mammals, growth in thickness (breadth and depth) takes place at the periphery of the centre of the ossification of short and flat bones and the articular ends of long bones. The elongation of long bones takes place at both ends of the diaphysis and between the shaft (diaphysis) and the epiphyses of the bone. At the end of the growth, the epiphyses and the diaphyses fuse and the cartilage disappears until it is not apparent in older mammals, at which point the growth in length stops. The growth in breadth/depth may continue more slowly throughout life (Davis, 2000; Popkin et al., 2013). Previous studies by Legge & Rowley-Conwy (1988) of red deer at Star Carr, by Davis (2000) of modern sheep, by Vigne et al. (2000) of modern and Mesolithic wild boar and of Popkin et al. (2013) of modern sheep, have demonstrated that there is a good correspondence between width/depth and age for some skeletal parts such as the scapular neck, the proximal extremity of the humerus and radius, the acetabulum of the pelvis and breadth of the astragalus.

In order to test whether bone measurements constitute a reliable proxy for age at death estimates for cattle, we took the metric data of long bones, including the scapula, astragalus and calcaneus from modern calves of known age and in most cases, known sex and breed (n = 27). After statistical analysis of the modern data, regression models were constructed to predict age at death. Finally, the strength of these prediction models was tested using a Middle Neolithic assemblage of complete calves’ skeletons.

**Material and methods**

**Modern reference collections**

The metric data from 27 individuals with known age at death were collected from the Natural History Museum of London, Muséum d’Histoire Naturelle of Geneva (Switzerland), Museum für Haustierkunde (Halle, Germany), Muséum National d’Histoire Naturelle (Paris, France), University of Bournemouth (England) and English Heritage (Portsmouth, England, Table S1). During the search for study material, multipurpose breeds were examined to provide a more reliable analogue for prehistoric animals. Both sexes are represented in the study (10 female and 12 male; Table S1). However, the sexes were not distributed evenly with respect to age; consequently, it was not possible to examine whether there are differences in growth between sexes. The ages range from neonatal to 12 months, with the average age of 3 months and 27 days. There were a number of breeds used in this study, which does give a larger error margin than perhaps those constructed using one breed. However, as previously noted by Prummel (1987), homogeneity within a sample can produce a narrow age estimate specific for that breed. Sixty-six measurements from scapula, humerus, radius, ulna, metacarpus, femur, tibia, metatarsus, astragalus and calcaneus were registered with a calliper (precision: tenths of millimetre), following von den Driesch (1976), adapted to unfused shafts (unf.) or epiphyses (epi., Figure S1).
Archaeological test material

For the archaeological test case, a group of nine complete Neolithic skeletons of calves were selected in order to test the prediction models by comparison with dental estimates. This unique single deposition of calves (Figure 1) was found in the enclosure ditch (South rampart, sector BC-BG) or the enclosure site, Bois de la Roche, Camp des Romains, at Bourguignon-Lès-Morey [BLM; Haute-Saône, France; Figure 1(a)] dated from the ‘Néolithique Moyen Bourguignon’ (4200–3600 cal. BC). Arbogast & Piningre (2007) had demonstrated that all the individuals were close in age (around 6 months) using the scheme by Higham (1967). This material was measured by two of us (R. G. and K. D.) in April 2010. In our first age estimations, only individual (ind.) 53 showed strong discrepancy between dental age and the post-cranial estimate. There was a complicated intricacy of bones in the area surrounding ind. 53 [Figure 1(b)]. The head of ind. 61 was a better candidate for ind. 53 as it was in line with the vertebral column of the latter. Therefore, one of us (R. G.) revisited the material in June 2012 in order to record the dental age of an isolated head identified as ind. 61. This dental age was very similar to the one given by the post-cranial material from ind. 53. Consequently, we finally decided to consider that this head should be associated with ind. 53.

Statistics and regression modelling

As for all mammals, the growth of cattle starting from birth is reputed to fit a logistic model with a short period of slow growth just after birth, then a fast linear growth model during the two first years, after which there is a fast asymptotic growth stabilisation (Quittet & Denis, 1979). This should be also true for most of the skeletal measurements. Therefore, when dealing with only the first 15–18 months of life, this model may be simulated with a linear model (Vigne, 1988).

The nonparametric Kruskal–Wallis test for variance was used in order to see whether there was significant variation between breed types. The null hypothesis of this test is that all the samples are taken from populations with same median (two-sided, $p > 0.05$; Dytham, 2003).
This test was used as the sample size was smaller than the required sample size (n = 20) for a parametric test.

