J Forensic Sci, Sept. 2005, Vol. 50, No. 5
Paper ID JFS2004297
Available online at: www.astm.org

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Heat-induced Dimensional Changes in Bone and their Consequences for Forensic Anthropology

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ABSTRACT: An understanding of heat-induced transformation of hard tissue is vital before a full interpretation of burned human remains can be successfully achieved. Samples of modern sheep ($n = 60$) were analyzed resulting in 5440 data points. An experimental approach was undertaken that explored the bi-variable impact of heating temperature and duration of burning. Subsequent heat-induced bone changes included the progression of color from natural through to blue-white, the significant loss of weight, the reduction in mechanical strength, the development of distinct fracture patterns, alterations in the microscopic porosity, substantial alterations in crystalline structure and reduction and expansion in size. Collation and integration of this information demanded a revision of the four stages of heat-induced degradation of bone previously presented by Mayne Correia (1) and Thompson (2). The results demonstrate that heat-induced shrinkage is also accompanied by expansion and that both can be statistically significant. This suggests that anthropological techniques applied to burned bone will likely be detrimentally affected and accuracy will be reduced.

KEYWORDS: forensic science, forensic anthropology, burned bone, heat-induced change

The collection, analysis and storage of burned human remains is difficult and fraught with problems. Although these are surmountable and should not deter one from dealing with human material in this condition. Even after around sixty years of study there is still a great deal that we do not fully understand regarding not only the transformative processes that heating causes in bone, as well as the most appropriate methods for studying this material. The aim of burned bone research is to provide knowledge of heat-induced changes in bone, and to use this information to improve anthropological techniques for use on the material. This must all be conducted within a social context, otherwise it will not be possible to apply the research fully to current anthropological situations, whether they be of a forensic or archaeological nature.

General Heat-induced Changes in Bone

Once the soft tissue has been removed, the hard tissues are exposed directly to the heat and fire. As with the soft tissues, bone and teeth undergo a number of substantial changes. These changes are not fully understood, but the broad pattern can be seen from experimental and actualistic studies. It is not necessary for the soft tissue to be removed before heat-induced damage is done to the hard tissues, but they do offer a significant level of protection (3,4). It must also be remembered that hard tissues are a complex material involving moisture, blood and bone marrow (5). As such, heat-induced transformations are complex phenomena. Unfortunately there is a distinction in the literature between heat-induced changes of soft tissues and those of the hard tissues. This dichotomy, which is entirely created and perpetuated by workers, ignores the fact that the two tissue types are intrinsically connected; they are a unified system (3,5).

The main microscopic stages of heat-induced bone degradation have been outlined and tabularised by Mayne Correia (1). The importance of her summary lies in the simplicity and effectiveness of its description of the complex changes that bone undergoes when it is burned. It is argued that bone, when heated, progresses through four stages of degradation. The first stage is Dehydration. Here the hydroxyl-bonds break and both the loosely-bound water (physisorbed) and bonded water (chemisorbed) are lost. The Decomposition stage is when the organic components of the bone are removed by pyrolysis. The third stage, Inversion, is identified by the loss of the carbonates. Associated with this is the conversion of the hydroxyapatite crystal structure to beta-tricalcium phosphate. The final stage, Fusion is characterised by the melting and coalescence of the crystal matrix. Based on more recent literature and experiments, Thompson (2) revised this table, removing reference to the conversion of the hydroxyapatite, which was far from being accepted as the norm, and lowering the commencement temperature of the Fusion stage.

The clearest form of dimensional change caused by burning is warping. Two key and widely accepted statements have been made in the literature regarding this phenomenon. First, heat-induced warping is more apparent in bone that was fleshed at the time of burning (6,7), and this implies that the heat-induced contraction of the muscle fibres pulls and twists the bone away from its natural shape. Second, that heat-induced expansion of air within the medullary cavity also causes dimensional change (8). The likely manifestation of this is an increase in size of the diaphysis, and particularly the epiphyses. In areas of dense bone with little cavity, heat-induced warping should be very limited. There are, however, fundamental problems with both statements. Both are speculative and not substantiated by quantitative data. It is also unlikely that contracting muscles would have the strength to cause the bone itself to bend or reduce in size. In addition, the porous nature of bone makes it improbable that air expanded by heating remains trapped within the medullary cavity under such pressures as to cause warping. This notion of air expansion cannot explain the limited warping noted in space-rich femoral and humeral heads by Wells (9). Therefore another explanation is required, one that focuses more on the bone itself. It could be that contraction of the periosteum or anisotropy in the collagen distribution within the bone cortex

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Received 31 July 2004; and in revised form 25 Oct. 2004 and 1 May 2005; accepted 1 May 2005; published 3 Aug. 2005.

are responsible. Chandler (10) noted how teeth curl towards hotter areas of the furnace when heated. This is a result of the mechanisms of the furnace but the influence of natural tooth curvature cannot be ignored (10).

