Thermodynamic resolution of periosteal reaction and taphonomic change

Risultati di un'analisi termodinamica della reazione periosteale e delle modificazioni ossee tafonomiche ("post-mortem")

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RIASSUNTO

I fenomeni di neoformazione ossea (come ad esempio la reazione periosteale) sono elementi importanti nella diagnosi delle malattie osteoarticolari. La valutazione di questi stessi nei reperti archeologici viene spesso compromessa dalla carenza di criteri di standardizzazione.
Le ossa, come qualsiasi altra forma di materia, possiedono molte proprietà. Alcune di queste, come peso e volume, vengono definite "colligative". Altre, invece, dipendono dalla natura stessa del materiale, risultando indipendenti dalla massa (proprietà "non colligative"). Lo studio di una di queste ("entropia") ci ha permesso di stabilire che le modificazioni tafonomiche, ovvero "post-mortem", delle ossa possono essere distinte con un buon grado di sicurezza da altri fenomeni reattivi che si realizzano sulla superficie ossea.
Lo studio termografico può pertanto essere utile per standardizzare le analisi paleopatologiche, consentendo valutazioni omogenee da parte di studiosi che abbiano ad operare su campioni provenienti da differenti siti archeologici.

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INTRODUCTION

Diagnostic conundrum

New bone formation (e.g., periosteal reaction) is one component of joint and bone disease (e.g., spondyloarthropathy, renal osteodystrophy) diagnosis (1,2). Its application in the archeologic record, and thus determine of its history and character, has been compromised by lack of standardization (3-7).

Assuring accuracy in assessment of bone pathology – The 'Y1K' problem?

There appears to be a need for an objective technique to validate macroscopic visual examination of bone for periosteal reaction. Distinguishing taphonomic (post-mortem environmentally induced) and ontogenic (e.g., growth of subadult bone) changes appears especially problematic. Wide discrepancies in a single sample set (3-7), with respect to periosteal reaction frequency, suggest a need for development of a standardized technique which would be comparable among investigators.

Absence of a generally applied standard has led to questioning of the potential diagnostic implications of periosteal reaction (6, 8-10). This question is at the heart of the field of paleopathology. If specific diagnosis was not possible, how could the field be justified as a science? There appears to be an answer, at least with respect to periosteal reaction.

The question of specificity of periosteal reaction appears fundamentally related to uncertainty in its recognition. While some investigators (3-5) have suggested extremely high rates of occurrence in some populations, others (6, 7) have not been so certain. Classic of this dichotomy is Irene Mound, variously reported (e.g., Larson, according to Mary Powell in her 1998 symposium presentation at the American Association of Physical Anthropology in Salt Lake City) as having no periosteal reaction or as afflicting one in four individuals (6). Our perception (11) was intermediate. How can this varia-

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tion be explained? A major factor may be difficulty distinguishing periosteal reaction from taphonomic changes, especially cortical abrasion. This could be referred to as a "Y1K" problem, use of data collected in a manner that has not been independently validated.

Discounting subtle periosteal reaction appears to be another major factor. The latter represents an untested hypothesis, perhaps premised in part on the speculation that trauma produces generalized periosteal reaction (8). As there is actually no independent evidence for the latter (12), it has been our perspective that subtle periosteal reaction should not be ignored/discounted.

Distinguishing periosteal reaction and taphonomic changes could be considered an artform, with a problematic learning curve. Inter-observer variation seems to reflect training and experience. It appears to have no relationship to standing in the field, nor to length of time actually involved examining the individual skeletons. We would suggest that it would seem reasonable to simply identify presence or absence of periosteal reaction. If one has to agonize in that decision (whether periosteal reaction is present or not), perhaps that is the decision. Evidence that varieties of periosteal reaction have separate diagnostic implications is quite scanty (12). Even localization on a specific portion of a skeletal element has only limited evidence for specificity [e.g., stress fractures and hypertrophic osteoarthropathy (11-13)]. Resolving current differences of opinion would be feasible if there were an objective technique for distinguishing periosteal reaction from taphonomic changes.

Options for recognition of periosteal reaction

Since periosteal reaction represents an appositional surface phenomenon and taphonomy alters that surface, a unique opportunity presents. Non-destructive characterization of bone surface has traditionally been pursued by macroscopic or radiologic examination (14). As the latter is limited in its sensitivity (12) and the former controversial, it seemed reasonable to consider other physical properties.

Bone architecture, characteristic of endothermic individuals, results in uniform thermodynamic characteristics (15). It seemed reasonable to explore thermodynamic perturbations induced by periosteal reaction and taphonomy.

