TECHNICAL NOTE

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Calculation of Percent Shrinkage in Human Fetal Diaphyseal Lengths from Fresh Bone to Carbonized and Calcined Bone Using Petersohn and Köhler's Data

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ABSTRACT: Calculation of age from fetal and newborn remains may be problematic, and when these remains are altered by maceration, decomposition or burning, age may be more difficult to discern. When soft tissue indicators are transformed, then two techniques exist for accurate age determination; dental development, which may prove difficult given the degree of tissue alteration; and appearance, size and fusion of ossification centers, including diaphyseal length, which may yield inaccurate ages if shrinkage is not accounted for. This study is undertaken to facilitate age calculation by systematically re-evaluating diaphyseal shrinkage and determine shrinkage rates from wet to carbonized states and wet to calcined states using Petersohn and Köhler's data, originally published in German and then published in Fazekas and Kósa (1978:362–369). Average shrinkage, standard deviation, minimum and maximum values are calculated for each diaphysis and then for all diaphyses between 4–10 lunar months (LM) and for newborns. Associated values for carbonized diaphyses are: 4 LM-32.50% ± 12.12%; 5 LM-14.04% ± 4.44%; 6 LM-6.78% ± 1.06%; 7 LM-4.18% ± 0.31%; 8 LM-3.47% ± 0.42%; 9 LM-3.05% ± 0.18%; 10 LM-2.46% ± 0.67%; and in newborns 2.16% ± 0.29%. Similar values for calcined diaphyses are: 4 LM-40.11% ± 17.51%; 5 LM-18.29% ± 4.42%; 6 LM-9.84% ± 1.27%; 7 LM-9.82% ± 0.51%; 8 LM-9.42% ± 0.72%; 9 LM-9.45% ± 0.33%; 10 LM-8.94% ± 0.37%; and in newborns 8.96% ± 0.49%. These findings suggest that percent shrinkage due to carbonization and calcination is greatest in the earliest age groups, decreasing substantially with advancing age. The rates of shrinkage, however, vary by the burning process utilized and age group studied. These general findings are similar to those of Petersohn and Köhler, yet specific values for percent shrinkage vary greatly from values cited in this analysis. These data provide a means to assess the degree of shrinkage that occurs for each diaphysis for each given age group.

KEYWORDS: forensic science, forensic fetal osteology, gestational age determination, lunar age determination, ossification centers, diaphyseal length, diaphyseal shrinkage, carbonized bone, calcined bone, mortuary practice, cremation, forensic anthropology

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Occasionally forensic specialists are assigned cases that necessitate the analysis of burnt human fetal remains, such as cases involving prehistoric cremations and modern cremains. These specialists must glean as much information from the skeleton as possible. One aspect of this analysis includes age determination.

Many methods exist to determine gestational age from the soft tissue of complete or even incomplete fetal remains. Through comparison to sonography, one can use studies specific to crown-rump length (1), crown-heel length (2–3), biparietal diameter (4–5), ear, hand and foot length and width (6–9), interocular and intermamillary index (10), abdominal circumference and the presence of other external morphological features, such as lanugo, as well as skeletal measurements obtained *in utero* (11–14) and combinations thereof (15–19). The accuracy of determination, however, varies depending upon the morphological features used, the source of the materials, the collection methodology employed, and the types of analysis conducted.

Generally, two methods exist for determining either lunar age or gestational age from hard tissue when soft tissues are radically altered by maceration, decomposition, fire and other factors. The first method, determination of gestational age from tooth formation (20–23), may prove problematic if the cephalic and facial regions are missing or radically altered either by fire or by collection methods, especially in the early fetal period when mineralization is just beginning for the maxillary and mandibular dentition or if parallax errors occur during radiography. The second method, appearance, size, and fusion of ossification centers (such as the size and subsequent degree of fusion of the tympanic ring to the squamous temporal around birth) generally includes determination of age from diaphyseal length (24–28), which may prove problematic due to shrinkage in the length and diameter of the diaphyses with the loss of water and organic matrix from the bone during desiccation and heating. During examination of a forensic fetal case involving such a fetus, assessment of crude gestational age can be made based on the overall dimensions of intact, unaltered fetal axial and appendicular segments as well as appearance of ossification centers in the cranial and postcranial elements. Next, a more precise gestational age can be derived by accounting for diaphyseal shrinkage from wet to carbonized bone, and then perhaps to calcined bone associated with the perimortem and postmortem period.

