To the Graduate Council:

I am submitting herewith a thesis written by Butler Fuller IV entitled "Sexual Dimorphism in Modern Black and White Cranial Vault Thickness: A Forensic Application for Sexual Discrimination." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Arts, with a major in Anthropology.

William M. Bass

William M. Bass, Major Professor

We have read this thesis and recommend its acceptance:

Lyle W. Konigsberg

Accepted for the Council:

Associate Vice Chancellor
and Dean of Graduate School

Sexual Dimorphism in Modern Black and White Cranial Vault Thickness: A Forensic Application for Sexual Discrimination

A Thesis

Presented for the

Master of Arts

Degree

The University of Tennessee, Knoxville

Ira Butler Fuller IV

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ABSTRACT

In forensic anthropology, the emphasis in research lies within the continual pursuit of the best methods for human identification through analysis of the skeletal remains available. Most of the methods developed by researchers both past and present have utilized the various skeletal collections curated at museums and universities throughout the country in order to try and deduce patterns and trends visible in the osseus record of human existence. Here, 126 specimens from the University of Tennessee (U.T.) William M. Bass Collection (n=31) and Terry Collections (n=95) are analyzed, to determine the level of sexual dimorphism present in the thickness of the cranial vault.

Measurement of the specimens was carried out using instruments developed by both the researcher and the University of Tennessee College of Engineering. The findings from these measurements have yielded information which may be useful in human identification, specifically sex assignment of unknown individuals.

The findings indicate a significant difference between males and females at many of the fifteen points measured on the skulls with females predominating in thickness in the more anterior portions of the skull (frontal and parietal bones) and males dominating in thickness in the more posterior portions of the skull (occipital and cranial base). The effects of race and age, on cranial thickness, are not significant in this sample as shown through statistical analysis. Membership in collection was also analyzed and the results showed that Terry members had thicker cranial vaults than the more modern U.T. specimens, with the exception of the posterior measurements on the occipital. Finally, methods of

reduction of the number of points needed to discriminate between the sexes are also pursued and the points of the frontal and parietal bones found to be the most informative in deducing sex.

It is shown that this method correctly discriminated nearly 70% of the material in the sample, yet the applications of this particular method of discrimination may be limited in that autopsied skulls, allowing for full access to the fifteen points measured, are essential. To recalibrate the method to fit fewer points, the original data set would be required and a new discrimination model would need to be constructed based upon the new parameters. Given this limitation, this method may prove more useful in sexing museum specimens or individuals in a curated study collection as opposed to specimens from the field. Further research into a more field-based method of cortical thickness discrimination is suggested and may be pursued further.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF PLATES

CHAPTER 1

INTRODUCTION

There are many methods by which the sex of human crania can be deduced either by quantitative or qualitative analysis of the available material. Morphological differences exist, of that there is no question; yet, when large portions of the skull are absent and the most telling morphological indicators of an individual's sex are not present, one must be able to move to more fine-grained analyses of differences which can only be touched upon with precision and accuracy in fine measurement. Here, an attempt is made to elucidate the finer differences between the sexes by measuring the bones of the cranial vault to determine how much sexual dimorphism is present in the thickness of the cranial vault as measured at fifteen points on the calvarium.

Other researchers have looked at the sex differences in the skulls of males and females within such a framework (Todd, 1924, Roche, 1953, Young, 1957, Adeloye, *et al.,* 1975, and Ross, *et al.*, 1976). The work of the majority of these researchers, however has been based primarily on the measurement of cortical bone thickness taken from lateral radiographs either cross-sectionally or longitudinally throughout childhood and the post-pubertal period or has been based upon a few measurements taken from a more limited area of the cranium. The majority of these measurements were taken along the sagittal plane thus greatly limiting the areas of the cranium studied.

This study seeks to go beyond such previous analyses based mostly on the midline measurements alone. Points were taken across a greater number of the skulls components including the occipital, parietal (medial and lateral), and the frontal bone lateral of the sagittal plane. The intent here is to elicit information on sexual dimorphism in cranial vault thicknesses from a wider portion of the cranium. The hope here is that in the case of fragmented crania from forensic settings or in archaeological contexts, those portions of the skull which are present may include points measured here and that those fragments can be sexed with some degree of reliability.

Barring any omissions in the literature search, such a comprehensive study of the skull has not yet been performed. The following study seeks to provide a valid technique for the discrimination of males and females based on cranial cortical bone thickness. It is the hope of the researcher that its relevance to studies in the forensic, anatomical, and archaeological realms (population profiles, mortuary practice, and mortality ratios) will be made apparent.

LITERATURE REVIEW

The most striking aspect of the literature search on this topic was in the paucity of related literature on this particular subject. There is a massive body of literature on the various aspects of skull growth and how the skull responds to changes and stresses both external (environmental) and internal (bio-mechanical). Also, there is a good deal of attention paid to racial and age-related aspects of cranial differentiation. This project addresses the shortage in vault thickness dimorphism studies primarily in an attempt to produce a workable forensic-based sexing technique for discrimination.

Sex-based differences in the thickness of the skull were noted in the early 1900's as various physical anthropologists plumbed the depths of difference between the sexes in order to gain a clearer insight into how the sexes differed osteologically (i.e. the skeleton). Among the first to tackle cranial vault thickness was T. Wingate Todd

(1924) in his landmark article which was cited in almost all of the literature obtained for this project. In his work, Todd analyzed the crania of 448 white males aged 18 through at least 80 years. While the focus was mostly directed at determining the degree of bone mass-loss due to aging, the work, nonetheless, represents one of the first attempts to analyze cranial vault bone thickness. Todd measured his crania at four points : glabella, opisthion, vertical point (vertex), and euryon. Todd found the greatest thicknesses in the frontal region of the cranium with decreasing thicknesses occurring as one proceeded posteriorly. Todd also noted a sporadic, yet consistent thickening with age, and he suggested that any resultant loss in bone mass and weight of the skull came from facial bone deterioration. The sporadic nature of the thickening encouraged Todd to caution against using bone thickening as a indicator of age.

Roche (1953) followed in the same vein as Todd when he studied thickness of the crania of sub-pubertal individuals in order to compare the rates of thickening of the vault bones between the sexes for children ages 3 months to 17 years. The measurements were taken by cephalometer from lateral radiographs of the subjects which consisted of 14 white males and 18 white females. Measurements were taken every six months in order to gain a clearer picture of the nature and amount of growth which occurs during maturation. Measurements were taken at nasion, the nasion-bregma midpoint, bregma, vertex, lambda, and right and left euryon. The male mean thickness exceeded that of the female mean except for both euryon measurements in which no significant difference in cranial thickness could be noted. The research indicated that bone growth slowed markedly after 5 years with only slight increases until around age 17 and that females had reached a greater percentage of their adult-thickness at any age than had males save for measurements at vertex; thus, not only is there a notable difference in thickness itself, but in rates of maturation as well.

Richard Young (1957) also researched the growth of the skull and vault bone thickness increase during maturation in white males.

The subjects comprised two groups from the Fels growth study. The first group consisted of lateral radiographs taken of white males from 1 month to 16 years while the second group served as subjects for studying skull thicknesses in later years - ages 20 through 62. While the aim of this study was mainly to analyze the growth of the frontal and parietal bones as they attain their adult morphology (size and shape), thickness was also measured. Nine points of thickness were taken on the frontal bone from the radiographs along with thickness measured at nasion and at lambda on the posterior parietal. Thickening of both bones was found to be positively correlated and thought to be of endocrine origin in both the dimensions of apposition and in resorption. The fact that the frontal region appears to thicken at a faster rate than in the parietal may be due to the developing frontal sinuses. Young suggests that the two tables of vault bone act independently in apposition and resorption, the outer table thickening in response to muscular action while the inner table responds to the underlying tissues of the brain.

Adeloye, Kattan, and Silverman (1975) conducted a study in which the crania of 300 Afro-Americans and 200 Euro-Americans were analyzed with reference to sexual dimorphisms which may be detectable in the thickness of the cranial vault at various stages in life. Thickness was measured on lateral radiographs at four points : A. 3 centimeters (cm) anterior to the coronal suture in the sagittal plane; B. 3 cm. posterior to the coronal suture; C. and D. 3 cm. superior and inferior to the lambdoid suture respectively.

This study differed from others due to the fact that through breaking the sample down into racial groups as well as the sexes, the study could analyze possible racial attributes of cranial thickness as well. All groups showed a rapid increase in thickness throughout the first two decades in life. The third decade saw changes among the four groups (white male, white female, black male, black female) at points A, C, and D. Small increases in cranial thickening were noted up to and well into the fifth and sixth decades. The measurement B showed the least variation among the groups.

The results showed that among Afro-Americans, differences between the sexes, numerically, was variable; however, at points A and D the female means exceeded those of the males during the third decade. Subjects who fell within the 60-plus decades showed a tendency for female thickness dominance at points A and C. The differences approached, yet were not significant at, the .05 level. Among whites the male mean exceeded the female mean at point B in all age categories yet did not attain significance. At point C, the female figures were higher during the third and sixth decades. A female tendency toward significant thickness difference occurred at point D after age 60. In comparing the races, Afro-American males exceeded the white male means in the posterior measurements while the white males showed thicker anterior measurements. The same pattern was noted for Afro-American females versus white females.

Pensler and McCarthy (1985) conducted a study of calvarial thickness by trying to determine what factors are most significant in determining skull thickness. Their sample consisted of 200 adult crania (ages 18-91) from autopsied individuals under post-mortem review. Measured were four points on the right and left lateral frontal bone and posterior parietal bones at sites used frequently as calvarial donor sites for grafting material. Multiple regression of the variables thought responsible for the differences in skull thickness was performed on age, race, weight, sex, and height. Weight and race appeared to be significant variables while sex was either significant or borderline significant for all eight measurements. What was shown was a tendency for the thickness measurements to increase from frontal to posterior parietal measurements, and for the white male to exceed the mean of white females, Afro-American males, and Afro-American females in the frontal measurements while Afro-Americans, of both sexes, exceeded whites in the posterior measurements.

Pensler and McCarthy also analyzed the side of the skull as a possible predictor of skull thickness which alludes to brain morphology as a possible contributor to cranial bone thickness. The analysis showed a tendency for the left anterior portions of the skull to exceed the right anterior measurements quite significantly. This is similar to the findings of LeMay (1977) who studied brain morphology and handedness, and its resultant effects on the skull. Right-handed individuals, it appears, have a brain morphology showing a counter-clockwise torque of the brain and cranium with the right frontal and left occipital regions of the skulls protruding somewhat in response to the greater impressions being made on the endocranium by those portions of the brain. The opposing hemisphere's brain poles do not produce such impressions on the endocranium and thus may not affect cranial bone thickness as much. Such analyses are outside the scope of this research, yet such effects cannot be ruled out in cranial thickness analysis and may indicate a subject for further research on how to detect the effects of brain morphology on the skull as opposed to sex-based effects.