Entropy

The second law of thermodynamics characterizes entropy. It derives from the Greek "εντροπη ("εν" - in; "τρεπειν" - turning). Entropy is the index of capacity for spontaneous change (16). It is not a colligative property of matter (17, 18). It is dependent on qualitative aspects of structure, not quantity (17, 18).

The "Y1K" solution?

Analogous to x-ray spectroscopy, analysis of entropy seems an ideal technique for assessment of physical variation in bone surface structure. This is premised on the hypothesis that normal bone has uniform entropic patterns of heat dissipation. This study was conducted to assess entropy variations in normal bone and those induced by periosteal reaction and taphonomy.

MATERIALS AND METHODS

SAMPLES

Assessment of variation of entropy with bone condition

Tibia were utilized to assess time course and uniformity of entropic patterns in normal bone and in the presence of taphonomic change and periosteal reaction. All available tibia from the Irene Mound, Georgia site were studied. 251 tibia were present for that analysis.

Assessment of variation of entropy patterns with etiology of periosteal reaction

An additional 10 tibia identified with hypertrophic osteoarthropathy related periosteal reaction (11) from the Terry Collection (National Museum of Natural History) were also examined, to assess independence of entropy findings from etiology in those individuals with periosteal reaction. The Terry Collection consists of 1706 skeletons from individuals who died in St. Louis (Illinois, USA) in the early part of the twentieth century (1, 2). Records of medical affliction and cause of death provide a window on actual bone damage by diseases at a time when therapeutic intervention was still a dream.

Theoretical basis for study of entropy

The second law of thermodynamics defines entropy (S) as the change in heat (H) over time (T). This translates into:

delta S = delta H/T, the van Hoff equation, as derived from Clausius Clappen (17, 18). Kinetic analysis reveals dC/C = KdT, where K = 2.303/T log a/(a-x), where 50% loss occurs if x = a/2. This is integrated to the integral from C_0 to C_t of dC/C = K (integral from T_0 to T_i of dT).

Technical analysis of entropy

Preliminary studies revealed that 1000 joules provided sufficient energy to uniformly heat adult tibia to 30 degrees Centigrade. Entropy was independently assessed in a manner blinded as to the nature of the tibia - normal, taphonomic changes or periosteal reaction. Thermographic spectra were assessed with the Flexitherm direct contact thermography unit (Westbury, New York). This unit transforms thermal energy into a color-coded representation of the thermal pattern. Each color in the visible spectrum of light is adjusted to identify specific temperatures

Thus, the thermal pattern was visualized in the form of a two dimensional color image and variation over time noted. Uniformity of thermal emission of the entire tibia was assessed at 27 degrees Centigrade, with time noted for heat dissipation from 30 to 27 degrees. All examination was performed in a manner blinded as to the nature of the bone. Entropy was assessed independently of knowledge of bone condition. Both homogeneity of the thermal spectrum of heated bone and the time course of heat dissipation were noted.

MACROSCOPIC COMPARISON

Key to understanding this study is recognition that the macroscopic examination was performed independent of, and without knowledge of, the entropy findings. Weight and length of all bones were also measured. This was a blinded, controlled study.

Macroscopic examination was independently performed to identify periosteal reaction and taphonomic changes, utilizing the technique (7), which seems reproducible in our hands (7, 19-23). Periosteal reaction was also recorded according to its nature: Striation, applique (periosteal plaques) and appositional (e.g., radial scars) (6, 24). Powell and Eisenberg (6) also included diffuse pitting. However, in the unremodeled form we believe such changes to actually represent taphonomic changes. We therefore did not group pitting with periosteal reaction in this analysis.

COMPARISON OF ENTROPY WITH MACROSCOPIC FINDINGS

Heat dissipation patterns and homogeneity (or lack thereof) were subsequently correlated with independently obtained data on macroscopic localization of normal and abnormal (e.g., periostitis or taphonomically altered) bone. Chi square analysis was utilized to assess significance of thermal patterns and t-test to assess significance of dissipation times.

