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Caliber Estimation from Cranial Entrance Defect Measurements

Ann H. Ross
University of Tennessee, Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Ann H. Ross entitled "Caliber Estimation from Cranial Entrance Defect Measurements." I have examined the final electronic 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, Major Professor

We have read this thesis and recommend its acceptance:

Richard Jantz, Murray K. Marks

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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A Thesis
Presented for the
Master of Arts
Degree
The University of Tennessee, Knoxville

Ann H. Ross
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Finally, I would like to dedicate this thesis to my parents, Elena and Michael Ross. Their guidance and affection has made this possible.

ABSTRACT

Estimation of caliber from entrance defects has long been rejected by forensic scientists. However, previous studies have been from the viewpoint of the forensic pathologist, and because their focus is usually upon soft tissue, therefore this is a role for the forensic anthropologist to pursue. Consequently, this study examined the relation between caliber and cranial entrance defects and maximum cranial thickness.

The calibers considered in this inquiry were .22, .25, .32, and .38. The sample consists of 73 specimens obtained at autopsy (thirty-seven of .22 caliber, five of .25, six of .32, and twenty-five of .38). The strength of the relation between caliber, minimum diameter, and maximum thickness was tested by conducting a Pearson correlation coefficients. An analysis of variance procedure was performed to test the null hypothesis that the mean minimum diameter is not significantly different between calibers. In addition, a multiple regression analysis measuring the association between minimum diameter, caliber, and maximum thickness was conducted. Discriminant functions and canonical variables were obtained and presented.

This method cannot be used for exact caliber determination from cranial measurements. However, the

discriminant functions can be used with caution to classify observations into groups defined by caliber using minimum diameter and maximum thickness as the predictors.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION

Law enforcement agencies and medical examiner facilities are increasingly employing the knowledge developed by forensic anthropologists in the identification of human decomposing and skeletal remains and indicators of manner of death. In the past, the area of wound ballistics has traditionally been examined from the perspective of the forensic pathologist. This is especially true in regards to soft tissues. Di Maio (1985) clearly enunciated the general opinion of most forensic scientists regarding the estimation of caliber size from entrance wounds:

> The caliber of the bullet that caused an entrance wound cannot be determined by the diameter of the entrance...The size of the hole is due not only to the diameter of the bullet but also to the elasticity of the skin and the location of the wound. An entrance wound in an area where the skin is tightly stretched will have a diameter different from that of a wound in an area where the skin is lax. Bullet wounds in areas where the skin lies in folds or creases may be slit-shaped (Di Maio 1985:97).

Bone wounds due to bullets would seem sufficiently different and this research involves re-examining some standards established by forensic pathologists from a forensic anthropological viewpoint. To this end I have developed a hypothesis that correlates bony entrance defects produced by low-velocity weapons or handguns to the caliber (bore diameter in inches or millimeters) of the projectile. The classification of low- or high-velocity projectiles is rather arbitrary. For the purpose of this study, handguns, which generally possess muzzle velocities of less than 1,100 feet per second will be considered low-velocity weapons (after Barach et al., 1986; Kirkpatrick, 1988). Because handguns are the most common form of firearms used in suicides and homicides, and because they produce many of the fatal head injuries in the United States (after Collins and Lantz, 1994; Kirkpatrick, 1988), progress in research methods and the development of a standardized reference of measurement would aid gunshot wound aspects of forensic investigation.

CHAPTER II

LITERATURE REVIEW

a. Ballistics

Ballistics is the area of study dealing with the motion of projectiles, i.e., bullets, and is further divided into internal ballistics, the study of projectiles in the weapon; external ballistics, the behavior of the projectile through air; and terminal ballistics, the study of the penetration of a medium denser than air by projectiles (Barach et al., 1986; Belkin, 1978; Di Maio, 1985; Ordog et al., 1984). One area of terminal ballistics, wound ballistics, is primarily concerned with the "...penetration, motion, and effects of missiles on animals" (Collins and Lantz, 1994:97).