A study of Rhodesian (now Zimbabwean) populations, both African blacks and whites, was undertaken by Ross, Lee, and Castle (1976) in order to assess the best method for determining cranial thickness differences between the races and any intra-racial sexual differences that may exist. The researchers noted that measuring skulls proved quite difficult as the bony irregularities of the inner surface of cranial bones make determining consistent points of measurement problematic. The authors also noted that skulls can differ widely in morphology as one skull may have an inordinately thick occipital bone while maintaining "average" thickness in all other locales while another skull may not show such patterning. Two methods for measuring skull thickness were developed. The first consisted of removing the calotte with an autopsy saw and measuring two points lateral to either side (3-4 cm.) of the sagittal plane avoiding the frontal sinus and two points at the thinnest portion of each temple. This method was used in measuring 218 adult crania of both races and sexes. The second method consisted of photographing the portion of the skull not removed by autopsy and measuring the cross-sectional area of the brain pan and the skull cap and measuring the area taken up by the autopsy-created "rim". There were 20 subjects in each race and sex category measured using this method. Method 1 showed that white women had the thickest skulls anteriorly followed by black women. The males followed the same pattern. Women were shown to have thicker skulls than men in analysis of variance statistics while racial affinity was of little consequence. Method 2 produced no significant difference between the races in the females yet white men were shown to have significantly thicker skulls than black men in this area of the cranium. The authors cite the purity (racial) of these differences and debunk the findings of Adeloye, et al. on the grounds of admixture in the African-American population.

Upon noting a trend toward reduction in cranial vault thickness from Neolithic to modern populations, Ishida and Dodo (1990) conducted a study of 152 (105 male, 47 female) modern crania, comparing them to 55 (30 male, 25 female) adult Jomon Neolithic crania. The intent was to study the apparent trend toward cranial thinning in the last 4,000-9,000 years. While such studies of gross reduction over time are outside the realm of this project, there were significant differences in the modern crania noted between males and females. Six points were measured on each cranium; right and left frontal eminences, bregma, right and left parietal eminences, and lambda. The researchers did conclude a slight left-side predominance in the frontal and parietal eminences which did not reach significance for either sex. Female means were significantly greater than the male means at the frontal and parietal eminences of both sides. Bregma and lambda did not follow suit in female predominance. A Mahalanobis D-square distance of 1.53 showed that the centroids of the male and female were significantly different. A frequency distribution of the discriminant scores produced similar results showing different male and female means at left frontal eminence, bregma, left parietal eminence, and lambda. The Jomon skulls were, overall, thicker than modern populations and the male was thicker than females in each sample.

This same line of investigation was used by Smith, Wax, Becker, and Einy (1985) on the skulls of 111 adults from Jordan and Israel (12,000 - 1,800 years B.P.). Again, while pre-historical studies of populations from this time may be outside the scope of this study, the researchers did note a trend toward thickness reduction in the cranium as a whole. They noted, however, that reduction in cranial thickness was less dramatic in the frontal regions than in the posterior portions of the skull and that the frontal regions of the female crania seemed to maintain an overall dominance in thickness over the frontal regions of the male as the age of the skulls became more contemporary. Thickness was measured at bregma, vertex, lambda, and at nasion. No significant difference was noted between the sexes in the thicknesses recorded, yet a trend was noted in that there was a tendency for the skulls to be thicker in individuals of greater age.

Several other authors have produced research investigating the various aspects of cranial growth and development and considering an individual's sex as a possible contributing factor in bone growth. Ohtsuki (1977) looked at possible sexual dimorphism as it related to various aspects of the developing cranium in 118 modern human fetuses from the fourth inter-uterine month to term age. Sexual dimorphism usually cannot be detected in the bones of such young individuals as was borne out by the findings. Bibby and Dundee (1979) looked at gross cranial size and internal space by measuring various angles of the facial cranium and the mandible. While thickness of the skull was not a part of the analysis, their results after measuring 144 white males and 124 white females on radiographs led them to conclude that males had, on average, an 8.5% larger cranium than females at most angles studied. Other authors producing research on possible effects of sex on cranial development, yet who deal little with cranial bone thickness include Sekiguchi, Savara, and Arya (1973) and Baughan and Demirjian (1978) who deal with sexual dimorphism in cranial growth rates on a more gross level. These studies are based on external measurements of the bones and how these measurements are affected by height, age, and pubertal growth spurts.

Several other authors have undertaken cranial thickness and growth/development studies, with a focus of cranial thickening in relation to age. The bones of the cranium tend to thicken well into the seventh and eighth decades of life and the patterns by which the growth occurs is of interest. Works on cranial thickness and development in relation to chronological ageing include Davenport (1943), Israel (1968 &1973) Tallgren (1974), Israel (1977), Fishman (1979), Ruff (1980), Garn, Rohmann, Wagner, and Ascoli (1967), Baer and Harris (1969), Macho (1986), Inman and Saunders (1937), and Kaye, DeCarli, Luxenburg, and Rappaport (1992).

Another category of literature on cranial thickness involves the various aspects of possible environmental and genetic effects on the complete development of the bones of the cranium which would, naturally, include the attainment of full, mature thickness. Some of the research has had an unorthodox focus. Ivanhoe (1979) studied the effects of varying degrees of geomagnetic energy and its effects possible effects on cranial thickness. The study focused on how the fluctuations throughout time have produced both variation *and* non-random distributions of cranial thickness among populations living during times of change in the geomagnetic forces of the Earth's shifting magnetic field. The brain produces electromagnetic discharges during normal function; as humans have shown a tendency toward left-hemispherical dominance in brain morphology, the skull has responded with thickening of the bones in that region. Ivanhoe postulates that the thickening of the bone is in response to higher levels of electromagnetic output in that portion of the brain. Ivanhoe thus supports the theory that cranial, and in fact full body gross morphology, is more plastic than genetic in nature.

Other researchers contributing to the body of literature on cranial thickness and maturational development include Giblin and Alley's (1944) study of the means by which the skull responds to the fixation of the coronal suture. Pucciarelli (1980), and in a follow-up study, Dahinten and Pucciarelli (1981), look at the way that age, sex, and nutrition may effect the development of the skull and the expression of discontinuous traits in rats. Olivier (1969) added a study measuring and comparing the skulls of Neanderthals to the average thicknesses of cranial bones at 4 points (frontal eminence, parietal eminence, obelion, and asterion) and found the Neanderthal means to exceed that of more modern populations by a significant margin. Finally, Regodon, Franco, Robina, and Lignereux (1991) study the internal cranial volumes of two breeds of dogs in order to determine whether inter-racial and gender differences can be determined by cranial volume. Of the sample of 70 (35 males and 35 females) dogs, of two different breeds, a 99.95% minimal confidence level was achieved in discriminating between the breeds and larger-skulled males as opposed to the small-skulled females.

In summary, the literature on this subject is somewhat scanty and presents mixed results as to the value of sex in determining cranial bone thickness. If we are to believe Roche (1953), Young (1957), Adeloye, et al. (1975), and Pensler and McCarthy (1985), then there seems to be support for the theory that males and females may differ significantly in the area of cranial vault bone thickness. Others may postulate that brain morphology or "handedness," like LeMay (1977), may account for the varying degrees of thickening seen in the skulls of different individuals of both sexes. If this is so, then the effects of these differences may require further research.

CHAPTER 2

MATERIALS AND METHODS

The materials consisted of 126 crania: 31 from the University of Tennessee Bass Collection and 95 specimens from the Terry skeletal collection curated at the Smithsonian Institution in Washington, D.C. All of the skulls were previously autopsied prior to curation to allow greater access into the cranial vault. Some forensic specimens were eliminated from the total pool of crania available due to limited vault access from gunshot apertures or blunt trauma damage only. Those skulls missing portions of the bones upon which measurements were taken were rejected.

The sample consisted of 22 black males with ages of 18-72 years, 38 black females with ages of 24-97 years, 29 white males with ages of 12-73 years, and 29 white females with ages of 25-91 years. Further information on the sample measured can be found in the Appendix.

All of the measurements were taken by this investigator with prior knowledge of the particular specimen's age, race, and sex. The points measured were chosen with reference to research of a similar nature (see Literature Review) and based on cranial landmarks and points as defined in Bass (1987) and in Krogman and Iscan (1986). The purpose was to explore possible differences in sexual dimorphism in areas of the cranium not yet measured by other researchers. With this in mind, points were chosen which, for the most part, were not along sutures and were not along the exact sagittal plane of the skull (see Figs. 1- 4, pages 12-19).

All measurements of thickness were taken with hinge calipers. Points were located on the surface of the crania using sliding calipers

Figure 1

Frontal view of the skull indicating the relative positions of measurements 1 - Nasion-Bregma Midpoint, 2 - Left Lateral of Nasion - Bregma Midpoint, and 9 - Right Lateral of Nasion-Bregma Midpoint. The points indicate the ideal position of the point of measure for each skull yet the actual point of measure can be, and not infrequently, has been moved within several millimeters to avoid endocranial irregularities. Distances and indications of distance are not to scale.

