Field Paleoradiography of Skeletal Material from Early Classic Period of Copan, Honduras

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ABSTRACT

The inclusion of paleoradiography in a research project vastly enhances our understanding of prehistoric life histories, extending research possibilities beyond the diagnosis of skeletal or soft-tissue pathologies. As part of a larger interdisciplinary research project, the skeletal remains of two elite individuals from the Early Classic Period of Copan were subjected to radiographic evaluation; K'inich Yak K'uk Mo (Hunal Burial 95-2), founder of the Early Classic Dynasty, and the primary female interment from the Motmot tomb (Burial 37-8). Previous work documented individuals for visible changes in long bone structure associated with reduced activity levels or pathology were documented. The goals of radiographic analysis included documentation of additional pathologies and subsequent changes in long bone density due to physiological/functional adaptation such as disuse atrophy. Further, we were able to calculate long bone cross-sectional geometric properties, allowing us to quantify these possible changes in cortical bone distribution due to trauma. The research highlights the potential that paleoradiography can have for a research project beyond the assessment of pathology. In particular, the adaptability of the technology for both field and laboratory settings is demonstrated.

The site of Copan is located in the southeastern periphery of the Maya world in modern day Honduras (Figure1). The chronology of Copan is divided into three periods; the Protoclassic, or Predynastic Period (ca. A.D. 100 – 400), the Early Classic (ca. A.D. 400 – 600), and the Late Classic (ca. A.D. 600 – 850). The skeletal remains of the two elite individuals analyzed in the current study date to the Early Classic Period.

The Principal Group in Copan represents the remains of the Classic Maya capital. The Principal Group is divided into northern plazas and a complex of superimposed structures to the south. The Temple of the Hieroglyphic Stairway (Structure 10L – 26) and a ball court mark the transition between the northern and southern sectors. The Acropolis is divided into two courts by Structure 10L – 25 (The Dance Platform) and Structure 10L – 16. The latter is the highest point in the Principal Group and represents a pivotal period in the history of the Acropolis <1>.

Located in the earliest levels of the Acropolis, the Hunal Tomb (Burial 95 – 2), based upon stratigraphic, ceramic, and epigraphic evidence, has been dated to ca. A.D. 400 – 450 <2>. The remains appear to have initially rested upon a reed mat and were accompanied by shell and jade ornaments, bone implements, and ceramics <2>. The skeletal remains have been attributed to K'inich Yak K'uk Mo', founder of the Early Classic Dynasty of Copan, who arrived and consolidated power within the Copan Valley in AD 426 <3-5>.

Excavations below Structure 10L – 26 <6> uncovered the Early Classic Period Motmot Tomb. A young female was the principal interment in the Motmot tomb (Burial 37 – 8). Based upon iconography found on a circular marker associated with the tomb, it was constructed during the reign of the son and successor of Yak K'ak Mo' <6>. The skeletal remains from this tomb included the principal female interment, the focus of this research, and at least one "trophy skull" <4, 5, 7-9>. Associated material artifacts suggest that the principal Motmot interment may have been a day-keeper, an individual associated with divination and curing <6>.

Recent studies by Buikstra and colleagues <10, 11> documented remarkable evidence of blunt force trauma among these elite individuals. Radiography added further detail to interpretations derived from the gross evaluation of pathology <10>, while also addressing a number of specific research questions. At the most basic level we were concerned with documenting pathological processes that may not have an externally visible manifestation. Secondly, the radiographs allowed us to assess any post-traumatic changes in bone structure that may be evidence of individual-specific forms of pathology and activity-related changes such as disuse atrophy. Based upon the assumption that the distribution of diaphyseal cortical bone reflects levels and patterns of habitual biomechanical stress <12, 13>, we also investigated changes in long bone cross-sectional geometric properties subsequent to the observed trauma.

MATERIALS AND METHODS: RADIOGRAPHY

Radiographs were taken using a Soyee Products Inc. portable veterinary x-ray unit. Distance, lead aprons, and isolation ensured researcher safety. The research project, which included both a field laboratory setting (Motmot Burial 37-8) and tunnels within the Acropolis (Hunal Burial 95 – 2), precluded the use of conventional radiographic film. Additionally, there were no facilities for loading or processing of standard film readily available. Therefore 8 x 10 inch sheets of 800 speed Polapan 803 Polaroid film, a black and white photographic film, were used. Polaroid film has a number of advantages over conventional radiographic film when dealing with field conditions <14> including instant assessment of exposure and positioning and sharp, positive images (Figure 2A and B). Disadvantages, however, include the limited size of the film, which at times necessitated multiple exposures to capture long bone images. Even so, the use of Polaroid film was determined to be the best course of action. Exposures were generally set at 80 kV/15 mA while the focal film distance was approximately 40 inches (100 cm). The latter was maintained through the use of a collapsible x-ray stand constructed from electrical conduit piping and PVC fittings.