The amount of tissue damage is determined by the amount of kinetic energy lost by the projectile in the body (Callender and French, 1935; Coates and Beyer, 1962; Di Maio et al., 1974; Harvey et al., 1945). Kinetic energy is illustrated as $KE = WV^2/2g$, where: W=bullet weight, V=velocity, g=gravitational acceleration. Bullet weight and velocity determine the kinetic energy possessed by a projectile with velocity being the most critical component (Berlin, 1976; DeMuth, 1966; Hopkinson and Marshall, 1967; Ordog et al., 1984). A variety of factors are responsible for the amount of kinetic energy lost in the body: "...amount of kinetic energy possessed by the bullet at the time of impact..." (Di Maio, 1985:46), mass, yaw (deviation of the missile from its flight path), caliber or size of bullet, shape, deformation, and density of the tissue being struck (Callender, 1943; Fatteh, 1976; Ragsdale, 1984). Some, such as Lindsey (1980), reject the concept that velocity is the primary mechanism in the wounding force and suggest that the kinetic energy formula is solely a formula for kinetic energy and not of wounding capacity. Others, notably Barach and coworkers (1986), maintain that mass or weight is as critical in wound production as velocity since KE is a product of both weight and velocity, and not merely velocity.

Principally, there are three mechanisms of tissue damage due to bullets: laceration and crushing, shock waves, and cavitation (Adams, 1982; Hopkinson and Marshall, 1967; Ordog et al., 1984). Laceration and crushing are generated by the projectile displacing the tissues in its track and are recognized as the primary wounding mechanism produced by handguns (Fackler, 1986; Hopkinson and Marshall, 1967). The degree and amount of laceration and crushing are dependent upon missile velocity, shape, angle of impact, yaw, and tumbling (Adams, 1982; Ordog et al., 1984). Fackler (1986), however, adds that the shape and construction of a bullet are not significant factors at such low-velocities as observed in handguns. Shock waves, the second mechanism often cited as significant in wounding, occur by the compression of tissues that lay ahead of the bullet, are generated by high velocity missiles generally exceeding 2,500 feet per second (Hopkinson and Marshall, 1967; Ordog et al., 1984), and thus not a major factor in most handgun wounds.

A missile's ability to produce a temporary cavity is considered an important component in wound production and degree of destruction (Barach et al., 1986). Most researchers agree that the wounding effect of the cavitation phenomenon is only significant in velocities surpassing 1,000 feet per second (Amato et al., 1974; DeMuth, 1966). When a missile enters the body, the kinetic energy imparted on the surrounding tissues forces them forward and radially producing a temporary cavity or temporary displacement of tissues (Belkin, 1978; DeMuth, 1966; Ragsdale 1984). The temporary cavity may be considerably larger than the diameter of the bullet, and rarely lasts longer than a few milliseconds before collapsing into the permanent cavity or wound (bullet) track (Kirkpatrick, 1988)(Figure 1).

> The size and configuration of the maximum temporary cavity depend on missile velocity, mass, caliber, shape, construction, and deformation, as well as target substance (Ragsdale 1984:302).

The permanent cavity, or wound track, is the defect generated when the tissues in the projectile's path