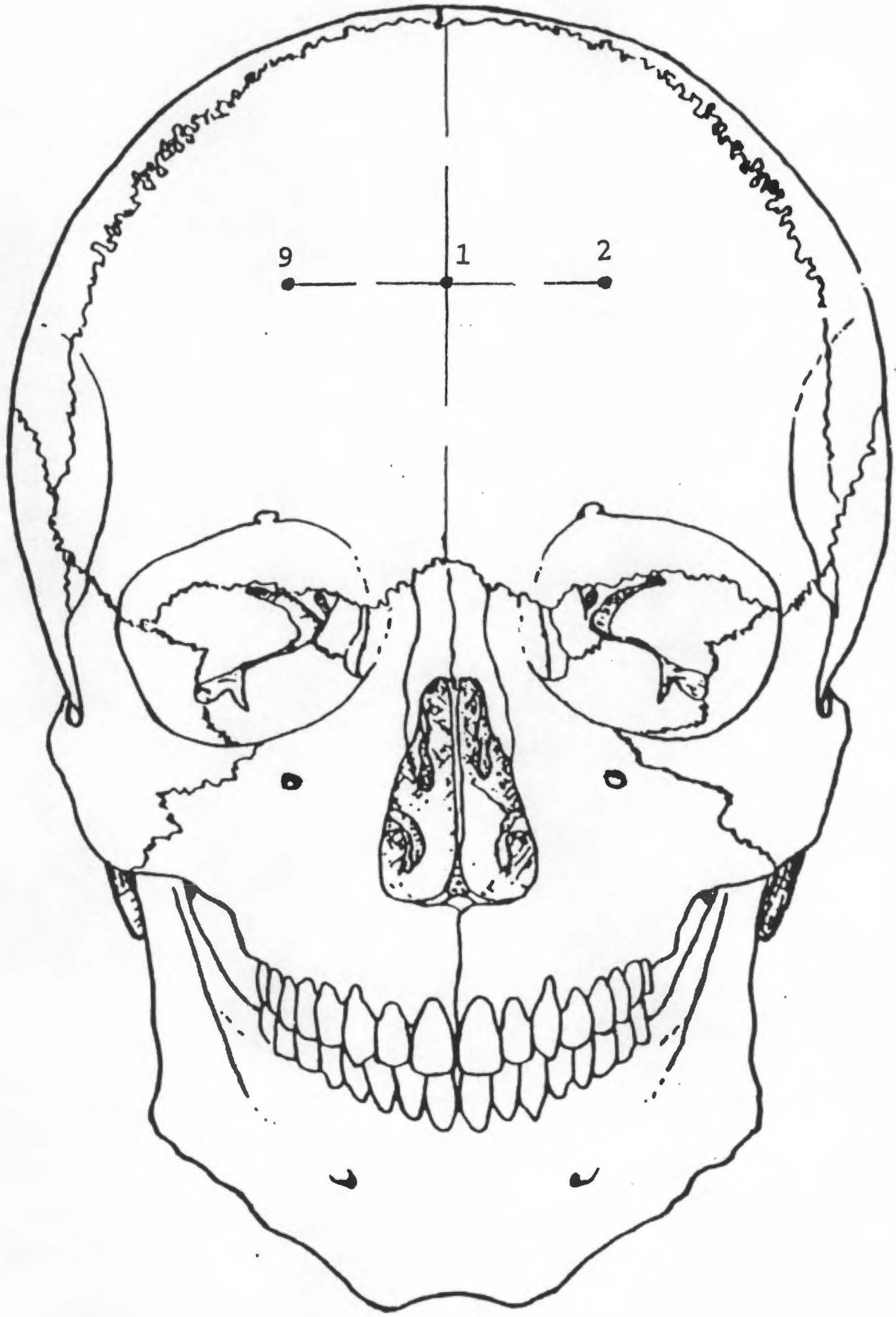
9
1
2

Figure 2

Left lateral view of the skull indicating the positions of points 2 - Left Lateral of Nasion-Bregma Midpoint, 3 - Postero-Lateral of the Coronal/Sagittal Intersection, 4 - Inferior Temporal Line measurement, 5 - Mid-Parietal Left, 6 - Posterior Parietal measurement, and 7 - Occipital Latero-Inferior of Lambda. Measurement 7 may not necessarily coincide with the title of the point so designated for every specimen. Morphological differences may place the point more lateral then inferior of lambda. Points 9 - 14 oppose on the right side of the skull.

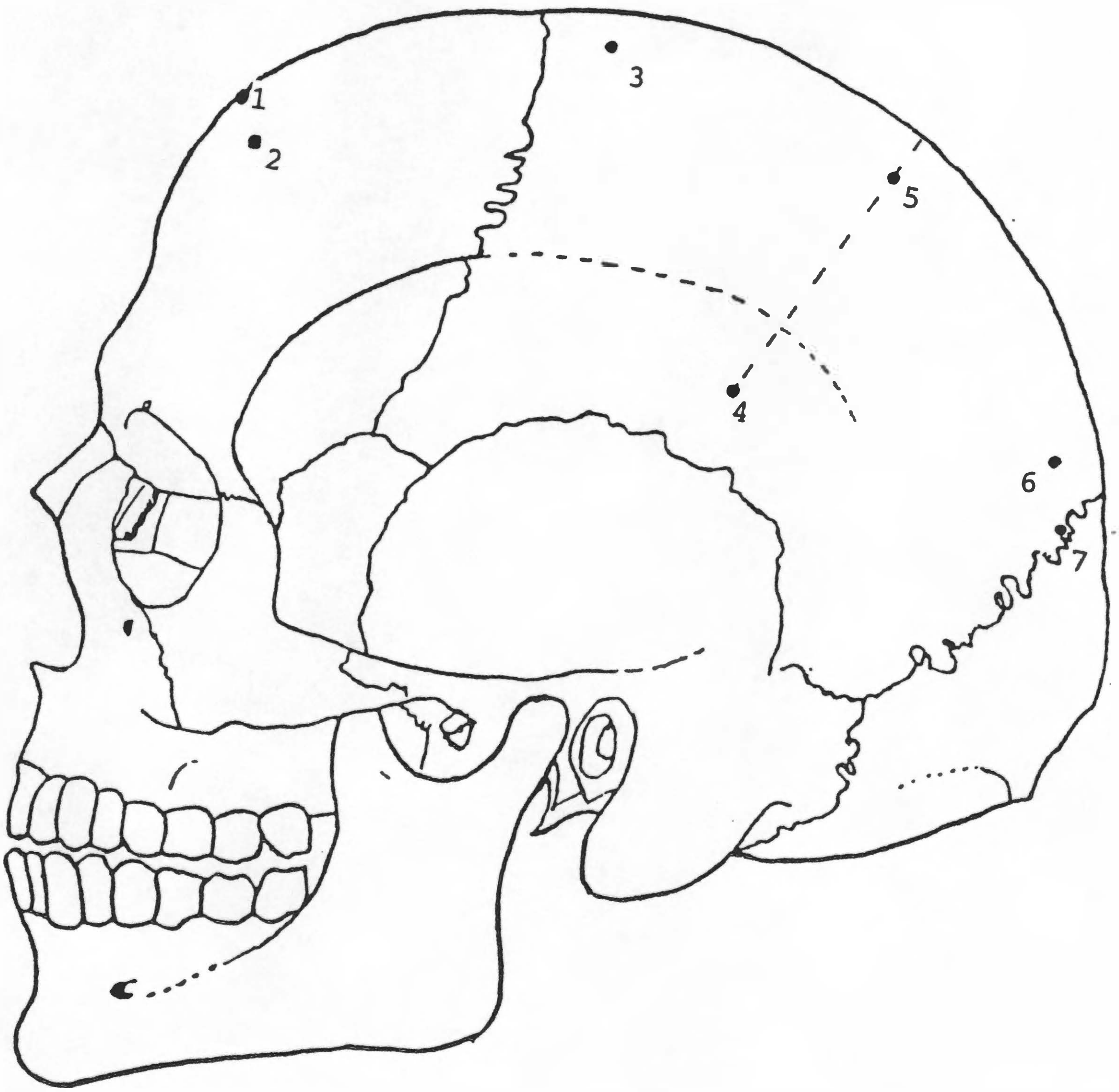
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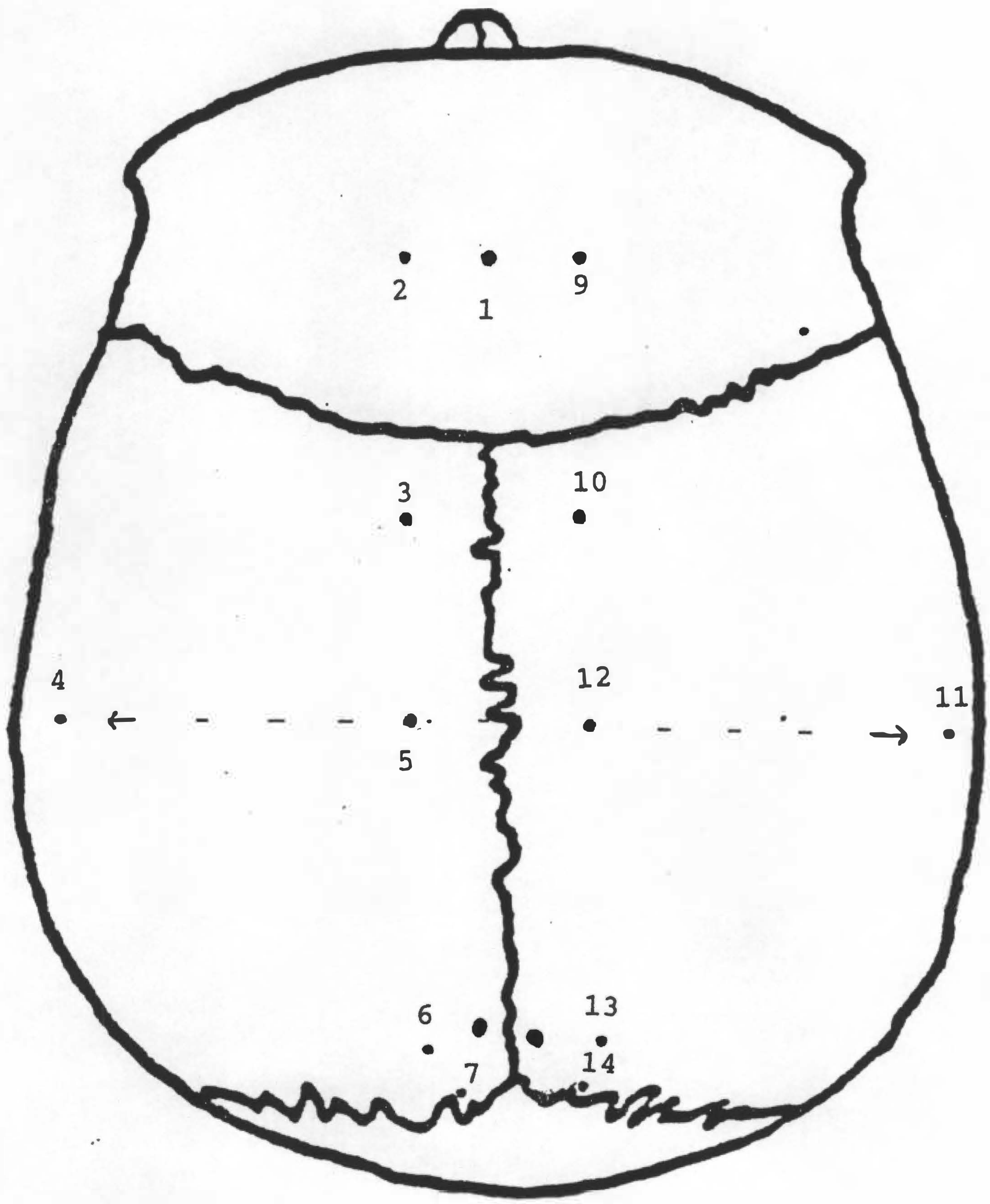
Figure 3