Power fluctuations at both locations made it difficult to maintain the above settings, requiring increased exposure time. Further, a number of the elements were almost completely covered in cinnabar. Cinnabar, a naturally occurring form of mercury, is radiodense and at times was so ubiquitously applied that the resulting radiographs were nondiagnostic.

Standardized anterior-posterior and medial-lateral radiographs were taken <15, 16>. Skeletal elements were stabilized with foam in order to maintain position such that the plane of interest was parallel to the film. Given the curved nature of the humerus, radiographic magnification was not consistent throughout the bone. An average magnification rate of 3% was assumed and subsequently used to adjust the cross-sectional properties. Bone length was determined using a portable osteometric board, while biomechanical length <13> was measured directly from the radiographs. Measurements, utilizing Mitutoyo Digital Calipers, were taken directly from the radiographs at 35% (mid-distal), 50% (midshaft), and 65% (mid-proximal) of biomechanical bone length. Measurement error throughout all three trials ranged from 0.01 mm to 0.57 mm. Measurement error tends to be larger for endosteal areas <16>. Given that the measurement error was small, they should not significantly affect the calculation of biomechanical properties. Further, since measurement errors will affect both sides equally, right-left intra-individual comparisons should remain robust.

PATHOLOGY ASSESMENT

Yak K’uk Mo’

Buikstra et al. <10> documented a number of traumatic lesions of the skeletal remains of Yax K’uk Mo’ including a parry fracture of the right forearm, altered sterno-clavicular articulations, significant bony alterations to the left shoulder girdle, and other less extreme insults.

Injury to the right radius of Yak K’uk Mo’ did not result in disuse atrophy of that element (Figure 3A and b). Cortical density remains normal and there is clear gross and radiographic evidence for the development of arthritic lipping at the articular surfaces. The bony callus is mature, indicating that the fracture was stabilized and that the healing process was no longer active at the time of death. Conversely, the fragments of the ulna did not heal properly (Figure 4a and 4b) and the two fragments are quite radiolucent, suggesting disuse atrophy. The radius may have acted as an internal splint, preventing significant movement at the site.

The distinctive reaction of the cortical bone of the radius and ulna is interesting in the light of results from experimental pig and dog long bone ostectomies <17, 18>. This research suggests that the rendering of either the radius or the ulna useless results in diaphyseal hypertrophy of the unaffected bone. The extension of these results to the current discussion, however, must be tempered by the fact that the radius and ulna are weight bearing bones in the above animals and will therefore be more susceptible to shifts in compressive and tensile loads.

The sterno-clavicular articulations were displaced laterally, forming pseudo-articular facets (Figure 5). Further, these articulations also displayed exuberant cartilaginous ossification. The thinned caudal portion of the gladiolus was depressed, causing the superior portion to project ventrally, displacing the gladiolus/manubrium articulation to the dorsal surface of the gladiolus, the apparent result of blunt force trauma to this region.

The most significant bony restructuring involved the left shoulder girdle (Figure 6). The superior third of the glenoid fossa and the coracoid process of the scapula were together separated from the body of the scapula. The fracture was not reduced and the bone fragments never reunited. Gross examination <10> noted marked arthritic changes at the shoulder joint, with pronounced arthritic development and eburnation of the inferior third of the humeral head (Figure 7).

Motmot

Despite her gracile appearance <10> there is no evidence to suggest that the Motmot principal interment suffered from deossification, or suffered cortical or trabecular bone loss due to disuse atrophy. The only radiographically visible insult was a parry fracture of the right ulna (Figure 8). Cortical and trabecular bone thickness appear normal. There was no displacement of the ulnar fragments and the fracture healed in near perfect anatomical alignment. The midshaft bony callus is well integrated and was not actively remodeling at the time of death. It may be that the fracture was splinted <11>.