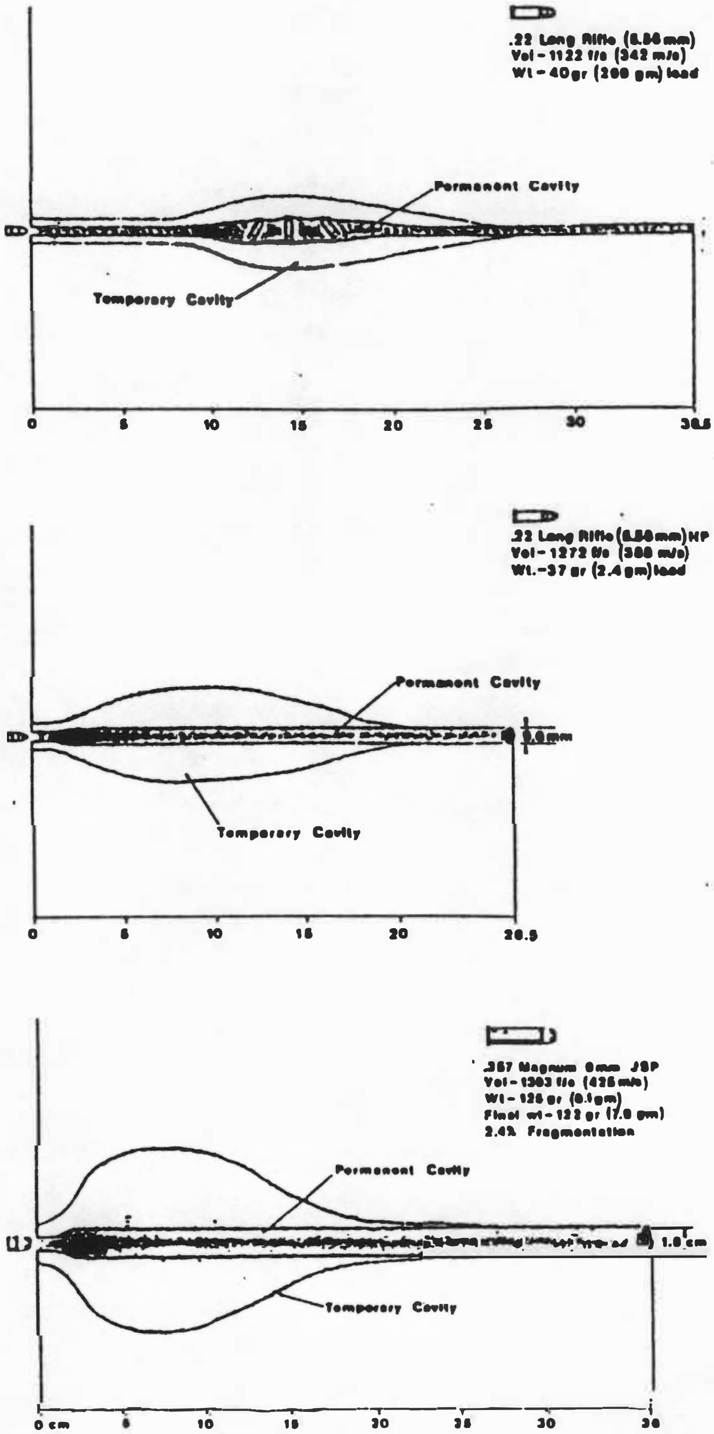
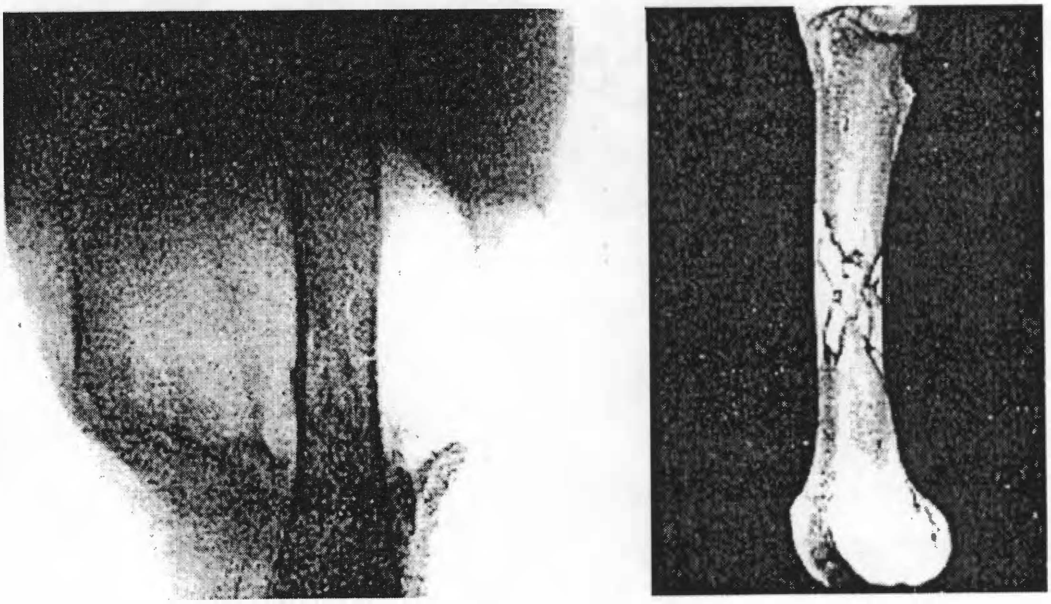