Wells (9) argues that bone will tend to distort and shrink in a fairly constant manner. He claims that this is expected given the tendency for the internal structure, disposition of the trabeculae, the relative amounts of compact or spongy bone, the density of the tissues and their relationship with other structures will be fairly constant (9). This can only be true if the burning conditions are similar however. When burning conditions vary, the amount of shrinkage can be expected to vary accordingly. Shipman et al. (11) argue that the degree of heat-induced shrinkage is directly correlated to temperature. This statement has subsequently been supported by others (12), although not necessarily with the same degree of conviction. McKinley (12) adds that variability can be expected between different individuals and different skeletal elements.

There seems to be a critical temperature at which the degree of shrinkage caused by burning significantly increases. This temperature has been set at around 800°C (7,8,13–17). Dehydration and the removal of the organics from the bone are important but as the cause of much of the heat-induced shrinkage is due to changes in crystal structure (12), it is likely that much of this difference in degree of shrinkage is also related to changes to the crystal structure. Indeed this 800°C dividing point falls near the beginning of the Fusion Stage of heat-induced bone degradation. It is in this stage that the inorganic phase begins to coalesce and fill the pores left by the evicted water and organic phase. This will result in a reduction in bone size. Another potential influence on the degree of shrinkage is the proportion of spongy to compact bone relative to the plane of measurement (11,18). Both Gilchrist and Mytum (18) and Shipman et al. (11) neglect to explain why the differences in bone type are influential. However Gejvall's earlier work (19) highlights that the design of spongy bone is such that it can withstand pressures from multiple directions and as such may shrink only slightly as a consequence of burning yet retain its original shape. In addition there is some confusion in the literature as to which is the more influential bone type with regard to heat-induced shrinkage. Gejvall (19) and Gilchrist and Mytum (18) argue that compact bone will shrink the most while McKinley (20) and Van Vark (21) argue that the spongy bone will shrink the greater amount. It could be however that all workers are correct. It may be that the spongy bone shrinks the greater amount with regard to actual measurement, but it could be that compact bone shrinks the most with regard to its own pre-burning thickness. That is to say relative versus absolute shrinkage. For example, a 5 mm reduction in spongy bone size is greater than a 2 mm reduction in compact bone thickness, however if the area of compact bone is only 4 mm thick while the area of spongy bone is 20 mm thick, the compact bone will have shrunk by fifty percent to the spongy bone's twenty-five percent. Another variable is the biological age of the bony tissue, which has been demonstrated as being significant because older bone contains a greater amount of collagen cross-linking that restricts shrinkage (15). Regardless of how supportive the collagen cross-linking is, it can only be influential up until the point that heating destroys the collagen. It should also be borne in mind that Holland's (16) experimental work led him to state that the amount of shrinkage produced by low-level burning (under 700°C) will be less than the intra-observer error produced when remeasuring the same bone samples.

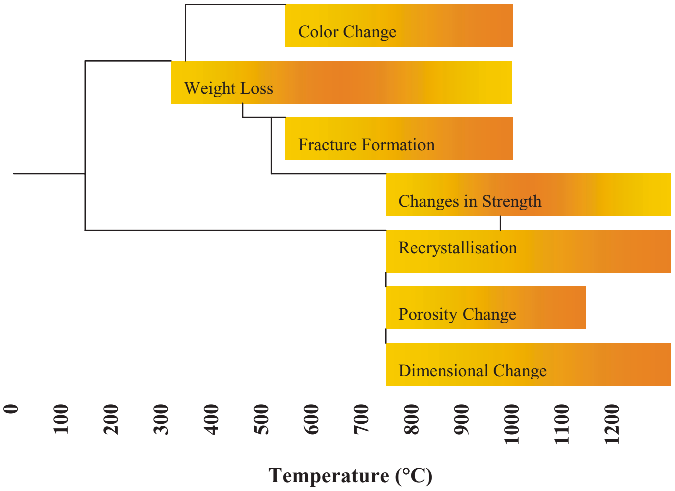

FIG. 1—*The relationships between the heated-induced changes in bone. Note that darken shading implies greater intensity of change.*

The aims of this research were therefore threefold: 1. To investigate the nature of heat-induced dimensional change using controlled repeatable experiments and statistical analysis; 2. To gain a fuller understanding of the role of microscopic alterations in causing heat-induced dimensional change; 3. To assess how these changes will impact the practice of forensic anthropology.