Superior view of the skull indicating the positions of the points measured on the calotte.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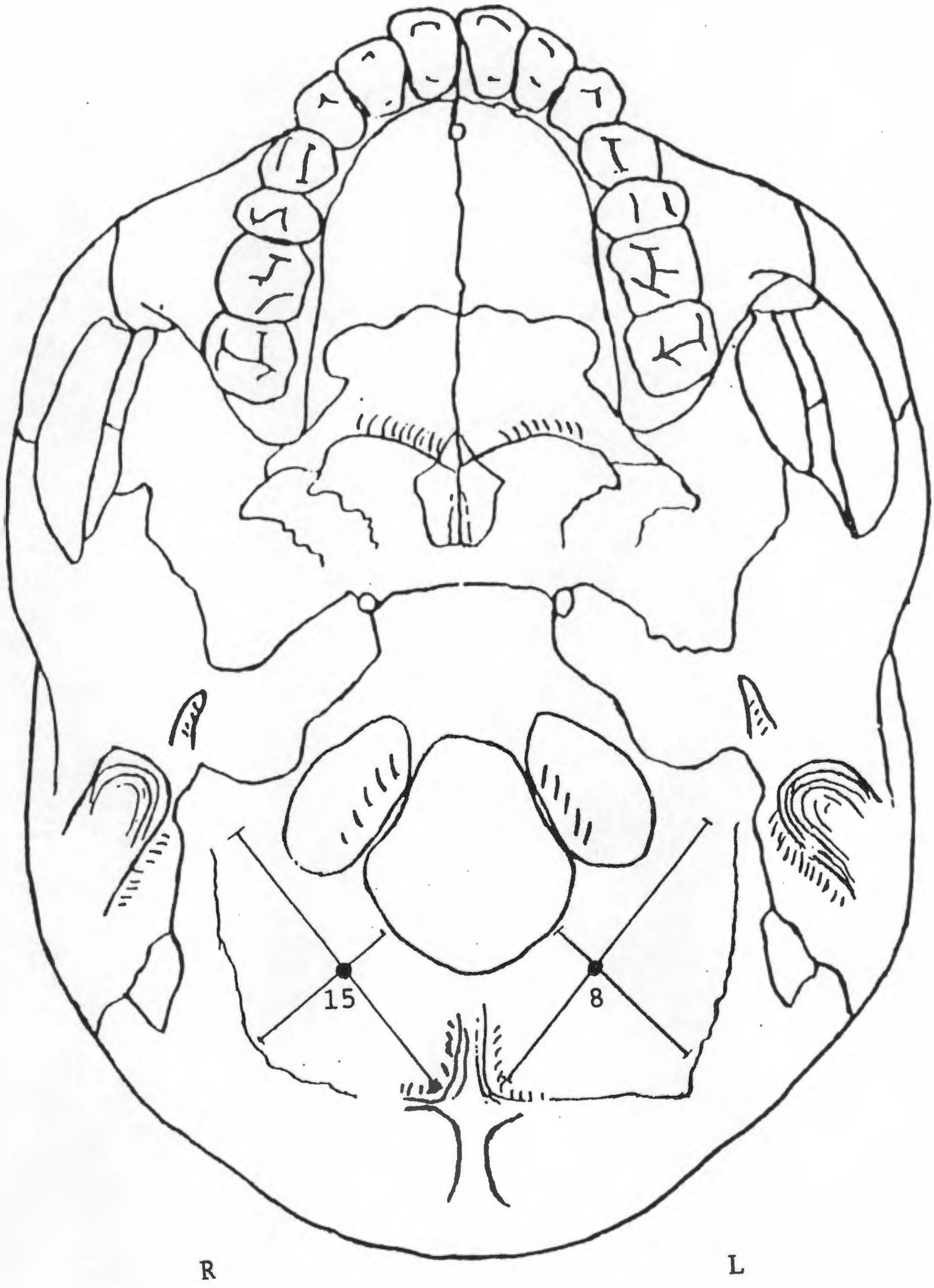
14

Figure 4

Basilar view of the skull indicating the positions of measurements 8 - Occipital Latero-Inferior of the External Occipital Protuberance Left and 15 - Occipital Latero-Inferior of the External Occipital Protuberance Right.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whose points were set at 2.54 centimeters, and in the case of the Inferior Temporal Line measurements, a ruler and piece of string or flexible straight-edge. Marks were made on the calvaria using a number 2 pencil. All points were subsequently erased.

The benefits of using autopsied crania in this sample are that the calvarium can be removed to allow inspection of the internal cranial vault table. The purpose is to avoid extra inner-table features or anomalies which may invalidate the measurement. All points measured can be adjusted up to 10 millimeters from the original point. The object was to gain a measure of thickness for a region of the bones, not a single point.

The Anthropology department at the University of Tennessee did not, at the time of actual measure, own calipers large enough, or with deep enough "arms," to allow for accurate measurement of points along the mid-line and mid-parietal region of the calotte without the measurements being taken on the sides caliper tips. Therefore, two sets of calipers were created for this study in consultation with Dr. William M. Bass, Dr. Richard L. Jantz, and Mr. Ken Thomas of the University of Tennessee College of Engineering.

The only literature available on the subject of tools used to measure such remote portions of the cranium was a work by Munizaga (1962) who developed a device for measuring unautopsied skulls through the foramen magnum using straight metal rods on both the stationary and mobile surfaces of an osteometric board. The distance between the rod tips, one of which was in contact with the endocranial surface the opposite on the ectocranial surface, would be the thickness of the bone in that region. Though advantageous certainly, this device would only be useful in measuring bone thicknesses in line with the foramen magnum.

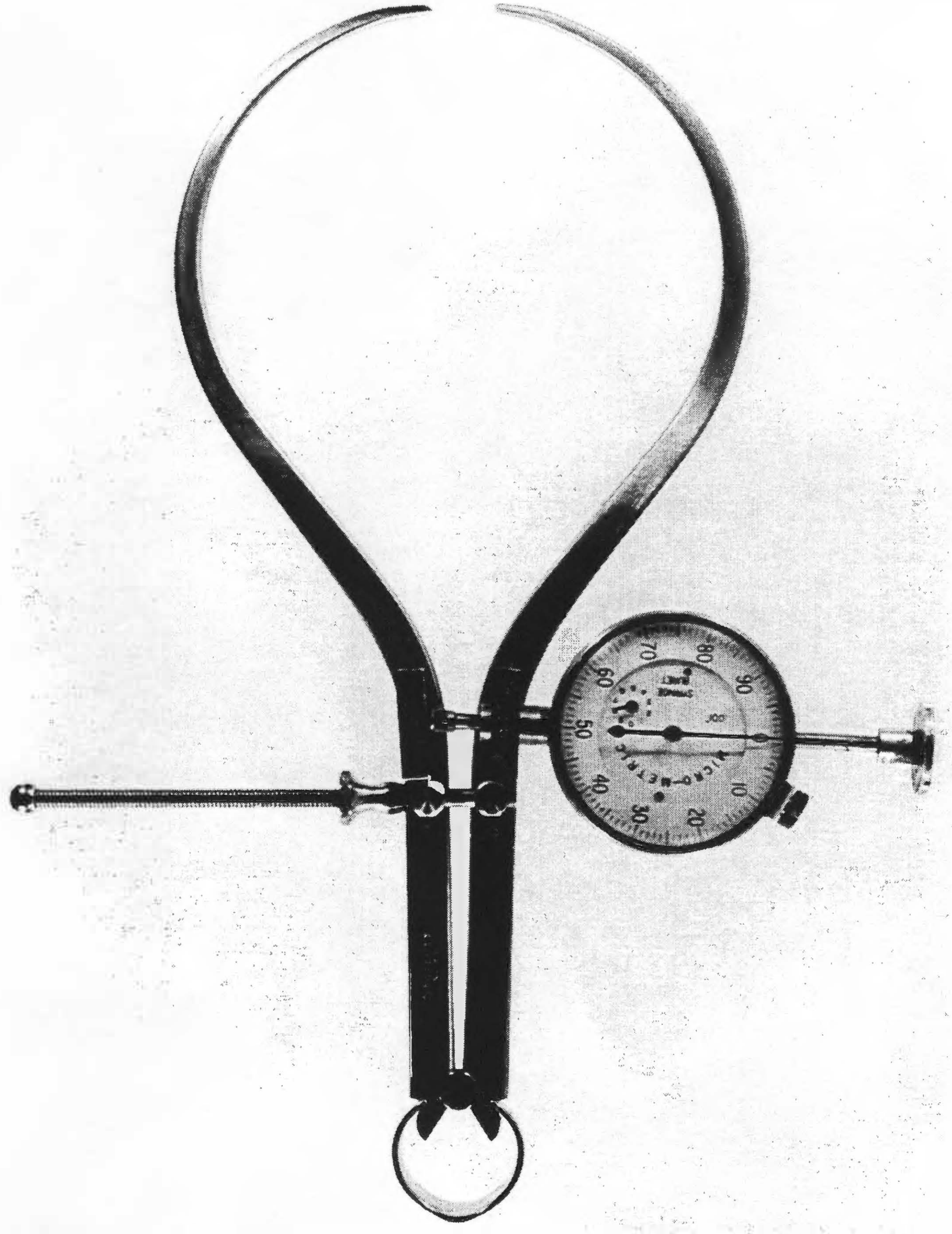
Two sets of calipers with 10 and 12-inch arms were ordered through the College of Engineering. These calipers provided greater access to the para-sagittal region and produced more accurate measurements of thickness. These instruments allowed for more reliable measurements on the caliper's tips. Measurements on the edges of the tips tend to produce thicker readings.

The Steritt 10-inch and 12-inch calipers were fitted with a Syringe Buret dial which measured in thousandths of an inch. Calipers of two sizes were requested to deal with the wide range in variation in cranial size. Some skulls were longer or taller and the extra two inches of arm were required to measure along the sagittal plane. A single dial was donated by the College of Engineering for interchangeable mounting on each caliper. This would allow for removal of the dial in order to transfer it from one tool to the other in the event of damage to the equipment, or for measurement of an unusually large or small specimen. The mountings were constructed by Mr. Thomas. As fate would have it, the full range of morphologies encountered could be measured reliably with the 10-inch calipers of our creation and with Greupel hinge calipers donated both by the University of Tennessee and by the Smithsonian Institution.