Figure 1. Permanent and temporary cavity formation.
Source: M.L. Fackler, Physics of missile injuries. In *Evaluation and Management of Trauma.* N. McSwain and M. Kerstein, eds. Connecticut: Appleton-Century-Crofts, 1987.

are expelled from the body (Huelke and Darling, 1964). The cavitation phenomenon has been used to explain the fracturing of bone not in the direct path of a missile (Figure 2). Furthermore, the bone fragments will often function as secondary projectiles, which thereby will often increase tissue disruption (Fackler, 1987; Hopkinson and Marshall, 1967; Kirkpatrick and Di Maio, 1978). Nonetheless, Barach et al. (1986), Fackler (1988), Ragsdale (1984), Ragsdale and Josselson (1988), argue that handguns also generate some proportion of cavitation. Similarly, skeptics contest that the temporary cavity phenomenon is nothing more than the simple displacement of tissues akin to blunt trauma (Fackler, 1988; Lindsey, 1980).

Once the missile strikes the body, not only is the amount of kinetic energy displaced into the surrounding tissues important, but also the density of the tissue being penetrated. Consequently, the wounding capacity of a missile striking bone will be greater than in soft tissues, as bone acts as a superior retardant force that is more effective at decelerating a projectile and increasing the energy transfer than less compact substances (Adams, 1982; Ordog et al., 1984). In addition, cancellous bone, the spongy bone found on the epiphyses of long bones, will experience less damage than the more compact cortical bone, because the KE can more readily dissipate within the honeycomb structures of the cancellous bone (Belkin, 1978;



A B

Figure 2. a. Radiograph of sheep femur showing the temporary cavity and fracture b. reconstructed femur.
Source: D. Hopkinson, T. Marshall
Firearm Injuries. British Journal of Surgery 54:350, 1967.

Fatteh, 1976; Huelke and Darling, 1964; La Garde, 1916).

b. Sites of entrance and exit on the skull

Gunshot wounds can be identified as either penetrating, when a bullet enters a substance but does not exit, or perforating, a through-and-through passage of an object by a bullet (Di Maio, 1985). On flat bones such as those found on the cranium, scapulae and pelves, projectile trauma is relatively easy to determine with a high level of accuracy. Entrance wounds at these sites are most often marked by a circular or oblong perforation with varying degrees of internal beveling.

Because the skull is formed of an inner and outer table, entrance and exit sites are usually easily determined. When a bullet enters the skull it produces a sharp-edged "punched-out" hole in the outer table, with a larger corresponding "beveled-out" hole on the inner table (see Figure 3). Similarly, as the bullet exits the cranial cavity, the inner table appears "punched-out" with beveling on the outer table (Di Maio, 1985; Spitz and Fisher, 1993) (see Figure 4).