Petersohn and Köhler (29) systematically measured and recorded raw data for diaphyseal length for both sides of the body from fresh to dry states, carbonized and calcined states for all six diaphyses—the humerus, ulna, radius, femur, tibia, and fibula—in 52 human fetuses ranging in age from four to ten lunar months (LM) and in newborns. These data are currently available either in their original German source or in tabular form in Fazekas and Kósa, *Forensic Fetal Osteology* (26). Prior to this manuscript, a systematic re-analysis of shrinkage from fresh to dry states was conducted by Huxley (30). Currently, this analysis systematically re-examines and analyzes percent shrinkage from fresh to carbonized and calcined states. While these raw data are available from the other sources listed above, the analysis provides a means by which to assess the effects of shrinkage in forensic fetal remains.

Materials and Methods

According to Petersohn and Köhler, 52 fetuses ranging between 16–53 cm in crown-heel length were used in this analysis. The exact source, populational affiliation, and sex ratio of these materials are neither published in the original German source, nor in Fazekas and Kósa (26). The human fetal and newborn skeletons were collected from autopsy materials by one of the authors from Germany. The skeletal elements were stripped of cartilage and periosteum, measured and weighed three times each; the median was recorded for fresh bone length and weight. Dry bone length and weight were recorded after allowing the bones to air-dry on a shelf, when the elements no longer registered change in length or weight. Carbonization was accomplished by burning the materials over open flame and calcination was reached at approximately 1000° Celsius.

The data used in this analysis were initially derived from a series of tables published in *Forensic Fetal Osteology* by Fazekas and Kósa (26), then confirmed with Petersohn and Köhler. These data were entered into Excel for Windows, Microsoft Corporation, Version 5.0, 1985–1994 and shrinkage rates for each bone were calculated by means of the following formulae: For each fetal bone the values for carbonized bone (CB) and calcined bone (CL) are subtracted from the value for the fresh bone (F) length to quantify shrinkage. These values, for shrinkage due to carbonization and calcination, are then divided by fresh bone length (F) and multiplied by 100 to derive percent shrinkage $[(F\text{-}CB)/F \times 100]$ or $[(F\text{-}CL)/F \times 100]$. Next, for each lunar age group, the measures of central tendency and variability, the mean values, standard deviation, minimum and maximum values for percent shrinkage, were calculated, see Tables 1–6, (9–14).

Results

The analysis of Petersohn and Köhler's data suggests that percent shrinkage due to carbonization and calcination varies greatly by lunar age group and skeletal element (sex not given). Values are calculated for each of the diaphyses in each of the lunar age groups and for newborns. Systematic analysis of these data suggests that average values consistently decline with advancing lunar age for all diaphyses, while minimum and maximum values fluctuate greatly. Percent shrinkage due to carbonization and calcination will first be examined separately, then later compared.

The results of this analysis demonstrate that percent shrinkage from wet to carbonized bone varies greatly in the earliest lunar age groups. When these carbonized bones are analyzed by separate lunar age groups, the diaphyses from the fourth LM shows the largest shrinkage 32.50% ± 12.12%, although this finding may be influenced by the small cell sizes. Dramatic variations are noted in the range, from 17.56–50.16%. By the fifth LM, percent shrinkage averages 14.04% ± 4.44%, and the range more confined between

TABLE 1—*Humeral shrinkage rates for carbonized diaphyses from fetuses between 4–10 lunar months and newborns.*