BIOMECHANICAL PROPERTIES

The use of orthogonal radiographs to estimate cross-sectional biomechanical properties is a viable and robust methodology in circumstances when the bone cannot be sectioned or CT equipment is unavailable <19, 20>. Cross-sectional geometric properties, including cortical area (CA), medullary area (MA), and total subperiosteal area (TA) were calculated. Cortical areas were scaled to bone length[3] <21-23>. Orthogonal radiographs do not allow the estimation of the maximum and minimum second moments of area, I_{max} and I_{min} <20>, but second moments of area, I_X and I_Y, may be estimated. I_X and I_Y measure the bending rigidity of a bone in relation to the frontal and sagittal plane of axis respectively. While low values for second moments of area indicate that bone is distributed close to the central or neutral axis of a cross section, high reflect bone distribution relatively far from the central axis. High second moment values also reflect greater strength and ability to resist mechanical forces <24>. Finally, percent cortical area (%CA), a measure of the strength of a long bone under axial loading relative to total area (TA), was calculated. Cortical areas (CA, MA, TA) were standardized by biomechanical length^3 while the second moments of area (I_X, I_Y, J) were standardized by biomechanical length^4 and biomechanical length$^{5.33}$.

CONCLUSIONS

The utilization of radiography in the assessment of the skeletal material from the Acropolis of Early Classic Copan allowed us to greatly expand our research objectives and interpretive possibilities. The radiographs more precisely documented pathological processes of both individuals and changes in bone structure due to trauma that may show activity-related changes such as disuse atrophy.

While Yak K’uk Mo’ may have had normal cortical bone density <11>, the cortical bone is thin when compared to other groups. The very low %CA values calculated for Yak K’uk Mo’ (Table 1) suggest that bones may not have been strongly resistant to axial loading, though %CA by itself is not a reliable indicator of functional and mechanical demands <25>. Despite low values %CA, the second moments of area (Table 1) suggest that cortical bone was redistributed away from the neutral axis of both humerus, indicating substantial resistance to bending and torsional loadings <25>. Measures of medullary area support this conclusion (Table 1).

Further, comparison of Yak K'uk Mo's right and the left humeri suggests some interesting differences. There is a large degree of asymmetry between the humeri for %CA, by as much as 14%, suggesting that the cortical bone thickness is significantly thinner in the right humerus. Except at the mid-proximal location, measures of MA and TA are larger in the right humerus, indicating a relatively expanded medullary space and total subperiosteal area. The asymmetry values also reflect this difference (Table 3).

We must also consider the advanced age of Yak K'uk Mo' (>50 years) <10> when we consider changes in bone geometry due to trauma. There is an age-progressive loss of CA coupled with increases in TA and MA that together serve to maintain bone strength <26, 27>. The rate of endosteal bone loss exceeds subperiosteal bone deposition after 40 years of age, resulting in both overall bone loss with age <24, 16>, and bone redistribution in order to maintain resistance to mechanical forces <12>. It is likely that with trauma-induced disuse atrophy of the right forearm, that the loss of cortical area was accelerated in the right humerus relative to the left humerus.

The restructuring of the left shoulder girdle more than likely resulted in radical structural and functional changes. While this fracture could have contributed to degenerative changes and paralysis, there is no evidence of disuse atrophy in the left upper limb, and moderate arthritic development in the elbow, wrist, and hand. The high values for I_X at the left mid-proximal humerus (Table 1) are interesting in that this is the region most intimately associated with the fracture of the coracoid process and glenoid fossa. The primary function of the muscles that originate on the coracoid process involve movement in the anteroposterior plane, therefore the high I_X value at this location, which suggests increased resistance to anteroposterior loadings, is a somewhat anomalous result. Physiologically, this suggests near normal activity despite the separation of the bony elements, but perhaps with a limited range of mobility.

As described by Buikstra et al. <10>, the skeletal remains of Motmot are quite gracile. Motmot did not suffer from osteoporosis, osteopenia, or from any disuse atrophy which might account for her slight skeleton <11>. The only insult of note was a complete parry fracture of the right radius. The insult was completely healed and was not active at the time of death. There was no discernible difference between the right and left radius and ulna in terms of cortical thickness or density <11>. The asymmetry documented in humeral MA for the Motmot individual suggests a slightly expanded medullary space in the right humerus (Table 3).

While these differences seem slight, the comprehensive picture is one of subtle physiological adaptation following trauma. As a cautionary note, while inter-individual patterning of cross-sectional properties may be useful, they do not necessarily provide an accurate characterization of the orientation of loads to which these bones were subjected <28>. That is, while we may reliably discuss the relative redistribution of cortical bone in Yak K'uk Mo' and Motmot individually, discussion should not attempt to describe the nature of the loadings.

Paleoradiography vastly increases our ability to document the pathological processes that affected these centuries old individuals during their lifetime. Additionally, the utilization of radiographs allowed us to expand our understanding of how these processes may have affected biomechanics, and subsequently, long bone geometric properties. That is, not only were we able to document *what* processes occurred, but we were able to address *how* these processes actually affected the individual. The flexibility of the technology to accommodate a wide range of research conditions and the broad spectrum of questions that can be addressed, make paleoradiography a valuable research tool.