RESULTS

Time course of heat dissipation

Time of heat dissipation is illustrated in figure 1. The results created two bell-shaped curves, suggesting two separate phenomenon (t-test = 15.116, 249 d.f., 1-tailed, $p < 0.0001$). Time of dissipation

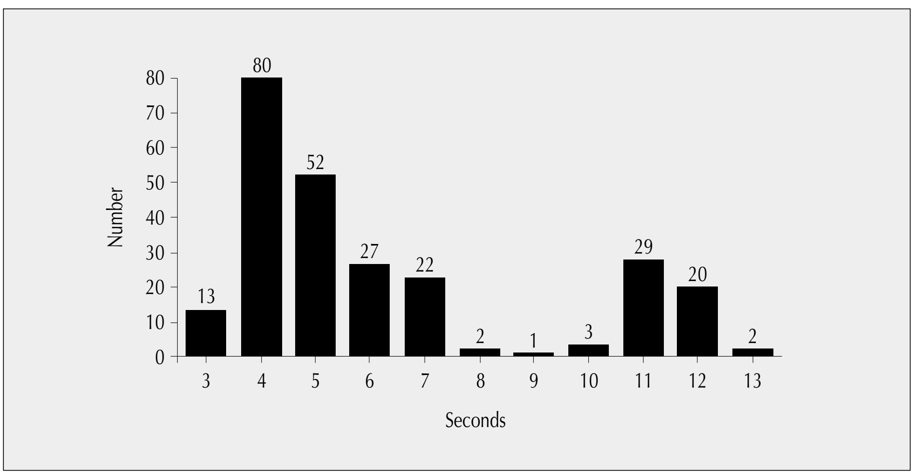

Figure 1 - Thermal dissipation time reveals variant entropy with taphonomic damage. Note that all times less than 9 seconds were in either normal tibia or those with periosteal reaction. Note that all times greater than 8 seconds were in tibia affected by taphonomy.

was independent of bone size or weight, adult or subadult status.

Explanation of pattern separation

Comparison with macroscopic examination revealed complete separation (Fig. 1) of taphonomic changes and pitting (prolonged dissipation time) from normal bone and that affected by periosteal reaction. Tibia with the diffuse pitting pattern of Powell and Eisenberg (6) had identical times of dissipation to that of other forms of taphonomic change and were completely separate from that of periosteal reaction or normal bone. Time course of thermal dissipation was independent of severity of taphonomic changes or periosteal reaction.

Homogeneity of entropy

All 157 normal tibia manifest uniform patterns of entropy (Table I). Seventy-four percent of taphonomically-affected bone (and itted bone) also revealed uniform entropy, compared to only 15% of bone with periosteal reaction. The latter was limited to those tibiae with very diffuse periosteal reaction. No bone with limited distribution of periosteal reaction had homogeneous entropy. Eighty-five percent of 27 tibia with periosteal reaction had non-homogenous entropy patterns, all manifesting increased thermal patterns compared to normal bone. Fourteen percent of 67 tibia with taphonomic changes or pitting had decreased thermal patterns; 2%, increased. Increased thermal patterns (rate of heat dissipation) of periosteal reaction (compared to normal areas in a specific bone) contrasted with decreased patterns in taphonomic or pitting changes (Chi square = 70.9, $p < 0.0001$).

Thermal patterns of homogeneity were independent of bone weight and length, whether independently assessed or correlated (Table I). Homogeneity patterns were also independent of the severity of taphonomic change, pitting or periosteal reaction, with one exception. Homogeneity was regained, if the periosteal reaction was so severe as to preclude visual recognition of normal bone. Even those tibia with the most minimum periosteal reaction had increased thermal patterns (faster heat dissipation) at those sites. Seventy-five percent of those with minimal taphonomic changes had homogeneous patterns, indistinguishable homogeneity (74%) from those with severe taphonomic changes. The one tibia with taphonomic changes manifesting the increased thermal pattern did have very severe damage, not possible to confuse with periosteal reaction.

Table I - Difference of thermal pattern of bones, according to their main characteristics.

	Normal	*Periosteal Reaction*	*Taphonomic*
Thermal pattern			
Homogeneous	100%	15%	74%
Non-homogeneous			
Increased	0	85%	2%
Decreased	0	0	14%
Tibia weight (grams)			
Average	107	136	125
Median	116	156	146
Subadults only			
Average	58	*	44
Median	58	*	58
Tibial length (cm)			
Average	28	31	29
Median	31	32	32
Subadults only			
Average	22	*	21
Median	21	*	18
Ratio of weight to length	0.13	0.17	0.15

* No subadults had periosteal reaction

Variation of entropy as a function of macroscopic character of periostal reaction

Examination of surface reaction according to its nature revealed increased discernable thermal patterns in all groups (with one notable exception), unless the reaction was so generalized that normal bone was rarely recognizable. Those tibia had homogeneous patterns. Thus, striation, applique and appositional patterns were indistinguishable thermographically.

There was one pattern, however, which did differ: The pattern that Powell and Eisenberg (5) refer to as diffuse pitting. All individuals with such a macroscopic pattern had homogeneous thermographic patterns.