	Sample Size	Average Shrinkage, %	Standard Deviation, %	Minimum Value, %	Maximum Value, %
4 LM	6	17.56	2.51	14.09	20.82
5 LM	47	9.80	3.71	5.36	20.00
6 LM	14	5.61	1.21	3.87	7.65
7 LM	8	3.71	0.57	2.86	4.55
8 LM	4	3.12	0.35	2.82	3.61
9 LM	6	2.85	0.37	2.16	3.22
10 LM	12	2.54	0.87	1.72	4.44
Newborn	2	2.72	0.64	2.26	3.17

TABLE 2—*Ulnar shrinkage rates for carbonized diaphyses from fetuses between 4–10 lunar months and newborns.*

	Sample Size	Average Shrinkage, %	Standard Deviation, %	Minimum Value, %	Maximum Value, %
4 LM	3	40.86	12.18	33.03	54.89
5 LM	31	15.43	7.33	5.77	37.14
6 LM	9	7.53	2.58	4.37	11.87
7 LM	7	4.48	1.79	3.20	8.05
8 LM	4	3.31	0.23	3.08	3.52
9 LM	5	3.22	0.35	2.65	3.53
10 LM	11	2.53	0.31	2.00	3.02
Newborn	2	2.07	0.05	2.03	2.10

TABLE 3—*Radial shrinkage rates for carbonized diaphyses from fetuses between 4–10 lunar months and newborns.*

	Sample Size	Average Shrinkage, %	Standard Deviation, %	Minimum Value, %	Maximum Value, %
4 LM	3	32.89	5.68	27.18	38.54
5 LM	37	15.58	7.29	4.98	38.94
6 LM	14	8.01	2.77	4.71	13.26
7 LM	6	4.48	1.97	2.73	8.09
8 LM	4	4.14	0.61	3.68	5.04
9 LM	6	3.21	0.52	2.74	4.15
10 LM	12	2.47	0.42	1.93	3.41
Newborn	2	2.22	0.31	1.99	2.44

TABLE 4—*Femoral shrinkage rates for fetuses between 4–10 lunar months and newborns.*

	Sample Size	Average Shrinkage, %	Standard Deviation, %	Minimum Value, %	Maximum Value, %
4 LM	6	21.11	3.10	16.82	24.47
5 LM	44	9.65	3.66	5.65	19.08
6 LM	14	5.82	1.22	4.44	8.20
7 LM	8	4.34	1.49	3.08	6.81
8 LM	4	3.27	0.14	3.11	3.44
9 LM	6	2.85	1.13	1.77	4.98
10 LM	10	2.38	0.41	1.86	3.24
Newborn	1	1.97	0	1.97	1.97

TABLE 5—*Tibial shrinkage rates for carbonized diaphyses for fetuses between 4–10 lunar months and newborns.*

	Sample Size	Average Shrinkage, %	Standard Deviation, %	Minimum Value, %	Maximum Value, %
4 LM	3	32.42	2.96	29.00	34.14
5 LM	44	12.38	5.70	1.47	27.96
6 LM	14	6.06	1.74	4.01	9.27
7 LM	8	4.00	1.30	2.77	6.55
8 LM	4	3.82	1.24	2.57	5.00
9 LM	6	3.17	0.57	2.61	4.21
10 LM	12	2.41	0.45	1.82	3.33
Newborn	2	1.99	0.20	1.97	2.00

TABLE 6—*Fibular shrinkage rates for carbonized diaphyses for fetuses between 4–10 lunar months and newborns.*

	Sample Size	Average Shrinkage, %	Standard Deviation, %	Minimum Value, %	Maximum Value, %
4 LM	1	50.16	0	50.16	50.16
5 LM	16	21.40	11.79	6.83	52.33
6 LM	7	7.63	4.18	4.30	16.63
7 LM	3	4.05	0.72	3.29	4.71
8 LM	4	3.14	0.80	1.97	3.68
9 LM	6	2.97	0.70	2.27	4.21
10 LM	10	2.41	0.74	1.12	3.48
Newborn	2	1.99	0.11	1.91	2.06