To statistically test the ages predicted using teeth (based on eruption and wear) and unfused bones (using our models presented here) within the modern reference samples, we used Mann–Whitney U test because the range for the dental age could not be defined as a normal distribution.

All statistical analyses were carried out in R (version R.2.13.1), a free open platform programme.

Table 1. The linear model parameters produced from linear regression the known age and the 66 bone measurements from the modern individuals taken as references, according to the linear model. Scapula Ld: (Greatest) dorsal length; HS: Height; BG: Breadth of glenoid cavity; SLC: smallest length of coracoid process; LG: length of the glenoid cavity; GLP: Greatest length of processus articularis; Humerus/Radius/Femur/Tibia/Metacarp/Metatarsus: Dp: Distal breadth of the proximal end fused; Bp: Breadth of the proximal end fused; Dpunf: breadth of distal end unfused; Ddp: depth of the distal end epiphyseal; Bp: breadth of the distal end epiphyseal; Dp: depth of the proximal end epiphyseal; Humerus Dd: breadth of the distal end unfused lateral side; Humerus BT: breadth of the trochlea; Ulna L0: length of olecranon medial side; L0: length of olecranon lateral side; BPC: breadth across the coronoid process; SDO: Smallest depth of the olecranon; Femur DCFunf: depth of the caput femoris; Astragalis GL: greatest length of the lateral half; GLM: greatest length of medial half; Di: depth of the tibial half; Dc: breadth of the distal end; Calcaneus SDc: shortest distance of the corpus; Bp: breadth of the proximal end

For measurements, see supplementary data 1 and Table S1.

Significance codes: p = 0.0001 ***, 0.01 **, 0.05 *, 0.1 .


Results and comparisons

Age prediction models

The parameters of the linear regression models between the age and the 66 bone measurements from the 27 modern individuals are presented in Table 1. A good correlation between age and the measurement taken was observed for most of them. For example, a coefficient...
of determination ($r^2$) of 0.8 was seen for the following measurements: Tibia-GL; Scapular-Ld, HS and LG, and of 0.7 for Scapula-BG; Humerus-GL; Radius-GL; Femur-GL; Bd and Ddepi; Ulna-BPC and GL and Calcaneus-GL. The 20 measurements, which had an $r^2$ lower than 0.5 were not used to predict the age at death for BLM cattle. Within the sample set, the Kruskal–Wallis tests gave no significant difference between breed types for any of the bone measurements.

**Testing the models with a Neolithic assemblage from Bourguignon-Lès-Morey**

Figure 2 shows the ages predicted from the 46 selected bone measurements of the nine BLM individuals (inds.). For each bone listed, the mean predicted age is represented with mean upper and lower 95% confidence limit. Age estimates vary from birth (or before birth) to 6 months for inds. 1, 2, 40, 45, 53 and 67, but only from 1 to 4–5 months for inds. 3 and 49, and from 2 to 8 for ind. 39.

In addition to the predicted age from the measurements, dental age was estimated using the Higham (1967) and Legge (1992) methods (Figure 2). They vary from 1 to 6 months for inds. 3, 40, 45, 49 and 67, from 3 to 7–9 months for inds. 1 and 2, and from 6 to 10 months for inds. 39 and 53. There are strong discrepancies between the ages estimated by the two dental methods for all the inds., where both methods were used (seven of the nine inds.).

**Comparison of models with the external dental and bone measurements age estimation methods**

The ages estimated from bone length following the method of Bünger-Marek (1972) are also shown in
Figure 2 if they are within the represented range of age as to allow comparison between the models developed here and the former prediction methods.

For most individuals, where the Bünger-Marek (1972) models were used to predict age from the greatest length measurements, the predicted age was greater than the 95% confidence interval (CI) of the age estimations coming from our models. This is because these models are based on foetuses and therefore only applicable for this age group. In addition, they were based on one breed (German Black and Lowland). Therefore, there is no allowance for variation between breed types, contrary to our linear models, which are based on several different breeds.

For all the nine inds, the dental age estimated using Legge (1992, Figure 2) scheme coincided better with the means from the skeletal elements than that of Higham (1967). Higham’s scheme was drawn from Silver (1963), which was itself constructed from a mixture of 19th and 20th century veterinarian observations of live animals, that is, eruption through the gum. Legge (1992) is based on the radiography study of Brown et al. (1960), that is, on eruption through the jaw bones. This difference between dental eruption schemes is due to different appreciation of dental eruption in live and dead animals. Therefore, Legge’s scheme appears to be better adapted for estimating age at death of archaeological remains.