Materials and Methods

A sample of 60 complete sheep long bones was used for ethical reasons. Bones from the same animal were used in each trial, thus six animals were used in total. Justification for the use of sheep bone as an appropriate analogue for human bone can be found in Thompson (2). The sheep were recently deceased, and the bones were still quite greasy. Some soft tissue was attached to the long bones, especially at the limb joints. Long bones were chosen as they are easy to measure and are important in many anthropological techniques.

Soft tissues adhering to the bones was removed using a scalpel, following gentle heating in water. It is acknowledged that heating alters the constitution of bone, however it is accepted that changes begin after heating at 100°C, and the water used here never reached that temperature. Following removal of the soft tissue, the bones were allowed to dry on a wire rack.

Eleven dimensional measurements were taken on the long bones. They are detailed in Table 1. These measurements were chosen in order to examine heat-induced dimensional changes in a variety of aspects across the hard tissues. Each measurement was taken three times and the mean was used in all further analyses. The bones were placed on heat-proof ceramic trays and inserted into the muffle

TABLE 1—*The dimensional measurements recorded from the experimentally-burned hard tissues.*

Dimension	Measurement
1	Maximum length of bone
2	Maximum proximal epiphyseal width
3	Minimum proximal epiphyseal width
4	Maximum proximal epiphyseal length
5	Maximum distal epiphyseal width
6	Minimum distal epiphyseal width
7	Maximum distal epiphyseal length
8	Maximum proximal diaphyseal width
9	Minimum proximal diaphyseal width
10	Maximum distal diaphyseal width
11	Minimum distal diaphyseal width

TABLE 2—*Percentage shrinkage due to heating.*

	Dimension	500°C 15 min	500°C 45 min	700°C 15 min	700°C 45 min	900°C 15 min	900°C 45 min
D1[a]	5 Minutes	1.94	1.2	1.64**	2.44*	5.52	5.35*
	15 Minutes	1.96	1.39	1.81**	2.92*	5.56	5.57*
	25 Minutes	1.96	1.5*	1.95**	3.34	5.69	5.76*
D2[b]	5 Minutes	0.9	0.88	4.25***	19.33*	7.29*	14.45**
	15 Minutes	0.86	1.47	4.86***	5.58*	8.03*	15.16**
	25 Minutes	0.87	1.83	5.23***	6.24*	9.1*	15.71**
D3[b]	5 Minutes	0.79	−4.53	−1.72	3.07*	6.52	36.18*
	15 Minutes	10.13	−3.84	−1.1	4.4*	7.4	37.06*
	25 Minutes	0.84	−3.19	−0.37	5.22*	8.73**	37.68*
D4[b]	5 Minutes	−1.59	1.15	14.09*	5.24	19.15	14.62*
	15 Minutes	−1.59	1.15	14.6*	6.88	20.54	16.2*
	25 Minutes	−1.46	2.06	15.68*	8.67*	21.55	16.47*
D5[b]	5 Minutes	2.67	3.04*	7.02***	6.02**	10.62**	4.96
	15 Minutes	2.7	3.61**	7.57***	6.88**	11.59**	10.39**
	25 Minutes	2.73	4.14**	8.29***	7.26**	13.58*	10.79**
D6[b]	5 Minutes	0.93	6.57	3.88**	4.1**	5.67**	−3.92
	15 Minutes	1.06	7.35	5.1***	5.06**	6.77**	−2.71
	25 Minutes	1.06	8.04	5.82***	5.85**	7.94*	−1.93
D7[b]	5 Minutes	2.34	10.15	11.64***	7.32	15.26**	−2.04
	15 Minutes	2.4	11.16*	12.45***	8.53*	16.64**	−0.6
	25 Minutes	2.4	13.04**	13.59***	9.57*	21.12*	0.15
D8[c]	5 Minutes	3.28	0.47	5.51	7.42	9	24.57
	15 Minutes	3.35	1.28	6.25**	8.32	10.04	25.4
	25 Minutes	6.13	1.82	6.77**	9.1	10.43	26.23
D9[c]	5 Minutes	6.83**	−0.12	0.85	7.81	15.86	12.32
	15 Minutes	6.94**	0.98	1.97	9.12	17.99	13.66
	25 Minutes	6.97**	1.86	6.24**	9.66	19.35	14.8
D10[c]	5 Minutes	5.79**	−0.07	7.27**	4.62	9.43*	11.98*
	15 Minutes	5.84**	0.83	8.02**	5.74	10.63**	13.17*
	25 Minutes	5.77**	1.72	9.52**	6.47	11.66*	13.76*
D11[c]	5 Minutes	7.65**	−0.45	5.24	5.92	11.81*	18.18*
	15 Minutes	7.65**	0.64	6.5	6.38	13.68*	19.17*
	25 Minutes	7.75**	1.68	7.61	7.7	16.5*	20.66*