9.65–21.40%. Average values for diaphyses from fetuses in the sixth LM continue to decrease, with values of 6.78% ± 1.06% with a range of 5.61–8.01%, although the sample sizes are again limited. Average values for the seventh LM are 4.18% ± 0.31%, with a confined range of 3.71–4.48%. The eighth and ninth LM are very similar to each other, 3.47% ± 0.42% and 3.05% ± 0.18%, respectively; the corresponding ranges 3.12–4.14% and 2.85–3.22%. The tenth LM and newborn age cells have minimal shrinkage due to carbonization. During the tenth LM, values are only 2.46% ± 0.67% with very minimal variation in range 2.38–2.54%. Finally, in the newborn age cell, shrinkage averages 2.16% ± 0.29% and the range between 1.97–2.72%. These data suggest that values generally decrease by more than half during each LM between 4–6 LMs, then start to taper off at 7 LM, then slowly decline between 8 LM and newborn age cells (see Tables 1–6, Fig. 1).

Shrinkage rates from wet to calcined bone are shown in Tables 7–12, and are listed by diaphysis, lunar age group, associated cell size and measures of central tendency. Generally, shrinkage rates in calcined bone remain high over the course of fetal development, beginning from the earliest age groups and ending in the newborn age cells. In the fourth fetal month, average percent shrinkage for all diaphyses is 40.11% ± 17.51%, the range 21.49–68.98%. By the fifth LM, this value decreases by more than half, 18.29% ± 4.42, with a more confined range between 13.91–25.24%. Between the sixth to ninth LM, the value remains steady, from 9.84% ± 1.27 to 9.45% ± 0.33%; corresponding ranges are 8.42–11.26% and 9.13–10.00%, respectively. In the tenth LM and newborn age groups, the values are nearly identical, 8.94% ± 0.37% (range 8.35–9.42%) and 8.96% ± 0.49% (range 8.37–9.52%), respectively.

For carbonization and calcination, the mean values for each of the diaphyses are averaged by lunar age group to obtain an overall value for all lunar ages and newborns (see Table 13). When percent shrinkage for carbonized and calcined diaphyses are compared, extreme values are noted in the earliest lunar age groups. The value for carbonization is roughly 81.03% of that for calcination in the fourth LM. This value decreases to 76.76% in the fifth LM and to 68.90% in the sixth. The seventh LM shows a substantial drop to 42.57%. In the eighth and ninth LM, the values stabilize to 36.84% and 32.28%, respectively. In the tenth LM and in newborns, the difference in percent shrinkage remains stationary at 27.52% and 24.11%, respectively. The difference between shrinkage due to carbonization and calcination is not as great in the early LM periods, yet the value becomes more substantial with advancing lunar age. These values are represented graphically in Fig. 1, which compares lunar age (newborns are plotted at 10.5 LM) on the x-axis and percent shrinkage on the y-axis.

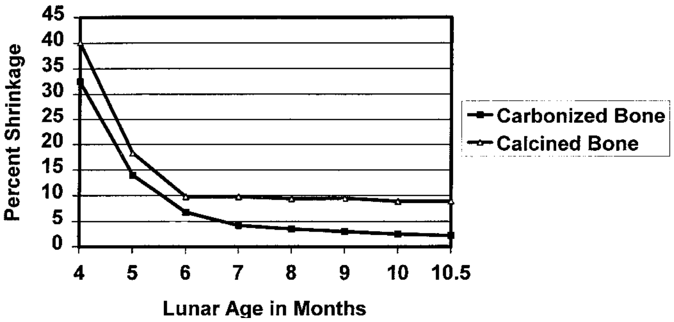

FIG. 1—*Comparison of combined diaphyseal shrinkage rates for carbonized and calcined bones from fetuses between 4–10 lunar months and newborns.*

Discussion

Diaphyseal shrinkage rates from wet to carbonized and calcined states are dramatic in the earliest lunar age groups. An initial amount of shrinkage from wet to dry states primarily reflects desiccation of water and organic matrix, which has been discussed elsewhere (30). Both carbonization and calcination, resulted in loss of organic components—matrix proteins and cells—from the diaphyses and the medullary marrow. The percent of shrinkage de-