External beveling of an entrance site, however, may be observed when a bullet strikes the skull tangentially or perpendicularly to the bony surface (Coe, 1982; Peterson 1991). A missile striking the skull tangentially, as may occur in graze wounds, produces a keyhole defect where

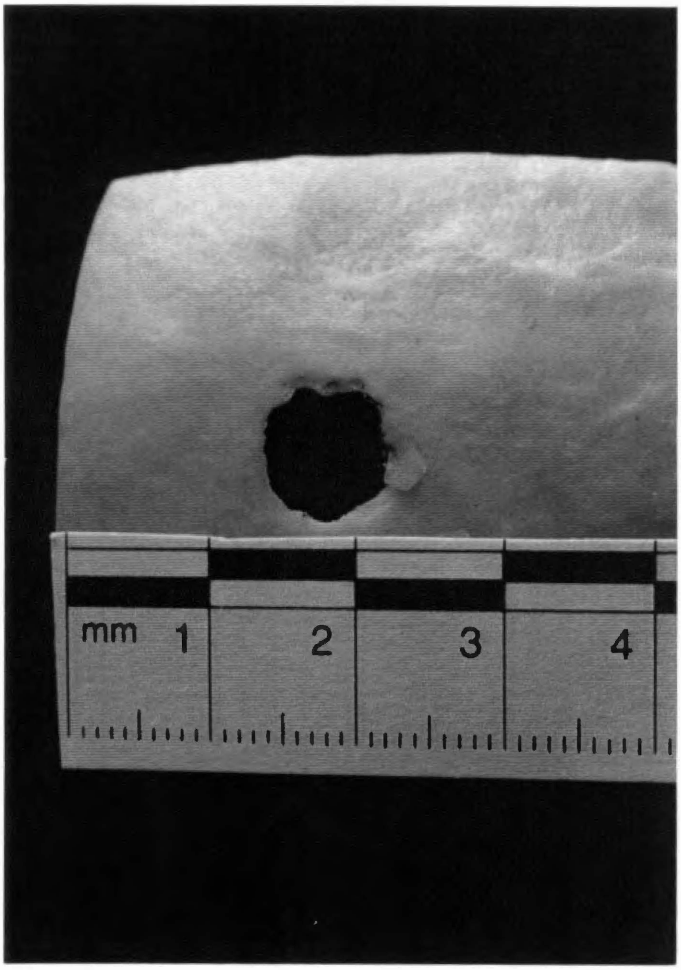


Figure 3. Typical outer table entrance site.