Note: [a] is total bone length, [b] is an epiphyseal measurement, [c] is a diaphyseal measurement; $p \leq 0.01$ (***), $p \leq 0.05$ (**) and $p \leq 0.1$ (*) significance highlighted.

furnace at 200°C and allowed to heat up to the desired temperature. The bones were then kept at that temperature for specific periods of time. The bones were heated to 500°C, 700°C or 900°C for 15 or 45 min. Ten bones were used for each burning regime. After removal from the furnace the bones were allowed to cool for five minutes before being re-measured. Pairwise statistical tests were then used to assess dimensional change. In addition a further range of analytical techniques were used to examine heat-induced changes in bone (22,23).

Results and Discussion

Heat-induced Dimensional Changes

Several trends occur within the data. The first regards the decrease in sample sizes as a result of increased burning intensity. The reduction in sample size is more severe with certain measured dimensions and this occurrence is due to two features. First, the differential heat-induced destruction of the bone is dependent on the bone itself (a function of bone morphology for example). Second, some measurements are still possible even if the bone has fragmented while others are absolutely not. For example, if the long bone has fragmented into several chunks, Dimension 1, which is total length of the bone, cannot be recorded whereas the dimensions across the epiphyses may well be possible. Therefore Dimension 1 would have a smaller sample size than the epiphyseal dimensions (Dimensions 2 to 7).

The second main trend seen in Table 2 concerns the mean measurement values themselves. In most cases with most dimensions, the mean measurement value decreases in size 5, 15 and 25 min after removal from the furnace. Clearly this temporal influence means that heat-induced shrinkage is more dynamic than has been previously realized. The continued reduction in bone size even after removal from the heating device has clear implications for experimental cremation methodology, although this will be less significant to those examining burned remains from forensic or archaeological settings. Researchers must now be aware of the fact that the length of time after removal from the heating source will influence the amount of heat-induced dimensional change recorded. However on a number of measurements ($n = 12$) the difference between the measurement before burning and that after removal from the furnace was not a reduction but an increase. Examination of the raw data shows that this occurs on one bone in % of the cells. This implies that the bones are increasing in size as a consequence of burning, and are then reducing in size as the material cools.

Table 2 summarizes the percentage shrinkage values. Of note here are the samples that have, demonstrated heat-induced expansion. Seventeen cases of overall heat-induced expansion out of a possible 198 cases are recorded (8.6%). However when one includes the samples that demonstrated heat-induced expansion in at least one of their ten bone specimens the figure rises to 97 (49%). The high presence of heat-induced expansion suggests that this is not all attributable to heat-induced warping. Rather this is the never-before recorded presence of heat-induced expansion of a non-warping origin. Table 2 also shows that heat-induced expansion is predominantly a low intensity burning phenomenon. This is likely due to the more influential heat-induced shrinkage over-riding the expansion at higher burning intensities. This also suggests that without the occurrence of heat-induced expansion, the degree of heat-induced shrinkage would be more substantial. Degrees of heat-induced warping were not recorded as this research focuses on metric alterations.

There is a further pattern in the heat-induced expansion and shrinkage data that requires explanation. Table 2 divides the eleven measurements into regions of bone. Dimension 1 is the total length of the bone, Dimensions 2 to 7 are measurements across the bone epiphyses and Dimensions 8 to 11 are measurements across the bone diaphysis. It can be seen that the greatest occurrence of heat-induced shrinkage and expansion across the bone as a whole occurs in the epiphyses. Both of these features are due to the nature of the bone in the epiphyses compared to the diaphysis. At first glance it would appear that spongy bone is the more flexible of the two forms of bone. It is however, designed to be rigid and to absorb forces from multiple directions and sources. It may be then that spongy bone has more random collagen orientation than compact bone and hence is offered less structural support. This would only be true until heating destroyed the collagen, although the random orientation of the remaining spaces may be structurally weaker than the collagen free compact bone. This conclusion tends to support McKinley (20) and Van Vark (21) who argue that spongy bone is more influential on post-burning dimensional size than compact bone rather than Gejvall (19) and Gilchrist and Mytum (18) who concluded the reverse.

Table 2 displays the statistical significance using T-tests of the percentage dimensional changes. It can be seen that the majority of statistical significance (84%) occurs due to heat-induced dimensional change at medium to high burning intensities. This should be no surprise as it is not until these situations that the Fusion stage can begin. What is also clear is that the very strong statistical significance is focussed on the column representing burning at 700°C for fifteen minutes. Burning beyond this temperature seems to produce weaker statistical significance in contrary to what is expected. This can be explained by the fact that as the bones burn, they progress through the Decomposition stage and the Inversion Stage to the Fusion Stage of heat-induced degradation. It is suggested that as the bones travel through the Decomposition stage they experience peak fragility and begin to fragment in the furnace thus reducing sample size. The weaker statistical significance at higher burning intensities can be attributed to this reduction in sample size.