TABLE 7—*Humeral shrinkage rates for calcined diaphyses for fetuses between 4–10 lunar months and newborns.*

	Sample Size	Average Shrinkage, %	Standard Deviation, %	Minimum Value, %	Maximum Value, %
4 LM	4	21.49	3.36	17.58	26.14
5 LM	47	14.04	4.09	7.90	23.46
6 LM	14	8.42	1.19	6.45	10.48
7 LM	8	9.04	1.31	6.78	11.33
8 LM	4	9.32	1.46	8.08	11.32
9 LM	6	9.17	1.29	7.56	10.41
10 LM	12	9.15	2.03	5.72	12.55
Newborn	2	9.52	0.16	9.40	9.63

TABLE 8—*Ulnar shrinkage rates for calcined diaphyses for fetuses between 4–10 lunar months and newborns.*

	Sample Size	Average Shrinkage, %	Standard Deviation, %	Minimum Value, %	Maximum Value, %
4 LM	3	48.41	13.52	38.71	63.86
5 LM	31	20.59	10.01	8.07	56.16
6 LM	9	10.29	2.76	7.12	14.30
7 LM	7	9.93	1.28	8.62	11.84
8 LM	4	8.39	1.66	6.58	10.60
9 LM	5	10.00	0.83	8.55	10.57
10 LM	11	9.42	1.04	7.54	11.19
Newborn	2	8.88	0.35	8.63	9.13

TABLE 9—*Radial shrinkage rates for calcined diaphyses for fetuses between 4–10 lunar months and newborns.*

	Sample Size	Average Shrinkage, %	Standard Deviation, %	Minimum Value, %	Maximum Value, %
4 LM	3	42.43	4.15	37.86	45.98
5 LM	37	19.79	8.37	8.25	50.44
6 LM	14	11.26	3.24	7.10	16.66
7 LM	6	10.06	1.07	8.88	11.59
8 LM	4	9.17	0.87	8.18	10.14
9 LM	6	9.64	1.05	8.23	10.71
10 LM	12	9.04	1.26	6.43	10.99
Newborn	2	9.09	0.06	9.04	9.13

TABLE 10—*Femoral shrinkage rates for calcined diaphyses for fetuses between 4–10 lunar months and newborns.*

	Sample Size	Average Shrinkage, %	Standard Deviation, %	Minimum Value, %	Maximum Value, %
4 LM	6	24.14	3.41	18.92	27.37
5 LM	44	13.91	4.23	9.25	25.25
6 LM	14	8.78	1.60	6.51	11.58
7 LM	8	9.64	0.89	8.41	11.10
8 LM	4	10.18	1.84	8.03	12.47
9 LM	6	9.13	0.85	7.47	9.89
10 LM	10	8.96	1.29	7.20	11.43
Newborn	1	8.37	0	8.37	8.37

TABLE 11—*Tibial shrinkage rates for calcined diaphyses for fetuses between 4–10 lunar months and newborns.*

	Sample Size	Average Shrinkage, %	Standard Deviation, %	Minimum Value, %	Maximum Value, %
4 LM	3	35.18	3.30	31.43	37.63
5 LM	44	16.18	5.89	5.05	33.37
6 LM	14	9.01	2.13	6.48	12.07
7 LM	8	9.67	1.59	7.39	12.00
8 LM	4	10.31	2.44	8.44	13.82
9 LM	6	9.43	1.25	8.08	10.69
10 LM	12	8.74	1.94	5.51	12.05
Newborn	2	8.46	1.10	7.68	9.24

TABLE 12—*Fibular shrinkage rates for fetuses between 4–10 lunar months and newborns.*