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Table 1: Body-size standardized cortical areas[a] and second moments of area[b,c] for K’inich Yax K’uk’ Mo’ at mid-distal (35%), midshaft (50%), and mid-proximal (65%).

	Left Humerus			Right Humerus		
Property[a]	35%	50%	65%	35%	50%	65%
CA	44.32	39.73	40.55	44.49	38.15	37.59
MA	49.11	63.23	83.05	62.24	74.82	74.34
TA	93.43	102.96	123.60	106.72	112.98	111.93
%CA	16.23	13.21	11.22	14.27	11.56	11.49

	Left Humerus			Right Humerus		
Property[b]	35%	50%	65%	35%	50%	65%
I_X	255.17	241.72	370.37	291.93	268.06	283.56
I_Y	213.99	246.33	259.49	262.71	262.05	236.58
J	469.16	488.05	629.86	554.64	530.11	520.13

	Left Humerus			Right Humerus		
Property[c]	35%	50%	65%	35%	50%	65%
I_X	520.72	493.27	755.81	595.74	547.03	578.65
I_Y	436.67	502.69	529.53	536.10	534.75	482.77
J	957.39	995.95	1285.33	1131.83	1081.78	1061.42

[a] Cortical areas were standardized over humeral biomechanical length^3.

[b] Second moments of area were standardized over humeral biomechanical length$^{5.33}$

[c] Second moments of area were standardized over humeral biomechanical length^4.

Table 2: Body-size standardized cortical areas[a] and second moments of area[b,c] for Motmot at mid-distal (35%), midshaft (50%), and mid-proximal (65%).

	Left Humerus			Right Humerus		
Properties[a]	35%	50%	65%	35%	50%	65%
CA	65.04	70.94	62.83	65.67	72.82	68.06
MA	30.82	31.76	35.46	28.27	35.91	34.29
TA	95.85	102.70	98.29	93.93	108.73	102.34
%CA	30.58	31.13	28.81	32.54	31.17	30.95

	Left Humerus			Right Humerus		
Properties[b]	35%	50%	65%	35%	50%	65%
I_X	321.97	372.35	286.56	289.29	380.05	328.57
I_Y	255.06	293.88	298.21	265.53	348.05	313.44
J	577.03	666.23	584.78	554.82	728.10	642.02

	Left Humerus			Right Humerus		
Properties[b]	35%	50%	65%	35%	50%	65%
I_X	581.57	672.56	517.61	515.13	676.73	585.07
I_Y	460.70	530.83	538.65	472.81	619.77	558.14
J	1042.27	1203.39	1056.26	987.94	1296.50	1143.22

[a] Cortical areas were standardized over humeral biomechanical length^3.

[b] Second moments of area were standardized over humeral biomechanical length$^{5.33}$

[c] Second moments of area were standardized over humeral biomechanical length^4

Table 3: Bilateral asymmetry values at mid-distal (35%), midshaft (50%), and mid-proximal (65%) based upon raw humeral diaphyseal dimensions for K’inich Yak K’uk Mo and Motmot after being corrected for magnification.

	Yak K’uk Mo’				Motmot		
Property	35%	50%	65%	Property	35%	50%	65%
CA	0.36	4.13	7.88	CA	2.28	0.60	4.89
MA	26.72	18.33	11.72	MA	12.59	9.46	6.80
TA	14.22	9.73	10.43	TA	5.38	2.51	0.83
%CA	13.84	14.26	2.36	%CA	3.03	3.13	4.03

FIGURE LEGENDS

Figure 1: Regional map of Maya world.

Figure 2: (A) Superior-inferior and (B) anterior-posterior radiograph of Motmot's skull.

Figure 3: (A) Anterior-posterior and (B) medial-lateral radiograph of Yak K'uk Mo's right radius.

Figure 4: (A) Anterior-posterior and (B) medial-lateral radiograph of Yak K'uk Mo's right ulna.

Figure 5: Anterior-posterior radiograph of Yak K'uk Mo's sternum (black arrow marks formation of radiodense bone at altered manubrium/gladiolus articulation as noted in text).

Figure 6: (A) Anterior-posterior and (B) medial-lateral radiograph of Yak K'uk Mo's left scapula.

Figure 7: (A) Anterior-posterior radiograph (B) anterior-posterior photo of Yak K'uk Mo's left humerus.

Figure 8: Anterior-posterior radiograph of Motmot individual's right forearm.

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