The Implications for Forensic Anthropology and Human Identification

Perhaps one of the most significant impacts of the revision of our understanding of burned bone concerns the use of anthropological techniques. These techniques are going to be severely affected by any heat-induced dimensional change that results from the occurrence of the Fusion Stage of transformation (Fig. 1). Previously the beginning of this Stage was thought to be high enough not to be experienced in most house fires and other forensic situations. Now that this commencement temperature has been lowered, it is clear that one should expect to see anthropological technique-influencing heat-induced dimensional change at temperatures consistent with house fires, mass disaster incidents and in archaeological funerary pyres. All cremated and burned human hard tissue from every context must now be treated with analytical caution.

As Thompson (2) states, the only heat-induced change in bone that will significantly affect the results of anthropological techniques is dimensional change Fig. 1. Changes in color will not influence the techniques, although may cause some degree of uncertainty with regard to whether the bones are burned or simply stained as a consequence of their depositional environment. However inaccuracy can result from using color change as a means of determining the degree of shrinkage during the implementation of a metric correction factor as in Grévin et al. (24). Fragmentation will make the application of certain techniques more problematic, but there are corrections in existence that allow one to compensate for broken bones. Anthropological techniques rely on unmodified bone dimensions that are altered by warping and shrinkage. Warping is relatively straightforward to address as an understanding of the unburned skeleton will allow one to dismiss bones that appear to be bent and twisted. Unfortunately heat-induced shrinkage is much more subtle and impossible to detect without *a priori* knowledge of the pre-cremation dimensions.

Wells (9) states that shrinkage is negligible. He was only partially correct. Shrinkage is small during the first three stages of degradation of bone as a result of heating. During the Dehydration, Decomposition and Inversion stages the water and organic matrix is lost causing a small degree of shrinkage. Accepted values range from nil to five percent. Once the Fusion stage commences, which Mayne Correia (1) placed as high as 1,600°C and Thompson (2) redefined as being closer to 1,000°C, the shrinkage becomes much greater. Values as high as thirty percent have been recorded. The effects of these shrinkage percentages will be seen to a greater extent in any metric analyses conducted rather than with morphological techniques as the feature itself may shrink but will still be present. Heat-induced shrinkage can affect the conclusions of uni-, bi- and multi-variate metric analyses by causing misclassification of one group as another (2,25,26). This problem is only compounded by the large overlap that often exists between the groups of study (for example, sex) within a population. Holck (27) describes how the frequency of females is greater than males in the archaeological cremation cemeteries that he studied. He acknowledges this as an acceptable outcome, although it may be the result of the misclassification of some males as female due to heat-induced shrinkage.

Predicting Heat-induced Change

To date only two attempts have been made to extrapolate from experimental burning experiments to the wider population. This is in keeping with the generally poor use of statistics in studies of burned bone (2). Thompson (2,26) extended his experimentally-gained percentage shrinkage values to incorporate the population while Shipman et al. (11) created a non-linear prediction equation, also for heat-induced shrinkage, from their primary data. Both of these attempts at predicting heat-induced shrinkage are ultimately flawed because they do not appreciate the multivariable nature of this shrinkage. A fresh attempt at predicting heat-induced dimensional change is made based upon, not just percentage dimensional change values and temperature, but also duration of heating, weight loss, alterations in mechanical strength and changes in crystal size and microscopic porosity.

Principal Component Analysis is first used to determine the most useful variables. Five Principal Components exist in the data derived from this investigation, and are displayed in Table 3. This data

TABLE 3—*Rotated component matrix resulting from principal component analysis of the influences on heat-induced transformation in bone.*