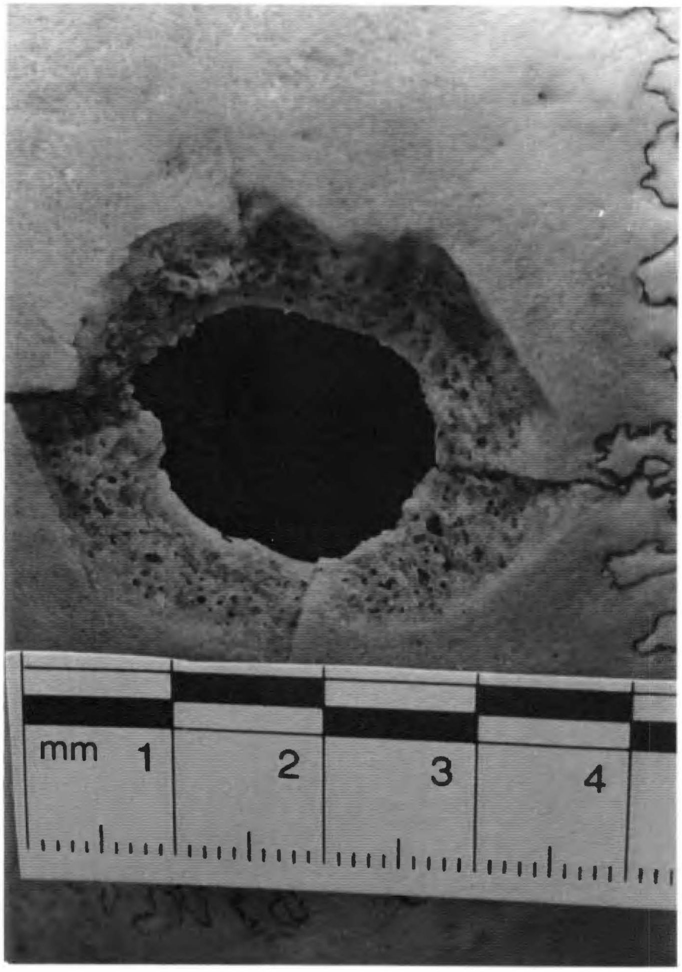


Figure 4. Typical exit site with outer table beveling.

entrance and exit defects overlap (Coe, 1982; Dixon, 1982; Peterson, 1991; Spitz and Fisher, 1993). In the keyhole lesion, one end of the perforation will resemble a typical entrance defect, while the other end will show external beveling consistent with exit holes (see Figure 5). The mechanism of injury used to explain keyhole lesions is that as the bullet enters the skull tangentially, the bullet is split, one portion entering the cranial cavity while the other is expelled producing the exit defect (Coe, 1982). However, as demonstrated by Dixon (1982) this is not always the case, the keyhole defect may be produced by a bullet that remains virtually intact. Keyhole defects, although, are not exclusive to entrance sites and have also been observed in exit sites (Dixon, 1984a).

External beveling of entrance sites produced when a bullet enters the skull perpendicularly is not well understood (Coe, 1982; Peterson, 1991)(see Figure 6). According to Coe (1982), the mechanism responsible in the majority of the cases is due to contact wounds, where the handgun is held against the head. "In such cases it seems plausible that the gases expanding in the subcutaneous tissues penetrate the marrow cavity of the bone and lift the outer table of the skull" (Coe, 1982:218). Although in cases of distant range, Spitz and Fisher (1993) attribute this phenomenon to bullet rotation. Peterson (1991), per contra, argues that the blowback from the pressure buildup

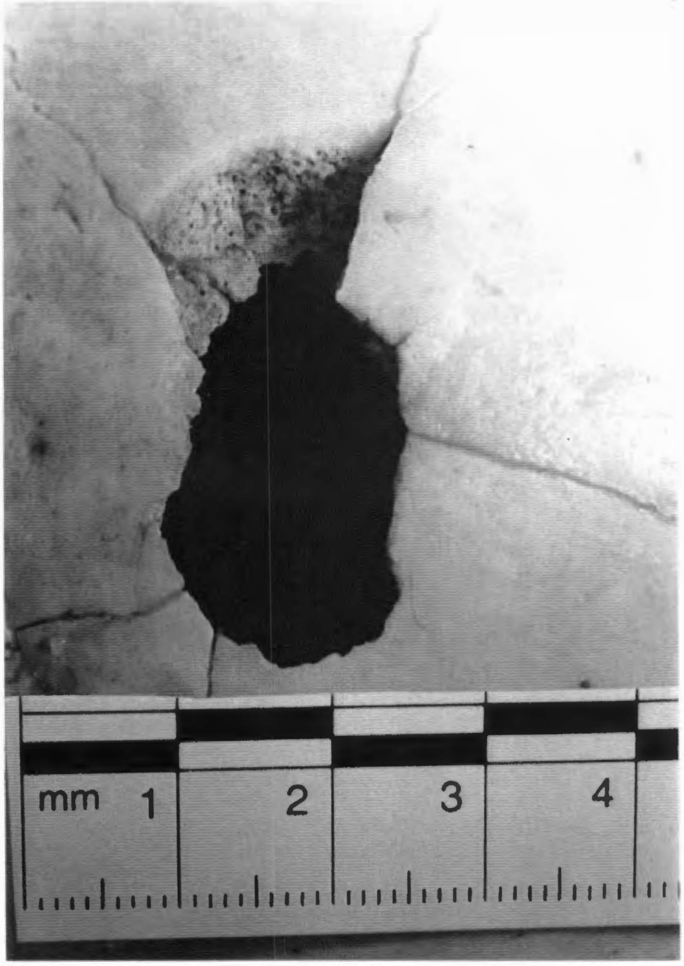


Figure 5. Keyhole wound resulting from a tangential source.