Since the dial was mounted on the stems of the calipers, the dial was only measuring the distance between the stems themselves, not the tips. To obtain measurements from the tips of these calipers, a pair of C.E. Tools digital calipers were donated through the College of Engineering. The tips of the calipers were set at exact distances from .5 millimeters to 15 millimeters with points at every one-half millimeter interval in between and verified with the digital calipers. Once the proper dial setting for a certain distance distance was obtained the reading was recorded and the next half-millimeter added and verified digitally. The distance, as read by the dial between half-millimeter measurements, was constant. Dividing this distance in half and recording that reading would produce a rounding point from which a measurement of the next one-half millimeter measurement would be recorded. A chart of these dial readings was created by this investigator in order to facilitate quick reference in determination of thickness. Examples of the various methods in which measurements were taken and a close-up view of the 10-inch calipers are available in Plates 1-5.

Plate #1

Photograph of 10-inch calipers used in the measuring of most of the crania included within the sample. The positioning of the dial in such a manner makes apparent the reason for an unorthodox system of measures. The reading on the dial is not concordant with the distance between the caliper tips thus producing the need for such a complex system of obtaining a fairly simple reading.


70
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.001

Plate #2

Measuring a point on the frontal bone on an autopsied specimen from the Bass Collection. The pictured cranium is included in the sample. Photograph is included to demonstrate the ease by which a measurement is taken using a two-handed grip on each arm of the caliper. The point being measured here is superior to the Nasion-Bregma Midpoint (#1) and was utilized for demonstration purposes only. According to the analysis done here, this portion of the frontal bone was not measured.

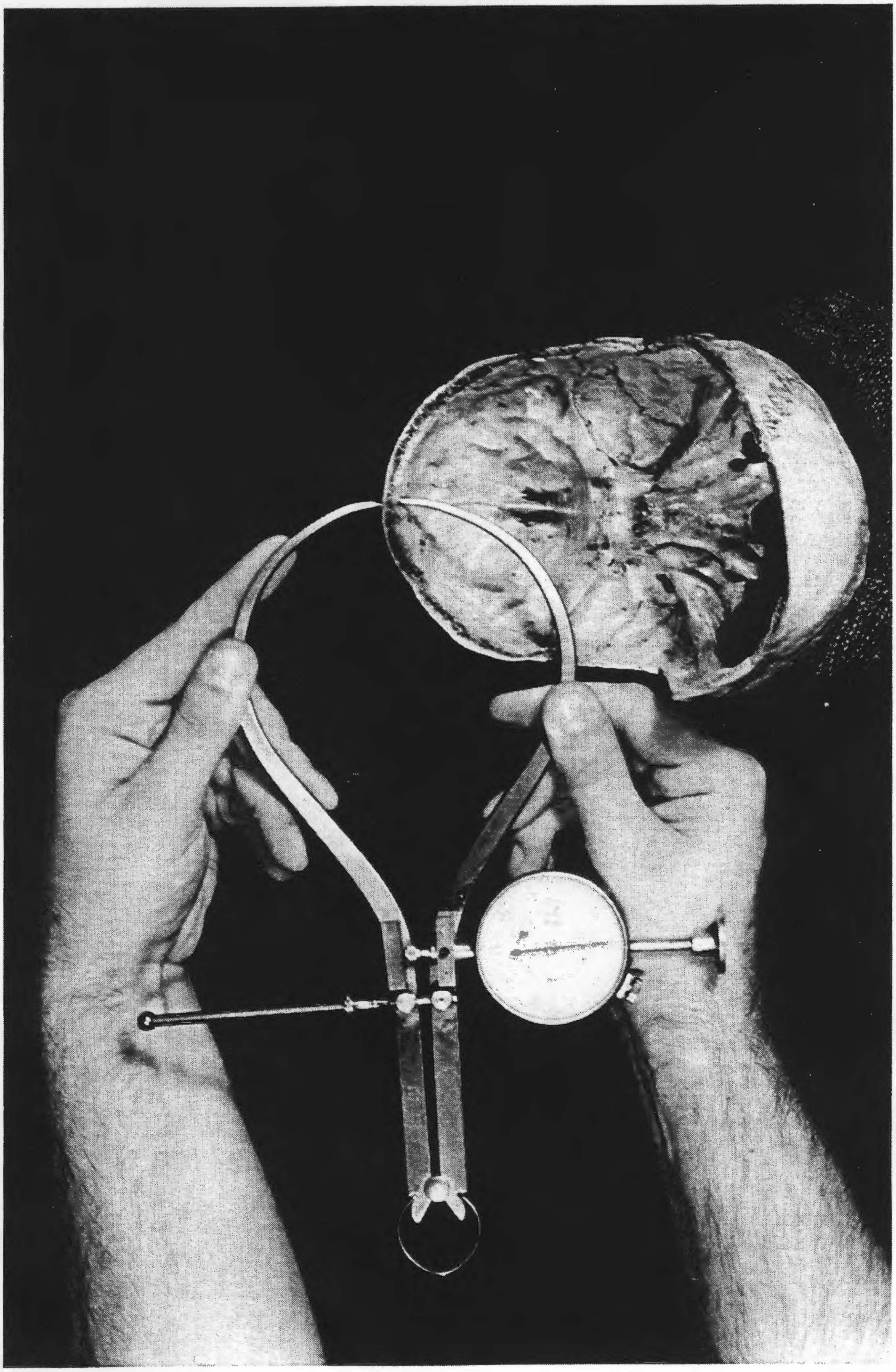


Plate #3

Close-up shot of the caliper tips as seen in Plate #2. Note the position of the tips and of the arms of the caliper as they are as close to perpendicular to the bone being measured as possible. Again, the point chosen here is for demonstration purposes only, this point was not used in this analysis.

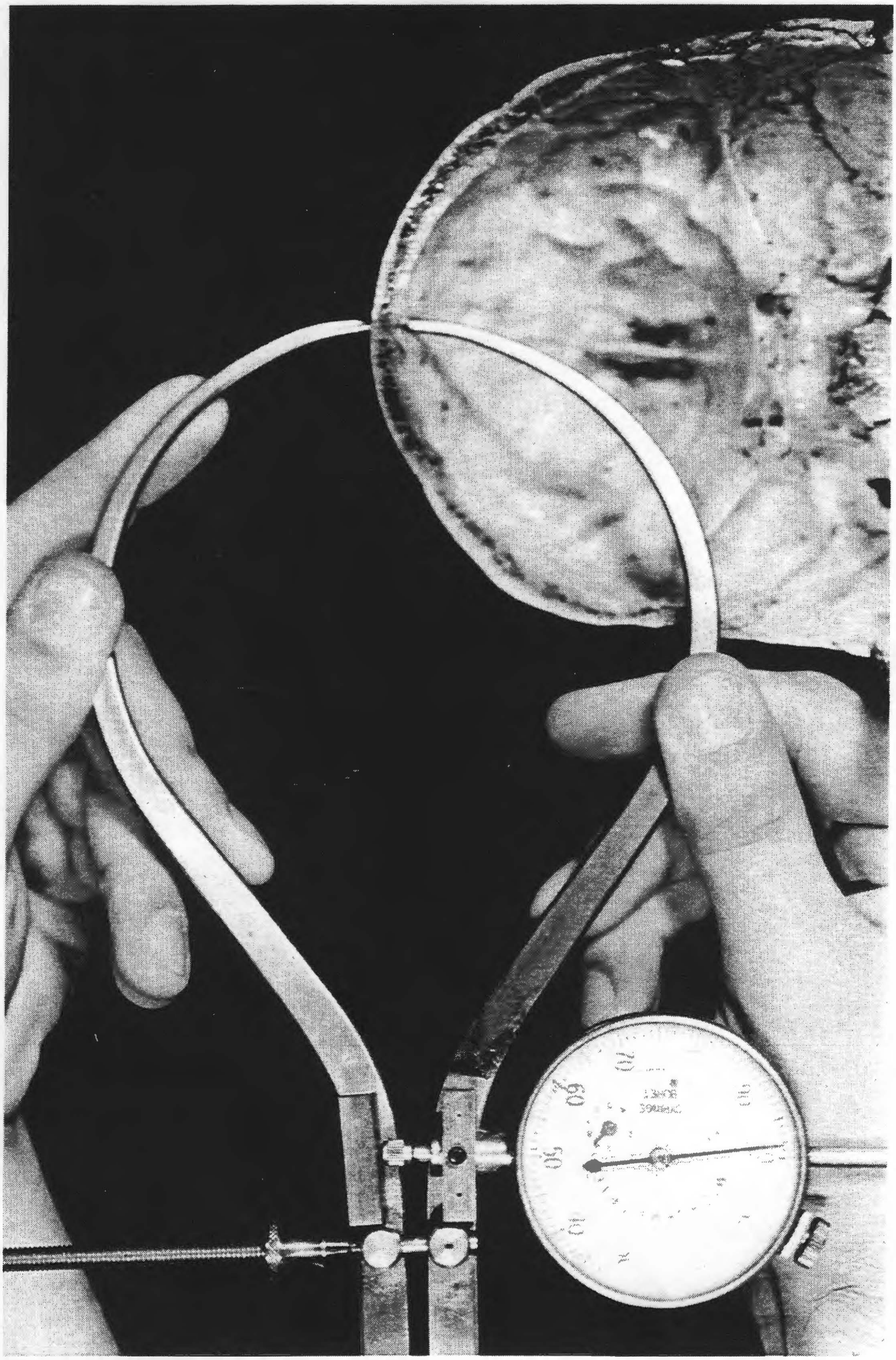


Plate #4

Measurement taken on the occipital bone. Here the calipers are inverted to take measurements on the squamous portion of the occipital bone. The dial does not slip in such a positioning of the tool due to the mounting with an Allen's screw. The point being measured is along the sagittal mid-line of the skull and was not included in this analysis. This point was chosen to illustrate another method for taking these measurements.