	Principal Component				
	1	2	3	4	5
Temperature	0.392	0.565	0.669	0.233	0.161
Duration	−0.506	0.332	−0.099	−0.196	0.765
% Weight loss	−0.832	0.190	0.438	0.280	0.033
Number of Measurements	−0.138	−0.890	−0.209	−0.357	−0.132
Crystal Size	0.257	0.517	0.533	0.210	0.582
Skeletal Density	0.020	0.091	−0.940	0.300	−0.133
Bulk Density	0.676	−0.071	0.371	0.642	−0.158
Microporosity	0.103	−0.223	−0.921	−0.269	−0.136
Mesoporosity	0.096	0.934	−0.145	0.240	0.202
Macroporosity	−0.952	−0.116	−0.104	−0.241	−0.105
D1 % Change	−0.321	0.686	0.178	0.018	0.628
D2 % Change	0.448	0.342	0.689	−0.015	0.455
D3 % Change	0.766	0.182	0.248	0.153	0.544
D4 % Change	0.985	0.094	0.123	0.068	−0.032
D5 % Change	−0.304	0.849	0.346	−0.259	0.023
D6 % Change	−.0941	−0.113	0.173	−0.193	0.188
D7 % Change	−0.876	0.297	−0.132	−0.356	0.036
D8 % Change	0.148	0.091	0.355	0.194	0.898
D9 % Change	0.351	0.075	0.199	0.911	0.034
D10 % Change	0.680	−0.230	0.381	−0.427	0.397
D11 % Change	0.025	0.376	−0.267	0.865	0.196

Note: Major associations (>0.550, < −0.550) are highlighted.

also incorporates the dimensional measurements and other microscopic analyses conducted on the bone (22,23). These five Components, each of which has an initial eigenvalue of greater than one, explain one hundred percent of the sample variance. The underlying causes of these five associations are difficult to explain. The first Component, as it associates weight loss, bulk density and macroporosity (pores with diameters between 13–70 μ) must be the loss of the organic phase. This must also be true of the second Component since it concerns the number of measurements and mesoporosity (pores with diameters between 0.1–13 μ). These five variables are all influenced greatest by the removal of the organic phase from the bone and seem to explain the heat-induced changes in Dimensions 1, 3, 4, 5, 6, 7, and 10. This concerns all bar one of the epiphyseal dimensions yet only one of the four diaphyseal dimensions. The strong association between temperature, skeletal density and microporosity (pores with diameters between 0.01–0.1 μ) implies the involvement of the recrystallisation of the inorganic phase. These first three Principal Components explain 83.77% of the variation in the sample, and the fact that they are attributable to the removal of the organic phase and the recrystallization of the inorganic phase adds considerable weight to the fundamental importance of these two singular features. The fourth Component associates bulk density with a degree of dimensional change thereby implying the influence of the changing microscopic porosity of the bone. The final Component associates duration of heating with crystal size and two dimensions witnessing heat-induced change. It is unclear what the underlying force of this association is, but the alteration of crystal size would be consistent with the data. Of interest is the fact that changes in crystal size are only moderately associated with one variable. This statement negates the fact however that changes in crystal size has a moderate association with the second, third and fifth Principal Components. Since crystal size can only alter during recrystallization of the inorganic phase, and not during the removal of the organic phase, this suggests that the underlying associations of Components 2 and 5 may not be entirely that of the loss of the organic phase.

The simplest method of predicting heat-induced changes in bone using sample data is through the creation of linear regression equations. Table 4 displays the results of equations generated using the experimental burnings of this research. It should be noted that the method of linear regression creation used here is termed "Stepwise." During this process an equation is generated by layering independent variables upon each other until the optimum equation has been formed. This is in contrast to the standard method of linear regression creation, which simply uses all of the independent variables of interest. This therefore allows for efficient equations to be created which only use the most relevant variables instead of using all of them unnecessarily.

To some extent, the notion of creating prediction equations for heat-induced change is nonsensical. There are simply too many variables and currently too little knowledge regarding them to create reliable formulae. However a distinct benefit of the "Stepwise" method of linear regression creation is that it allows one to determine the most influential variables, which in turn provides valuable information regarding the process of heat-induced change in bone.

Perhaps then, the most important point to make regarding the linear regression equations in Table 4 is that the most useful

TABLE 4—*Linear regression equations used to predict the influence of heating on certain variables.*

Dependent Variable	Equation (using most appropriate variables)	R2 Value
D1 % Change	. . .	
D2 % Change	−15.564 +1.5 (Crystal Size)	0.848
D3 % Change	25.726 −468.258 (Macroporosity)	0.757
D4 % Change	25.208 −311.342 (Macroporosity)	0.950
D5 % Change	. . .	
D6 % Change	−1.750 +242.815 (Macroporosity)	0.842
D7 % Change	6.948 + 184.843 (Macroporosity)	0.751
D8 % Change	−10.615 +1.426 (Crystal Size)	0.837
D9 % Change	−34.544 +27.957 (Bulk Density)	0.737
D10 % Change	. . .	
D11 % Change	. . .	
Temperature	207.015 +31.850 (Crystal Size)	0.704
Duration	. . .	
D1 % Change	−1.023 +0.131 (Duration)	0.789
D1 % Change	−6.273 +0.131 (Duration) +0.0075 (Temperature)	0.928
D1 % Change	5.606 +0.138 (Duration) −0.0607 (Number of Measurements) −1.092 (Skeletal Density) +0.01354 (% Weight Loss)	1.000

Note: dash indicates an equation could not be created.