Considered as whole, the post-cranial measurements correspond well with the dental age according to Legge (1992) for inds. 2, 3, 40, 45, 49, 53/61 and 67 (Table 2). For these seven inds., the observed mean of each element coincided best with the dental age where there were several measurements per element. The posterior elements coincide more frequently with the BLM inds. than the anterior ones: ind. 2 (femur, tibia, metatarsus, astragalus and calcaneus), ind. 40 (all), ind. 45 (all), ind. 49 (femur, metatarsus, astragalus and calcaneus) and ind. 67 (femur, tibia, metatarsus and astragalus). The elements of the anterior limbs (scapula, humerus, radius, ulna and metacarpus) coincide with the Legge (1992) age prediction for inds. 40, 45, 49 (only humerus, radius and metacarpus), 53/61 (except metacarpus) and 67.

For inds. 1 and 39, the majority of the predicted age mean was below the estimated dental age. For both individuals, the predicted ages from individual measurements and predicted age mean were tightly correlated. The post-cranial age estimates are only about 1 month younger than the dental age (Table 2).

### Assessment of the variability in ages predicted by the models for individual measurements

It appears that for all the nine individuals from BLM, the average ages estimated with the post-cranial measurements do not differ more than 1 month from the dental age estimated using Legge (1992). This congruence allows us to postulate that the mean ages estimated by the post-cranial measurements are reliable estimates of the age at death. In order to assess the prediction ability and variability for individual measurements within the BLM test sample, they have been scored and ranked for their ability to fall within the 95% and 99% CI for the mean age for each of BLM inds. (excluding ind. 3 as the total number of measurements was too small, \( n = 11 \)). Standardised limits for the categorisation have been used so that they will be applicable to future studies (Table 3).

#### First category

This category contains those measurements that predicted over 55% of the ages within the 95% CI and over 80% of the ages within the 99% CI (radius Dp, metatarsus Dd, metatarsus Bd, humerus Ddpepi, humerus BT, humerus Bdunf, astragalus GLl, ulna SDO, metacarpus Bd, calcaneus GB, astragalus GLm, radius Ddepi, radius Dpepi, metacarpus smallest breadth of diaphysis (SD), radius SD and humerus Dd). For the BLM material, radius Dp, metatarsus Dd, metatarsus Bd, humerus Ddpepi, humerus BT and humerus Bdunf predicted 100% of ages within the 95% CI. There is a greater

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Table 2. The age at death estimates for the Bourguignon-Lès-Morey nine individuals, according to Legge (1992) for dental ages, and to mean age predicted using unfused bone measurements

<table>
<thead>
<tr>
<th>Individuals</th>
<th>Legge (1992) dental age (months)</th>
<th>Mean skeletal age range (months) (95% CI)a</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3–6</td>
<td>1.9 ± 0.5</td>
</tr>
<tr>
<td>2</td>
<td>3–6</td>
<td>4.4 ± 0.7</td>
</tr>
<tr>
<td>3</td>
<td>1–3</td>
<td>1–4a</td>
</tr>
<tr>
<td>39</td>
<td>6–15</td>
<td>4.8 ± 0.5*</td>
</tr>
<tr>
<td>40</td>
<td>1–3</td>
<td>2.5 ± 0.3</td>
</tr>
<tr>
<td>45</td>
<td>1–3</td>
<td>2.8 ± 0.3</td>
</tr>
<tr>
<td>49</td>
<td>1–3</td>
<td>2.8 ± 0.3</td>
</tr>
<tr>
<td>53</td>
<td>6–15</td>
<td>2.1 ± 0.4*</td>
</tr>
<tr>
<td>67</td>
<td>1–6</td>
<td>2.6 ± 0.3</td>
</tr>
</tbody>
</table>

*aFor individual 3, age range is based on the overall range as the sample number is too small to base the mean skeletal age on 95% CI.

a*The Mann–Whitney tests for the comparison of Legge (1992) estimations with the predicted bone age were significantly different for individuals 39 and 53 (\( p < 0.05 \)).
tendency for measurements to underestimate predicted ages within this category (astragalus GLI, ulna SDO, radius Ddepi and metacarpus SD). Only the radius SD measurement predicted ages beyond the upper 99% confidence limit. Overall, the most reliable measurements in this category are astragalus GLI and astragalus GLm due to the number of BLM inds. \( (n = 8) \).