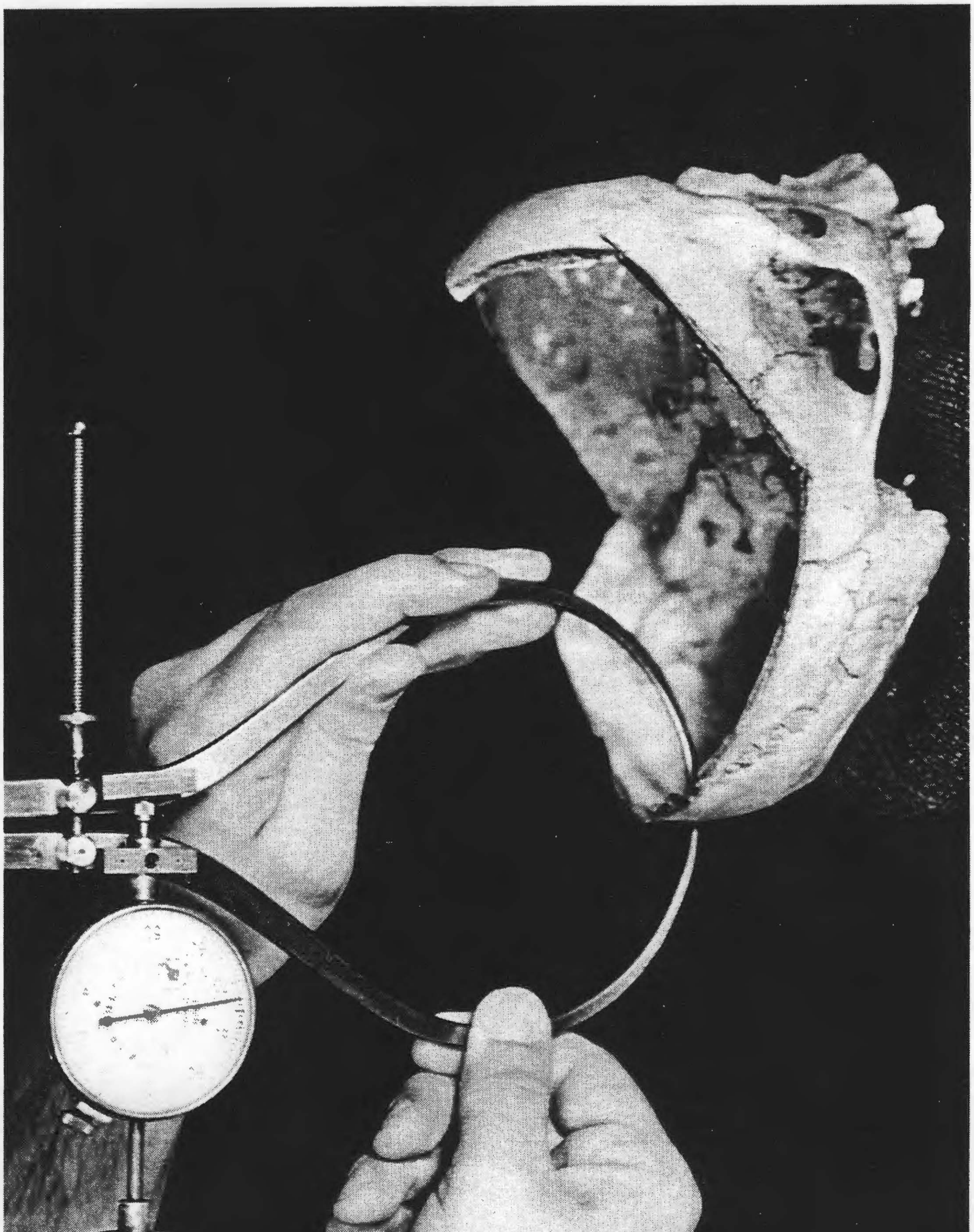
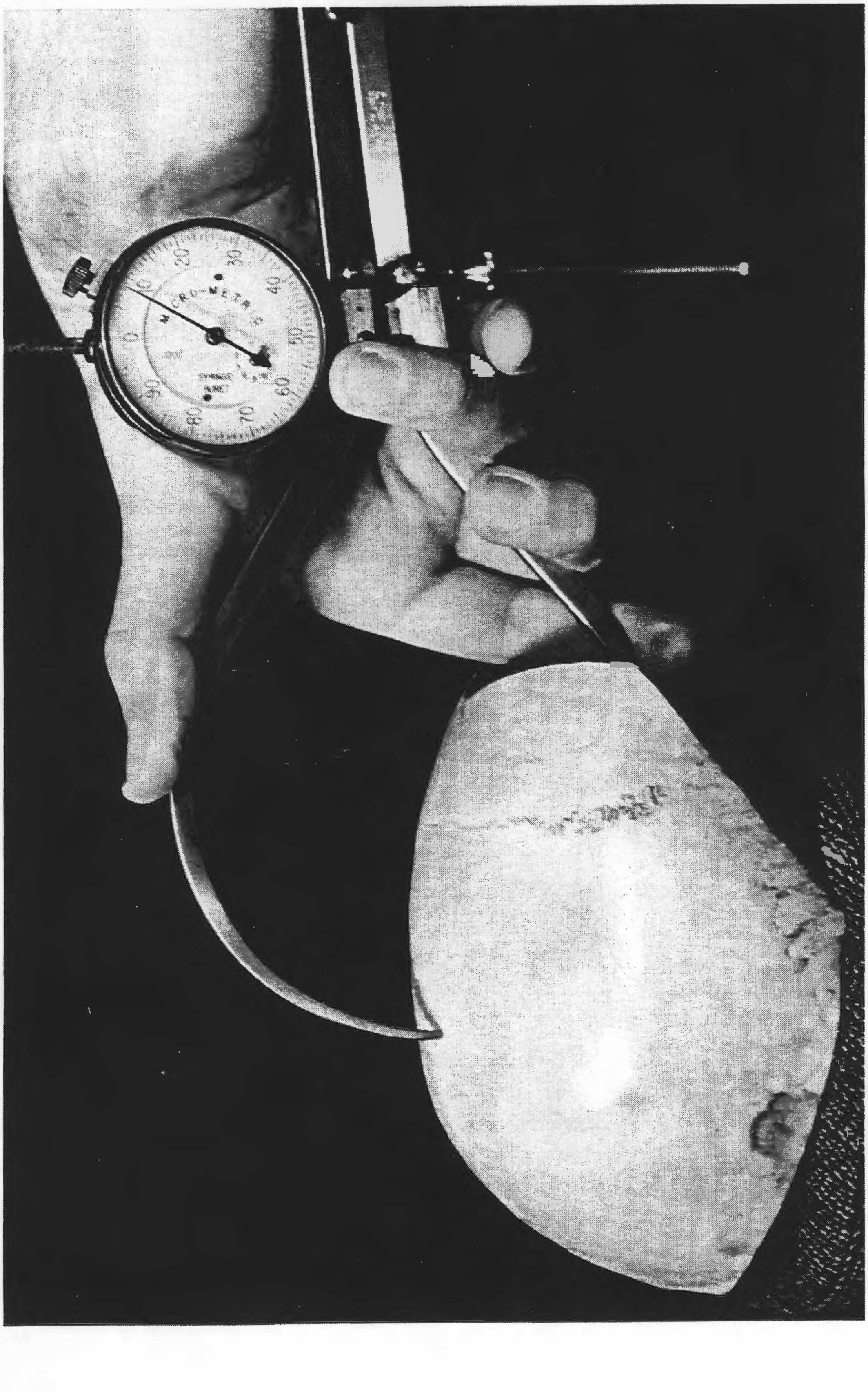


Plate #5

Measurement taken using the one-handed grip on the spring-loaded calipers. Pressure is applied on the lower arm of the caliper while the upper arm's tip rests on the point desired. Pressure continues until contact is made with the inner table of bone at which time the reading is taken from the dial and recorded for conversion into one-half millimeters. The point being measured here was chosen for illustration only.


MICRO-METRIC

On the frontal bone three points were measured (Fig.1): 1, Nasion-Bregma Midpoint (NMB) derived by two measurements to account for the curvature of the bone; (2), 2.54 centimeters left lateral of the NMB; (9), 2.54 centimeters right lateral of the NMB in line with both points 1 and 2. The points were, at times, adjusted within 10 millimeters of the original point to avoid internal vault features such as the frontal crest, bony nodes or depressions in the bone due to pathologies, arterial grooves, etc. The adjustments were made both superior to the original point of measure, or either left or right laterally. The point is subjective since what is sought is smooth tabular bone to give an accurate measure of true bone thickness.

On the parietals measurements were paired. Here, each measurement had its own counterpart on the opposing bone (see Fig. 2). Left parietal measurements (right parietal measurements being identical) include: (3), Postero-Lateral of the Coronal Sagittal Intersection taken 2.54 centimeters down from the Coronal-Sagittal intersection and then 2.54 centimeters posterior/superior to that point on the suture; (4) Inferior Temporal Line (ITL) taken 2.54 cm. inferior to the superior temporal line in line with the mid-parietal measurement; (5) Mid-Parietal, taken 2.54 cm. lateral to the right of the midpoint of the parietal bone as measures along the sagittal suture; (6), Posterior Parietal taken 2.54 cm. down the suture from lambda and then 2.54 cm. superior to this point on the lambdoidal suture; (7), Occipital-Infero-Lateral of Lambda taken 2.54 cm. lateral and inferior to the point of Lambda on the lambdoidal suture on the parietal edge (see Fig.3). In opposition to these points, on the right parietal are measurements 10, 11, 12, 13, and 14 which are located exactly opposite to those on the left parietal bone.

On the occipital bone, two points were chosen adjacent to the foramen magnum (see Fig.4): (8), Occipital-Latero-Inferior to the external occipital protuberance taken at the intersection of maximum length measurement and maximum width measurement of the depression adjacent to the foramen magnum. Point 15 is taken in the same manner as point 8 on the opposite side of the internal occipital crest.

According to other researchers (Adeloye, *et al.* 1975, Israel, 1977, Hunt, 1992 - personal communication), thickening of the bones of the cranial vault occurs throughout life, and especially during the later decades past 50 years. Nowhere is this trend more evident than in the frontal bone, as the studies cited earlier have indicated. This pattern is most discernable in females and has been noted in black and white individuals of both sexes. This trend shall be analyzed here to see if the increase is significant between both sex and race. Analysis will also be used to determine whether this trend invalidates or supports sex determination in this area of the cranium.

Analysis of the data was performed utilizing the Statistical Analysis System (SAS) with reference to methods described in the SAS instruction manual, Klecka (1980), Ott (1988), and Afifi (1990) for the purpose of familiarization with the various procedures and analyses. Suggestions for guidelines in the analysis were solicited from Drs. Jantz and Konigsberg. Steve Ousley and Beth Wilson aided in the actual analysis on the computer systems.