TABLE 5—*Comparison of published heat-induced shrinkage linear regression equations.*

Dependent Variable	Prediction Equation	R2 Value
D1 % Change	Shipman et al. (1984) $0.302X^3 + 0.0000826x^2 + 0.0000000704x - 0.688$	0.775
D1 % Change	This Research $-1.023 + 0.131$ (Duration)	0.789
D1 % Change	This Research $-6.273 + 0.131$ (Duration) $+ 0.0075$ (Temperature)	0.928

independent variables to use as predictors of dimensional change involve those connected with the heat-induced changes in microstructure. This is important for two reasons. First it again highlights the importance of the recrystallization of the inorganic phase in changing the dimensional properties of bone. Second it highlights the fact that the use of temperature as a predictor is inaccurate, and that the equations of Shipman et al. (11) and the like should be treated with much caution. Comparison of the equation published by Shipman et al. (11) and those created here (Table 5) clearly demonstrates the increased imprecision of simply attempting prediction using just a single independent variable.

Table 5 clearly shows the benefit of additional variables in linear regressions attempting to predict dimensional change. The R-squared value (which is a description of how well the regression line fits the data) of the linear regression equations created to describe dimensional change increases from 0.789 to 0.928 and then to 1 with the addition of extra variables. Further research into the heat-induced transformation of bone is required before more appropriate prediction equations can be created, tested and adopted by practitioners. However it can now be said that the simple concept of absolute temperature influencing dimensional change is no longer a valid model.

Correcting Anthropological Techniques

Anthropological techniques rely on unmodified bone dimensions for their accuracy and as has been discussed, heating and burning will cause substantial changes to occur in the hard tissues. It is therefore of great concern that this issue has not been investigated with any vigor. Little has been published regarding the influences of burning on the results of anthropological techniques. Thompson (2,26) discussed the effect of heat-induced shrinkage on uni- and bi-variate metric methods of sex assessment (although the conclusions are valid for all uni- and bi-variate techniques). He stated that significant misclassification of sex could be achieved when using metric sex assessment methods as a result of the changing relationship between the variables of measurement. This has also been stated by McKinley (12).

Since it has already been shown that heat-induced features do not mimic pathology and trauma (28) the osteological techniques of concern are those that assess biological sex, age at death, stature and ancestry. Techniques for these assessments are either viewed as morphological or metric depending on whether they use shape and form or discrete measurements to estimate the feature of interest. Both morphological and metric methods of osteological analysis can be affected by heat-induced changes in bone. Techniques can be affected directly, or indirectly if the heat-induced change witnessed is indicative of another more rudimentary change. For example, color change will not affect the results of anthropological techniques itself but the cause of the color change, the removal of the organic fraction, will affect the techniques being used. The most influential heat-induced events with regard to the altering of the results of anthropological techniques are the removal of the organic phase and the recrystallisation of the inorganic phase. These two heat-induced features account for all of the heat-induced changes and are therefore the fundamental causes of any inaccuracy in anthropological method due to burning.

All anthropological analyses conducted on burned remains will be wholly and fundamentally inaccurate. It is likely that the metric techniques will be more adversely affected than the morphological ones. In addition, the recrystallisation of the inorganic phase will cause changes in bone that are subtle and undetectable since the pre-burning dimensions are unknown. Any changes that would affect the morphological techniques are more likely to be detectable before application of the technique begins.

It is impossible to assess the level of inaccuracy generated due to heat-induced changes in burned bone. However, the level will depend on both the extent of the heat-induced changes and the nature of the anthropological technique. In general, the more severe the burning, the greater the degree of heat-induced change which in turn will increase the level of inaccuracy in the technique. With regard to the nature of the technique itself uni-variate, bi-variate and multi-variate techniques react differently depending on relationship between heat-induced dimensional change and component variables of the metric technique. Thompson's (2,26) discussions on the complications of using metric sex assessment techniques focussed on the influence of heat-induced shrinkage. These complications are further compounded now that the presence of heat-induced expansion has been noted.