### Second category

These are measurements, which gave less than 55% within the 95% CI, but more than 50% within the 99% CI. Within this category are the six measurements that have over 50% success rate for age prediction within the 95% CI (tibia Dpepi, tibia Bdepi and radius...
Dd). The remaining measurements all predicted >50% ages in the 99% CI (scapula BGunf, metacarpus Dd, tibia Bd, metatarsus SD, scapula LG and scapula GLP). Similarly, with measurements in the category 1, there is a trend towards predicting ages below the lower limit of the 99% CI (tibia Dpepi, tibia Bdepi, radius Dd, tibia Bd and metatarsus SD). Whereas scapula BGunf, metacarpus Dd, scapula LG and scapula GLP are consistently outside the upper limit the 99% CI.

Third category

This category contains measurements, where <50% of predicted ages are within the 95% and the 99% CI. These measurements (tibia Dd, femur SD, scapula SLC, metacarpus Bp, humerus Bp, metatarsus Dp, tibia Dd, femur DcFunf, radius Bp, humerus SD and femur Bp) are not reliable and considered bad age estimators. The femur SD, humerus and tibia measurements consistently predicted ages outside the lower limit of the 99% CI (>50% underestimated). Those measurements that predicted ages outside the upper limit of the 99% CI were the scapular SLC, metatarsus Dp, radius Bp and femur Bp predicted ages above the 99% CI limits, although the metatarsus and radius measurements have a tendency to predict ages under the lower 99% CI limit.

Fourth category

For the remaining measurements, none of the predicted ages were within the 99% CI (ulna BPC, tibia Bpepi, radius Bpepi, metatarsus GL, humerus GL, calcaneus GL and radius GL). The last five were completely outside the upper limit of 99% CI.

Overall, measurements from the astragalus and the metapodials (except for metapodials SD) are consistently within 95% and 99% CI and are therefore the most reliable bones in the study. Those bones that had an average success rate for age prediction were the tibia, radius (except radius Bpepi, Bp and GL) and humerus (except humerus GL and SD). The most unreliable bone is the femur. For calcaneus and ulna, they have only two measurements, which were average to poor in prediction performance. Early fusing bones do not appear to give ‘better’ results than later fusing bones.

From Table 4, it is clear that within the long bone measurements, the epiphysis and the depth measurements are the most reliable. Those with an average success rate were measurements of diaphyses, the proximal part of the bone and breadth measurements. The diameter of the diaphyses was inefficient for predicting age. All GL measurements were in category 4, which may suggest that these linear models are not approximate and the measurements are not reliable proxy for age.

Discussion

The first aim of this study was to explore if the metric differences between breed types (milk, meat and mixed) would not preclude the creation of predictive age models based on the measurements of post-cranial bones of calves dead before 12 months. Because of the small sample set, we demonstrated that the medians of different measurements from three breed types [milk (7), meat (4), mixed (5) and unknown (11)] were not significantly different (Kruskal–Wallis test; p > 0.05). This is either due to no significant differences between domestic breeds or the data set was insufficiently diverse for a significant result. Finally, we concluded that these differences were too small to be detected in our sample and insignificant to affect the predictive models. This indicates that post-cranial bone measurements may be used to estimate the age of young cattle.

The second part of the study was the development of linear age prediction models. A significant criticism of the use of linear models is that it ignores the ‘natural’ logistic growth curve experienced in animals. However, a linear model is the simplest and ‘truest’ fit to our investigations, which dealt only with the first 12 months after birth, that is, a time when the growth

<table>
<thead>
<tr>
<th></th>
<th>Diaphyses</th>
<th>Epiphyses</th>
<th>SD</th>
<th>Proximal</th>
<th>Distal</th>
<th>Breadth</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>25.0</td>
<td>8.0</td>
<td>7.0</td>
<td>11.0</td>
<td>14.0</td>
<td>13.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Categories 1 + 2</td>
<td>14.0</td>
<td>6.0</td>
<td>3.0</td>
<td>4.0</td>
<td>12.0</td>
<td>7.0</td>
<td>11.0</td>
</tr>
<tr>
<td>% Categories 1 + 2</td>
<td>56.0</td>
<td>75.0</td>
<td>42.9</td>
<td>36.4</td>
<td>85.7</td>
<td>53.8</td>
<td>91.7</td>
</tr>
</tbody>
</table>

SD, shaft diameter.

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curve of calves can be assimilated to a linear model (Quittet & Denis, 1979; Vigne, 1988). Therefore, the effects of outlier breed types are damped, and the intercept and coefficients are more statistically significant than if we used polynomial models.

The third aim of the study was to test the age prediction models with Neolithic calves of known dental age. The deposit at BLM, with only nine individuals, is the largest collection of complete Neolithic calves’ skeletons to our knowledge. We observe for the BLM individuals that the age estimates predicted by our models were consistent with dental age estimates using Legge (1992) and were consistent for isolated individuals.