CHAPTER 3

DATA ANALYSIS

As stated earlier, the analysis of the data produced during measurement was accomplished using the SAS statistical package. The first steps taken with the analysis were to test whether the groups were equally variable in order to determine the best model of discrimination. The next step was to run a multivariate analysis on all the measurements to elucidate the most telling points in discriminating between the sexes and then to see how well reduction of the data would improve the model. Next came finding exactly where the differences between the sexes were the most pronounced, and to what extent one sex was dominant in overall cortical bone thickness. Finally, the effects of age and collection were tested in order to try to tell if chronological age added any information in determining the thickness patterns observed and then to see whether the patterns were effected by being part of a specific collection. This last step was added as there are temporal differences between the Terry and University of Tennessee Forensic Collection specimens which could account for some of the differences in thickness.

The first step in the analysis consisted of testing the within-group variance in order to determine whether a standard discriminant model could be used. The null hypothesis for the variance states that the variances for both the male and female groups are equal and thus a significant *p*-value would reject this hypothesis thereby suggesting a different model in order to account for the unequal variances. The hypothesis was tested using a chi-square test from SAS and was tested at an alpha of .001. A *p*-value of .0053 was produced which though low, still allowed for a pooled covariance matrix to be used for the discriminant analysis. As the variances can be considered equal, a standard discriminant model was then selected.

A preliminary cross validation of the data was run for the purpose of obtaining an initial hit rate as to how many males and how many females were being correctly identified by the model itself. The cross validation used here left one specimen out and ran analysis without that specimen in order to place it correctly in its most likely sex group. Of the 59 males in the sample 38 (64.41%) were correctly classified as male by the simple discrimination. Of the 67 females in the sample, 46 (68.66%) were correctly classified as being female. This cross validation, which disregarded race, age, and membership in a certain collection, produced a hit-rate of 66.53% correctly classified into the proper sex-group. The null hypothesis to be rejected here is one in which the proportion of skulls correctly classified into their proper sex group by the model is no better than random chance (50% of being male or female). A chi-square test was run to see if the proportions of males and females correctly classified by the model is greater than the 50/50 chance proportion. A value of 13.774 was produced yielding a highly significant *P*-value of .0002.

As expected, an analysis of the points themselves revealed that some points chosen for measurement were more informative than others. In order to try to improve on the model used above, certain points may not be necessary in providing the best model by which to discriminate between the sexes. The means of the measurements taken at each point are provided in Table 1 along with *t*-test values and their respective *p*-values. The object of this test was to either accept or reject a null hypothesis that the means of females exceeded the means of their male counterparts. Negative values in the *t*-test column are rejections of this null.

In addition, to show which points were most important, standardized canonical values for each point are given in Table 2.

TABLE 1

T-TEST OF MEANS FOR MALES AND FEMALES

Point	Male Mean	Female Mean	*T*-Test Value	*P*-Value
M1	6.42	7.14	2.776	.0064
M2	6.16	7.44	4.398	.0001
M3	6.10	6.37	1.072	.2850
M4	4.54	5.06	2.302	.0230
M5	7.20	7.63	1.529	.1287
M6	6.42	7.06	2.426	.0166
M7	6.64	6.52	-0.489	.6275
M8	3.77	2.93	-2.894	.0045
M9	6.14	7.52	4.816	<.0001
M10	6.11	6.47	1.345	.1806
M11	4.49	5.04	2.273	.0246
M12	7.06	7.41	1.135	.2580
M13	6.26	6.74	1.830	.0698
M14	6.46	6.31	-0.670	.5055
M15	3.65	2.86	-2.927	.0041

TABLE 2

STANDARDIZED CANONICAL COEFFICIENTS

Point	Coefficient
M9	-.6313816820
M6	-.5215835758
M12	0.4877444309
M7	0.4213566804
M15	0.3879906359
M5	-.3532097010
M8	0.3195663375
M3	0.2268308497
M4	-.2204404969
M10	0.2003197044
M1	-.1687294019
M2	-.1555307636
M11	-.1414003049
M13	-.0278036375
M14	0.0066892534

* Points are in order of greatest contribution to sexual discrimination.

The locations of these points can be viewed in Figures 1-5 and for the purpose of these tables, the points are now called M1-M15.

Differences between the sexes at each point were analyzed utilizing the General Linear Model procedure in SAS. This procedure produces a Ryan-Einot-Gabriel-Welsch test of significance of differences in mean thickness between the defined groups (sexes) at each point. The purpose here was to define where one sex was consistently thicker than the other. The tests were run leaving the significance at the p=.05 level. Table 1 shows the points where sex played the most significant role in defining the groups as separate based on thickness means. Female means exceeded the means of males at all points, save for measurements M8 and M15, to a significant enough extent to define the sexes as two separate groups based on bone thickness. Females were especially dominant at points 1, 2, 6, 9, and 11 indicating a female tendency toward thickness in the frontal regions of the skull and some tendency toward greater bone thicknesses in the lateral and medial portions of the skull. Males tended toward greater thickness in the posterior portions of the skull, especially in the area around the foramen magnum and to a lesser and insignificant extent at points 7 and 14 around the squamous portion of the occipital.

Further tests were run ignoring the effects of race and sex/race interaction. Race was likewise tested as was a sex/race interaction to see whether either factor should continue to be taken into consideration as a factor whose effects need to be assessed in order to obtain a clearer picture of the differences in thickness. Another MANOVA was run testing the effect of race; a p-value of .0613 was obtained--effectively excluding any significant racial-based effects on thickness. In the case of a sex/race interaction, a discrimination was run using the same parameters as sex and race, and all 15 points had p-values which were insignificant. Thus, a sex/race interaction was disregarded. At this point, a concentration on the effects of sexual affinity is exclusively addressed, with an emphasis toward best model selection and which factors might be added to improve the hit rate.

As shown in Table 2, the points vary in significance when contributing to the differences between the groups under analysis, thus those points which are the most telling can be focused upon in an attempt to make the discriminant model more compact. The benefits of a more compact model are simple. First, it cuts down on the amount of the information which is necessary for discrimination and second it may diminish the portions of the skull necessary to perform a discriminant analysis for a forensic specimen.

The SAS system includes a stepdisc procedure which allows for model selection, either backward or stepwise, in order to select only those points whose differences between the groups' means meet a certain level of significance in order to qualify in the model. Both stepwise and backward selection procedures were performed in order to pare down the number of points needed to discriminate based upon this sample. The level of significance was set to .20 for inclusion into a stepwise-selected model and for exclusion from a backward-selected model so that at least five points would hopefully be included in the analysis. Stepwise selection produced a best-six model including, in order of significance: M9, M8, M4, M3, M6, and M7. Backwards selection eliminated points which did not qualify at the .20 level and selected, again in order of significance: M4, M6, M7, M8, M9, and M12. The procedures thus agreed on points M4, M6, M7, M8, and M9 as a best-five model for successful discrimination between the sexes. A summary of these statistics can be viewed in Tables 3 and 4.

In order to see how well the newer model may or may not improve successful discrimination of the sexes from this sample, a new discrimination and cross-validation was run on the best-five points as selected by stepdisc. Equal variance was again tested within the new parameters, and the null hypothesis of equal variances could not be rejected (with an insignificant chi-square value of 0.1256). A higher hit rate of successful placing of specimens into their proper

TABLE 3

SUMMARY OF STEPWISE SELECTED POINTS

Point	Wilks' Lambda	*F*-Value	*P*-value	Partial R-Square
M9	.84236967	23.204	<.0001	0.1576
M8	.77389302	10.883	<.0013	0.0813
M4	.75416842	3.191	<.0765	0.0255
M3	.73803696	2.645	<.1065	0.0214
M6	.72673342	1.866	<.1744	0.0153
M7	.71044166	2.729	<.1012	0.0224

TABLE 4

SUMMARY OF BACKWARD SELECTED POINTS

Point	*F*-Value	*P*-Value	Partial R-Square
M4	3.277	<.0728	0.0268
M6	5.762	<.0179	0.0462
M7	3.203	<.0760	0.0262
M8	11.328	<.0010	0.0869
M9	15.373	<.0001	0.1144
M12	3.390	<.0681	0.0277

groups (male or female) was obtained with 69.62% accuracy (49 of 67 females and 39 of 59 males correctly sexed). A chi-square test was run on these proportion to test their significance and a value of 19.496 produced yielding a p-value of .00001 or a 1 in 100,000 chance of such an occurrence happening based on chance alone. This test allowed for rejection of the null hypothesis that the proportion of specimens correctly sexed by the best-five is no better than assignment of sex based on random chance.

A factor which has yet to be included in the discrimination is age. Here, the interest is in whether or not there was a pattern of thickening of the bones with age as is suggested by Hunt (1992) and by the various studies of maturation and age-related changes in the bony morphology undertaken by authors cited in the introduction and literature review. The parameters were determined by SAS and the factor of age was added into the discrimination. Equal variances were tested at the .001 level and a correlation was obtained in order to see how well the points correlated with each other and with age. The groups were found to be equally variable as a chi-square value of .0152 was obtained when tested. The correlation between change in thickness and age was very poor as the coefficients in Table 5 should reflect.

Finally, the material of the two temporally separated collections included here. Do statistical differences in thickness exist between the individuals of both collections (U.T. versus Terry Collection specimens)? Different sex ratios exist between the specimens measured from the two collections and this difference could possibly account for some of the differences seen here (see Appendix). A test of equal variance of both groups was performed at the .001 level and a chi-square value of .1458 resulted, meaning a pooled covariance could be used in a possible model for discrimination between the collections. Canonical discriminant analysis was performed on both samples (31 U.T. and 95 Terry specimens) and p-value of .0005 supported the contention that the means, at each point, are different for the collections (see Table 6).

TABLE 5

CORRELATION COEFFICIENTS FOR BONE THICKNESS CHANGE WITH AGE

Point	Male	Female
M1	-.08320	.20342
M2	.03560	.11433
M3	.19772	-.01463
M4	.03602	.19347
M5	.11188	.00368
M6	.06616	.02321
M7	.10922	.02567
M8	.01605	-.17794
M9	.09519	.14418
M10	.25005	.13113
M11	.10491	.20744
M12	.04660	.07394
M13	-.04479	.04317
M14	-.19243	-.15546
M15	.00715	.05296

TABLE 6

DIFFERENCES IN THICKNESSES BETWEEN COLLECTIONS

Point	U.T. Mean	Terry Mean	*P*-Value of Significance
M1	6.40	6.93	.0828
M2	6.16	7.06*	.0119
M3	5.67	6.43*	.0095
M4	4.62	4.88*	.3441
M5	6.75	7.65*	.0059
M6	6.27	6.92*	.0367
M7	6.38	6.64*	.3392
M8	4.32*	3.00	.0001
M9	6.08	7.14*	.0030
M10	5.67	6.51*	.0056
M11	4.62	4.83	.4704
M12	6.48	7.50*	.0033
M13	6.12	6.64*	.0937
M14	6.56	6.32	.3696
M15	4.20*	2.91	.0001

* Indicate points where analysis produced two separate groups based on thickness. Significance level was .025. *P* - values indicate approximate significance of difference in thickness.