Correcting for the influence of heat-induced change can occur in one of two ways. First, in order to compensate for the heat-induced dimensional changes, the techniques themselves can be modified, for example, by changing the constants or increasing the error margins. Second, the measurements recorded can be modified so that the anthropological techniques of analysis are used on the estimated pre-burning dimensions of the bone rather than on the dimensions suffering heat-induced change. McKinley (16) states that most standard skeletal indices cannot be calculated on burned bone and Thompson (2,26) advocates the use of extreme caution. However, attempts have been made to employ the former solution when analyzing burned remains. Both Gejvall (19) and Van Vark (21,29) provided specific anthropological techniques with suitably broad error margins. This is problematic because it means that either every anthropological technique needs to be examined and modified in isolation or new techniques need to be created to replace the many techniques currently being used on unmodified non-burned skeletal remains. In light of the mathematical complexities highlighted by Thompson (2,26), this would be a very complicated and time-consuming task indeed. However, if one makes the assumption that all human bone will fundamentally act in a fairly uniform manner when burned, with explicit heat-induced transformations only varying in speed and severity based on external variables, it will be possible to predict the pre-burning conditions of the bone. An appreciation of every variable acting on bone is not required just as long as it is possible to say how far from the norm the burned bone has diverged. For example, how much larger have the inorganic crystals become or by how much has the micro-porosity reduced? These sorts of heat-induced transformations are possible to measure in the laboratory, and with a substantial body of experimental research, it will be possible to create regression equations that will predict pre-burning conditions with reasonable accuracy.

In turn, existing anthropological techniques will be applicable to these pre-burning bony dimensions and values. To recapitulate, it would therefore be possible to alter each measurement from every cremation using one of a limited suite of equations rather than having to mathematically correct every metric anthropological technique one wished to employ.

This solution to the issue of correcting the measurements of burned bone for analysis is only useful for the application of metric methods and not morphological methods. To correct for these would be much more convoluted. Theoretically, it would be possible to predict the dimensional change undergone as a consequence of burning, however the sheer number of planes of measurement that would need to be calculated in order to generate a three-dimensional likeness that could have the morphological techniques applied to it is likely to be prohibitive. A potential remedy to this could be the use of three-dimensional modeling software, however a specific computer program would need to be written for this application.

Conclusions

Although this piece of research has resulted in a significant step forward in our understanding of the influence of burning on the human body, there are still many more questions to answer. Perhaps the most significant of these should focus on the changes to the microstructure of the bone and teeth. It has become very clear that this area of change needs to be fully understood since all other changes and effects descend from transformations at this primary-level. Associated with this is the need to determine the relationship between bone, bone function, bone structure and degree of heat-induced alteration. Another important focus of future research should be the refining and modification of anthropological techniques of human identification. There are hundreds of techniques now in existence and although it is not necessary to test them all, research into the important and popular methods is absolutely vital. Until this is complete, the unfortunate situation is that all osteological profiles based on burned and cremated remains should be treated with an extensive amount of caution. It is also vital for the success of future cremation work and for a fuller understanding of the nature of heat-induced change that subsequent studies integrate their research questions with those that have been asked both before and concurrently. The disarticulated nature of the majority of the previous research is directly attributable to the scarcity of knowledge that is present today, even though research on burned and cremated human material has been performed for over 40 years.

Controlled experiments have demonstrated that bone is susceptible to decreases and increases in dimension as a consequence of heating and burning. These changes in size can be as large as 37% and can be very strongly statistically significant ($p \leq 0.01$). Significant heat-induced dimensional change occurs across all regions of the long bones and corresponds to the Fusion stage of bone degradation ($<700^\circ$C). These changes in dimension will severely reduce the accuracy of anthropological techniques applied to burned bone. Prediction equations are therefore required in order to compensate for these heat-induced dimensional changes, and these must focus on the underlying changes in the bone microstructure to succeed.

Acknowledgments

This research formed the bulk of a doctoral project undertaken in the Departments of Forensic Pathology and Archaeology, University of Sheffield, UK. The practical aspect of this research could not have been achieved without the help, advice and time of the following people: my supervisor Dr Martin Evison (Forensic Pathology); Erika Petersen (Archaeology, University of Sheffield) and Richard Stacey (Chemical and Process Engineering, University of Sheffield) provided access to the muffle furnaces; Ian Newsome (Forensic Pathology, University of Sheffield) the department's digital photography equipment; David Jarvis (Forensic Pathology, University of Sheffield) assisted with the radiography and John Proctor (Biomedical Sciences, University of Sheffield) likewise the electron microscopy; Dr Colin Smith (Palaeobiology, Museo Nacional de Ciencias Naturales, Madrid), Miranda Jans and Dr Matthew Collins (Biology and Archaeology, University of York) made available and conducted the ground-breaking use of porosimetry and Jen Hiller and Prof Tim Wess (Biological Sciences, University of Cardiff) the same with WAXS and SAXS.

Thanks also to Dr. Andrew Chamberlain (my second supervisor, Archaeology, University of Sheffield) and Dr. Becky Gowland (St John's College, University of Cambridge) who gave advice and comments on the draft versions of this paper as well as throughout the research.

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