	Sample Size	Average Shrinkage, %	Standard Deviation, %	Minimum Value, %	Maximum Value, %
4 LM	1	68.98	0	68.98	68.98
5 LM	16	25.24	11.81	11.25	55.66
6 LM	7	11.26	3.79	7.90	19.51
7 LM	3	10.58	0.34	10.36	10.97
8 LM	4	9.13	2.28	7.07	12.36
9 LM	6	9.35	1.20	7.11	10.43
10 LM	10	8.35	0.68	7.04	9.23
Newborn	2	9.46	0.33	9.23	9.69

creases with advancing lunar age, presumably reflecting an increase in inorganic matrix from replacement of the cartilaginous precursor, the loss of the metaphysis, the continued calcification of the diaphyses and increasing deposition of calcium salts in the final trimester (31–32). Certain bones—the humerus and femur—shrink much less than the ulna/radius and tibia/fibula complexes in the earliest age groups. As the humerus and femur are longer than the other bone complexes, shrinkage is dependent upon the initial length of the bone in relation to the composition of the matrix. The values decline with advancing age in direct relation to the replace-

TABLE 13—*Comparison of combined diaphyseal shrinkage rates for carbonized and calcined bones from fetuses between 4–10 LM and newborns*

		Average ±	SD %	Range	SD %
	Sample Size	Carbonized	Calcined	Carbonized	Calcined
4 LM	1–6	32.50 ± 12.12	40.11 ± 17.51	17.56–50.16	21.49–68.98
5 LM	16–47	14.04 ± 4.44	18.29 ± 4.42	9.65–21.40	13.91–25.24
6 LM	7–14	6.78 ± 1.06	9.84 ± 1.27	5.61–8.01	8.42–11.26
7 LM	3–8	4.18 ± 0.31	9.82 ± 0.51	3.71–4.48	9.04–10.58
8 LM	4	3.47 ± 0.42	9.42 ± 0.72	3.12–4.14	8.39–10.31
9 LM	5–6	3.05 ± 0.18	9.45 ± 0.33	2.85–3.22	9.13–10.00
10 LM	10–12	2.46 ± 0.67	8.94 ± 0.37	2.38–2.54	8.35–9.42
Newborns	1–2	2.16 ± 0.29	8.96 ± 0.49	1.97–2.72	8.37–9.52

ment of inorganic matrix for organic matrix, as shown by Felts (31).

These findings are similar to those published by Petersohn and Köhler (29). They make three general observations: 1) the loss of length and weight decreases with advancing fetal age; 2) warpage is more common in the earlier fetal periods, splintering and fissuring in the later; and 3) the loss of length (but not weight) is variable in homologous bones from opposite sides of the body in the same fetus. Their first observation is noted with re-analysis of these data, but their second and third can only be confirmed with visual inspection of the diaphyses and breakdown of data by the individual fetus, which are not available.

Nevertheless, the values for percent shrinkage listed in the present paper do not correspond with those of Petersohn and Köhler. The reasons for this discrepancy are not known; Petersohn and Köhler did not give the mathematical formulae for calculating shrinkage due to desiccation, carbonation or calcination nor provide a complete analysis by diaphysis or lunar age group.

Conclusion

These data on percent shrinkage from wet states to carbonized to calcined states can be applied in many contexts: forensic cases involving cremation, fires and historic/prehistoric burials that include fire in the mortuary practice. Where soft tissue is not preserved, tooth formation, and appearance of ossification centers, including diaphyseal presence and size, can be used to assign lunar or gestational age. Dental aging, however, may be difficult, since the teeth may not have formed, only partial remains may exist, collection methods may have altered the facial/cephalic regions and parallax errors may have occurred during radiology. By contrast, ossification centers, such as fetal diaphyses, may remain intact for side and segment classification. These data provide a means to assess degree of shrinkage occurring within each diaphysis for each age cell.

Few studies exist for such comparison. Petersohn and Köhler's raw data are available in their original German as well as in a series of tables within *Forensic Fetal Osteology* by Fazekas and Kósa (26), although percent shrinkage is not listed by skeletal element or lunar age group and description of the analyses is not systematic in coverage. These are the reasons that underlie the present study.

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