The final aim of the study was to assess the performance and variation of predicted ages from individual bone measurements, that is, an assessment based on the ability to predict ages within the 95% and 99% CI for the BLM sample. From this assessment, we propose four categories of bone measurements (category 1: >55% predicted ages within the 95% CI; category 2: <50% predicted ages within 95% CI and >50% within the 99% CI; category 3: <50% predicted ages within 99% CI; category 4: <0% within the 99% CI). From this categorisation, we found that measurements from the astragalus and metapodials (except metacarpus Bp, metatarsus GL and Dp) were the most reliable, followed by tibia, radius (except radius Bpepi and Bp) and humerus (except humerus GL, Bp and SD), and finally, the worst performing bones was the femur. For ulna (SDO and BPC) and calcaneus (GB and GL), the measurements for these bones were either reliable (ulna SDO and calcaneus GB) or poor (ulna BPC and calcaneus GL).

Previously, Prummel (1987a, 1987b, 1988, 1989) tested the methods of Bünger-Marek (1972) and Regli (1963) for predicting ages from the length of foetuses long bones and found that there was no consistency with poor age estimations. However, we have demonstrated that, for neonates and young calves, there are specific bones such as the astragalus and the metapodials, which are consistently reliable at age prediction. This assessment allowed for an overview of different types of measurements (i.e. from diaphyses/epiphyses, GL/SD, proximal/distal and breadth/depth). We found that epiphyseal elements and distal and depth measurement produced accurate age estimates. The shortest diameter and greatest length of the diaphyses were the poorest performing measurements. This could be explained by the fact that the growth in length and in thickness of the mammal long bones are the result of two different processes: the activity of the epiphyseal cartilage and of periostic ossification, respectively. This is also evident in the construction of log size index, as emphasised by Meadow (1999), where the length and thickness measurements behave differently.

The correspondence with dental age estimates using Legge (1992), and not with that of Higham (1967), suggests that caution should be taken when using the former. Higham (1967) is based on veterinarian observations of live animals; consequently, the eruption timings are based on the eruption through the gum. Further work is needed by archaeozoologists on increasing the observations from different cattle breed types (improved milk and meat; unimproved) to construct a more reliable approach to ageing animals using dental eruption and wear.

The use of unfused post-cranial bone measurements (namely radius, metapodials, tibia and astragalus) can be a good complement or even an alternative to dental and epiphyseal techniques for refining age at death estimates for calves. In relation to the question of determining natural mortality, that is, dead within the first month of birth or deliberate slaughtering, it is not possible to use this technique without further refinement of the models. Conversely, this technique is accurate enough for distinguishing perinatal mortality from post-lactation slaughtering (ca 9 months; Balasse & Tresset, 2002).

Future work is required to increase the modern data set, which may modify these results. A larger sample would allow for the use of more sensitive parametric tests. Obtaining modern reference material with accurate information (age at death, breed type and sex) of calves is difficult as they are of little importance to zoologists who curate museum collections. However, as demonstrated in this study, collection of this material can lead to new ageing methodology for archaeozoologists. Future studies should aim to increase the sample prior to any new study of bone prediction models. In addition, this result also calls for more statistical comparison of metric data from prehistoric and modern animals to first assess whether these measurements are consistently different between data sets and second, to understand this result in terms of selective breeding.

**Conclusion**

Metric data from 28 modern individuals were used to construct linear models to predict the age from bone measurements with a certain degree of security. The use of nonparametric tests has demonstrated that there was no significant difference between breed groups within this modern sample. However, the size of our sample is very small for each breed type. We have demonstrated that models can be constructed from modern metric data for
predicting ages for Neolithic animals on the basis of post-
cranial unfused bones. The application of the prediction
models on an archaeological assemblage of nine complete
calves dating to the French Middle Neolithic indicates
that the predicted ages were generally congruent with
the dental age using Legge (1992). The accuracy of the
predicted ages could be estimated to ±1 month. Conse-
quently, at least for the 10–12 first months of life of the
cattle, this technique provides more accurate age esti-
mates than the observation of the fusion of long bones.
In addition, for this range of age, it can provide a narrower
estimate compared with those derived from dental eruption
and development. Through our assessment, measure-
ments of the astragalus and metapodials were consistency
within the 99% CI. However, measurements of the femur
were poor at predicting age. Further work is needed to
understand the differences between breed types, sex and
specific ages and to refine and increase the modern refer-
ence sample in order to improve the prediction models.
The resolution of these models is such that they can be
used to discuss differences between perinatal mortality
and deliberate infant slaughtering. This in turn will allow
us further insight into the development of cattle hus-
bandry practices in the past.

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