Variation of entropy as a function of etiology of periosteal reaction

All tested individuals with hypertrophic osteoarthropathy- derived periosteal reaction had non-uniform thermographic patterns. All manifested increased thermal patterns at the sites of the periostitis.

DISCUSSION

Objective technique for assessment of bone integrity

Spectrographic evaluation of thermal entropy provides a reproducible, objective technique for assessment of bone integrity. The spectrographic or visible representation of heat dissipation allows facile visualization of bone surface integrity. Work is not a property of the system, but depends on the path (17, 18). Independence of entropy pattern from bone weight, length or maturity in this study validates the non-colligative nature of heat dissipation, as anticipated 15, 17, 18). The only factor affecting entropy was the condition of the bone surface. Examination of entropy allowed clearly distinguishing between taphonomic change and periosteal reaction.

Normal bone and taphonomic changes

The initial hypothesis of homogeneous normal bone entropy was confirmed. Taphonomic changes and pitting were characterized by reduced entropy, as manifest by decreased heat dissipation times. The periosteum, or at least the extracortical bone it produced, seems to play an important role in heat dissipation. When underlying intracortical bone is exposed (e.g., by taphonomy), entropy is lessened. Thus, thermographic assessment of entropy provides a clear opportunity to distinguish taphonomic changes and pitting from periosteal reaction. Comparison with macroscopic examination revealed complete separation of taphonomic change and pitting (prolonged dissipation time) from normal bone and that affected by periosteal reaction. Examination of entropy also characterizes the diffuse pitting pattern (in the absence of associated periosteal reaction) as indistinguishable from that found with taphonomy. Such pitting should not be considered periosteal reaction. While we believe pitting simply represents taphonomic alteration, as alternative explanations for pitting have not yet been scientifically substantiated.

Periostal reaction

Periosteal reaction was characterized by non-homogeneous thermal patterns, with affect bone temperature increased compared to normal bone. The latter may not be recognized when the periosteal reaction is quite diffuse. Diffuseness of reaction and associated bone thickening, however, did not affect thermal dissipation time (entropy). Increased thermal patterns allow periosteal reaction to be distinguished from taphonomic change (Chi square = 70.9, $p < 0.0001$), as the only case of taphonomic change with a similar pattern was so severe as to allow easy recognition, even if the thermal dissipation times did not clearly distinguish them.

Entropy as a function of etiology and nature of periosteal reaction

Thermal patterns were independent of variety of periosteal reaction or its origin. It has been suggested that periosteal reaction in Irene Mound is treponemal in origin (6, 7, 21). That studied in the Terry Collection complicated hypertrophic osteoarthropathy in tuberculosis and cancer (11). The findings were indistinguishable among the groups. Sole presence of diffuse pitting is not a manifestation of a periosteal reaction.

Implications

Independent correlation of spectrographic findings with our technique for macroscopic identification of periosteal reaction is intriguing. While Larson appears to significantly underdiagnose periosteal reaction and Powell and Eisenberg’s (6) approach accepts cases which we reject, our approach is the one objectively substantiated. It

SUMMARY

New bone formation (e.g., periosteal reaction) is one component of bone and joint disease diagnosis. Its application in the archeologic record has been compromised by lack of standardization. An objective technique for validating observations seems especially valuable when visual examination of a single data set results in widely disparate perspectives. Such discrepancies as to presence or absence of periosteal reaction are amenable to objective analysis.
Bone, as any other form of matter, has a variety of properties. Some are characterized by weight or volume and are referred to as colligative. Some are related to its intrinsic nature, independent of mass. The latter are referred to as non-colligative. Non-colligative properties of matter provide an opportunity to assess structure, independent of quantity. Study of one such property, entropy, revealed that taphonomic changes can confidently be distinguished from bone surface reaction. Contrasted with the homogeneous entropy of normal bone, the loss of surface bone inherent in taphonomy results in reduced entropy. Contrasted with the homogenous patterns of normal bone, specific non-homogenous patterns allow periosteal reaction to be recognized, independent of variety of periosteal reaction or its origin.
Thermographic approach allows observational techniques to be independently validated. Such validation allows for greater facility in interobserver archeologic site sample comparisons.

Key words - *Periosteal reaction, spondiloarthropathy, taphonomy, paleopathology, treponemal disease, entropy.*
Parole chiave - Reazione periosteale, spondiloartrite, alterazioni tafonomiche (“post-mortem”), paleopatologia, infezione da treponema, entropia.

would seem appropriate to subject all periosteal reaction to such objective assessment or at least comparison with a validated standard. Such would seem a potential solution to this “Y1K” problem - standardization.

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