Total sample standardized canonical coefficients (Table 7) illustrate which points are most informative in the differences between the collections.

These statistical analyses have shown that a significant difference exists between males and females in the area of cranial vault bone thickness. Females tend toward greater mean thickness in the anterior and medial portions of the skull while males tend to be thicker in the posterior and inferior portions of the vault and cranial base. The differences are substantial enough, according to this sample, that this discrimination method produces significantly better results than simple random assignment alone. The cause for these differences may have to do with the more pronounced frontal bossing of the forehead seen in females as opposed to males (Bass, 1987). Other explanations may be earlier maturation into adult morphology by females as opposed to males, or muscular action on the skull vault, especially in the posterior regions of the skull in the case of males. Deducing the exact causes of these differences is, again, beyond the scope of this thesis but could serve as the subject for further research.

The discriminant equations produced to differentiate between the sexes can be viewed in Tables 8 (all 15 points) and 9 (best 5 points). Measurements for each point (in half-millimeters) are entered into the equation and multiplied by the coefficient in the model corresponding to the point. Measurements should be entered into both equations with two figures, one for each equation, resulting. The larger number produced by the arithmetic on both equations should correspond to the sex of the individual to whom the skull belongs. In order to recalibrate the equations to fit the shorter best-five model, a new discriminant analysis was performed using only the best-five variables. Two new equations were produced based on the parameters created by the relationships between those five points alone.

Race has been shown to have negligible effect on skull thickness and there is no significant interaction. Investigation into

TABLE 7

STANDARDIZED CANONICAL COEFFICIENTS FOR COLLECTIONS

Point	Coefficient
M1	.0585003147
M2	.3220838146
M3	.1648503892
M4	-.1928523712
M5	-.4360399948
M6	-.1698134924
M7	-.7114340033
M8	.4880208320
M9	-.5368296997
M10	-.0445133664
M11	-.0774459354
M12	-.1741437297
M13	.2293054433
M14	.7229428493
M15	.4113946641

TABLE 8

DISCRIMINANT EQUATIONS FOR THE SEXES

Point	Male	Female
	-25.97173	-23.65177
M1	2.20881	2.05306
M2	-2.26153	-2.38394
M3	.89042	1.11024
M4	1.68489	1.45181
M5	.55516	.24954
M6	1.10045	.62735
M7	.86073	1.30193
M8	-1.17447	-.91160
M9	2.18145	1.68575
M10	.17155	.35902
M11	.24544	.10256
M12	-.58746	-.19145
M13	-.45580	-.48134
M14	1.54941	1.55660
M15	1.20860	1.55223

TABLE 9

DISCRIMINANT EQUATIONS FOR BEST-FIVE POINTS

Point	Male	Female
	-20.65512	-17.77686
M4	1.83880	1.55576
M6	0.83880	0.54864
M7	2.26753	2.68823
M8	-0.24611	0.19624
M9	1.54378	1.03542

racial differences between the sexes was not pursued here, but is seen as a course for further study. The assumed pattern of greater cranial thickness with age is not seen within the correlation matrix and is thus not supported within this sample. Adding age did little, in this case, for the discrimination and was thus ejected from further inclusion into the models for discrimination based here.

Finally, between-collection differences have been shown to exist. It appears that Terry specimens seem thicker at most anterior and medial points measured. The University of Tennessee specimens appear to be thicker in the posterior portions of the skull with general reduction in thickness at the medial and anterior points noted. There may be a trend toward overall cranial thickness reduction indicated here; yet, with the relatively short period of time separating the individuals of both collections, any grand trend is sketchy and may not be supportable. A significant difference, nonetheless, does exist, and two separate groups exist based on cranial thickness. Again, caution should be exercised here as sex ratio differences exist between the collections and should be taken into account with these findings (see Appendix for ratios from each collection).

CHAPTER 4

CONCLUSIONS

A method for discrimination between males and females based on the cranial vault thickness has been researched and pursued with some encouraging results. What has been shown here is that males and females do indeed differ in the thickness of the bones that comprise the vault of the skull. Here, a wider range of sites for measurement and a more comprehensive overview of thickness across the breadth of the skull was utilized to measure thickness differences in individuals of a wide age range. Studies in the past have been limited in the scope of their inclusiveness in both the areas of points measured and in the ages of those individuals comprising the samples.

Here, the effects of race have been discounted through analysis as a factor in thickness patterning. This result may be due to the nature of this sample. Further research into the exact effects of race in determining cranial thickness is needed. A suggestion by Hunt (1992) to pursue the notion that a pattern exists between changes in thickness of the skull and the age of the individual, specifically greater thickness with increasing age, bore no fruit here. Correlations between age and any resulting changes in thickness, either greater or lesser, were poor. Again, this may be due to the nature of this sample and might benefit from a study focused more on age-related changes in thickness in specific regions of the skull.

Females in this study exceeded the males in mean thickness in most anterior and medial (parietal) measurements, while the males provided greater thickness measurements strictly in the posterior and inferior occipital regions of the skull. Causal suggestions for this pattern were avoided, for the most part, due to being outside the main focus of this thesis. Possible suggestions include the female tendency toward bossing of the frontal bone, handedness and resulting brain morphology acting on the inner table of the frontal bone, and a larger nuchal musculature in males producing a more pronounced anchor-surface on the occipital and cranial base.

By far, the portions of the skull which produced the most striking differences between the sexes were the frontal and occipital bones. Those measurements on the parietals and temporals (if the lateral measurements did indeed fall on the temporals) were less divergent between the sexes and closer groupings of the specimens of both sexes occurred.

A method for reducing the number of measurements needed to discriminate between males and females was also suggested. By utilizing stepwise and backward selection, a best-five-points model was produced which increased the overall hit-rate of correct discrimination from 66.53% correctly sexed to 69.62%, a difference of around four individuals. The limitation to this method lies in the fact that coefficients cannot be picked out of the equations to match whatever points are available on a skull for measurement. Each of the coefficients in the equations are dependent upon all fourteen others. A new set of coefficients would have to be produced using SAS, or any other statistical package, and be based on the points available for measure and the original data set. Here, a new set of equations was devised using only the best five points (M4, M6, M7, M8, and M9) as new parameters, thus eliminating the effects, reflected in the original equations, of the ten points discarded.

Thus, it appears that for best results, all fifteen points need to be measured. The problem,obviously, is that to measure all fifteen points, access to the entire cranial vault would be necessary. The crania from forensic cases may not always allow for this as individuals do not always die from trauma to the cranium, but from other portions of the body, and an autopsy of the skull in order to gain access to the interior of the vault may neither be feasible nor expedient.

Finally, the differences in thickness between members of the two collections represented here were analyzed and distinct differences were noted. The members of the Terry Collection exceeded those of the U.T. Bass Collection in cortical thickness at most of the points anterior and superior to the lambdoidal suture. The more modern U.T. specimens were thicker than those of the older Terry Collection only in the posterior portions of the skull. One reason for the pattern seen here could lie in the skewed sex ratios for males and females measured (see Appendix). The exact nature of the differences is not known and could benefit from research focused more on the differences between the populations.

In conclusion, this researcher wishes to add that refinement of this study is planned and that modifications of the method of both measurement and application are still pending which may be pursued in a dissertation and that further studies of the effects of race, age, and antiquity (if applicable) may be addressed. A valid method of sexual discrimination for human identification purposes has been touched upon and could provide a stable of reliable techniques by which the science of Forensic Anthropology could benefit greatly.

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Appendix

SEX AND RACE RATIOS FOR THE COLLECTIONS

<u>Terry Collection</u>

White Females = 27

White Males = 15

Black Females = 36

Black Males = 17

n = 95

<u>Bass Collection (U.T.)</u>

White Females = 2

White Males = 18

Black Females = 2

Black Males = 9

n = 31

MEANS AND STANDARD DEVIATIONS FOR THE SEXES

Point	Male Mean	S.D.	Female Mean	S.D.
M1	6.42	1.389	7.14	1.499
M2	6.16	1.442	7.44	1.776
M3	6.10	1.428	6.37	1.404
M4	4.54	1.304	5.06	1.251
M5	7.20	1.658	7.63	1.503
M6	6.42	1.660	7.06	1.311
M7	6.64	1.476	6.52	1.154
M8	3.77	1.512	2.93	1.712
M9	6.14	1.556	7.52	1.658
M10	6.11	1.509	6.47	1.419
M11	4.49	1.317	5.04	1.400
M12	7.06	1.917	7.41	1.458
M13	6.26	1.587	6.74	1.379
M14	6.46	1.357	6.31	1.208
M15	3.65	1.520	2.86	1.491

MEANS AND STANDARD DEVIATIONS FOR THE RACES

Point	Black Mean	S.D.	White Mean	S.D.
M1	6.65	1.365	6.95	1.599
M2	6.92	1.773	6.75	1.724
M3	6.30	1.355	6.18	1.485
M4	5.03	1.192	4.59	1.372
M5	7.73	1.649	7.12	1.467
M6	7.10	1.567	6.41	1.380
M7	6.82	1.248	6.33	1.339
M8	3.61	1.859	3.02	1.397
M9	6.89	1.755	6.87	1.755
M10	6.40	1.490	6.20	1.447
M11	5.08	1.468	4.47	1.229
M12	7.56	1.651	6.92	1.683
M13	6.95	1.468	6.07	1.396
M14	6.55	1.391	6.20	1.132
M15	3.47	1.733	2.98	1.302

VITA

Butler Fuller is a native of Virginia presently residing in Baton Rouge, Louisiana and in pursuit of advanced degrees in anthropology at the University of Tennessee at Knoxville. He received a membership in the Phi Eta Sigma freshman honors society for honorable academic performance in 1986. Following in 1987 came an invitation to join the Golden Key honors society. A Bachelor's degree in the Arts, with honors, was awarded to Mr. Fuller on August tenth of 1990. Mr. Fuller has been awarded a Masters degree in Arts in Anthropology, with a concentration in Physical Anthropology on August twelfth of 1994.