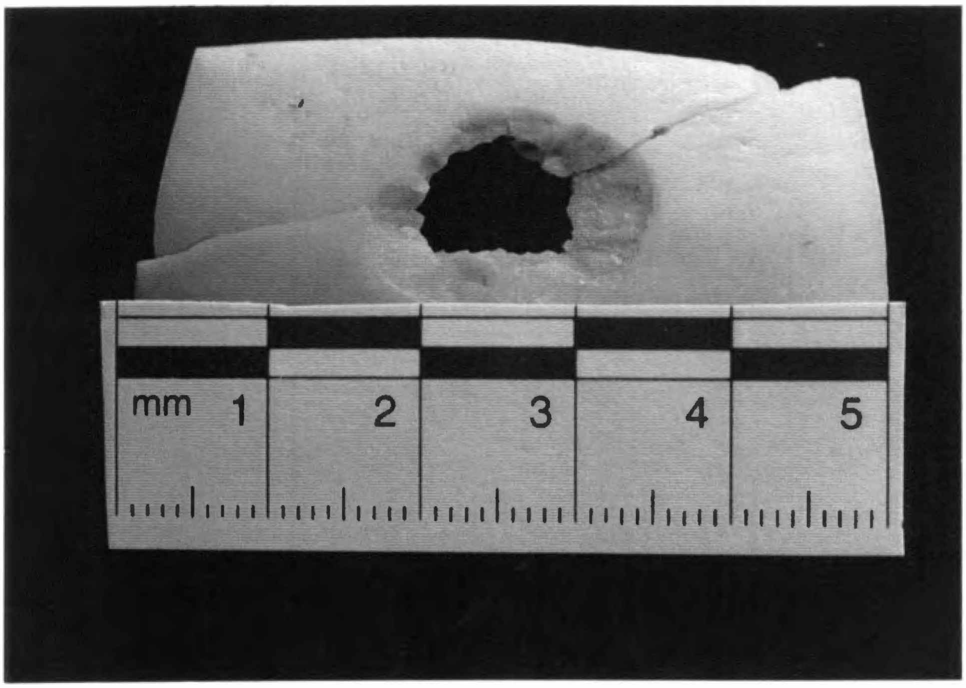


Figure 6. External beveling of an entrance site.

associated with temporary cavity formation is a more plausible explanation. However, an alternative hypothesis to explain this occurrence is proposed-- tissue density. The density of the tissue being struck is a factor responsible for the amount of kinetic energy being displaced and thus, the amount of tissue damage. Theorists have neglected to consider bone density and thickness at the site of impact as a possible element accountable for external beveling of entrance wounds produced when the bullet enters perpendicularly to the bony surface. This hypothesis will be explored in depth at a later date.

Smith et al. (1993) have observed atypical exit defects to the cranial vault mimicking blunt(closed head) trauma. Rather than the typical central defect with external beveling, they observed an epicenter of curvilinear radial cracking with plastic deformation or warping "...of bone due to slow loading and blunt trauma" (Smith et al., 1993). They ascribed this anomaly to slow-moving projectiles.

c. Fracture patterns on the skull

Spitz and Fisher (1993) used fracture patterns to determine the sequence of fire or which of the entrance defects occurred first. They claim that the fractures that originate from the second entrance defect are arrested by the radiating linear fractures from the first hole.

Similarly, Dixon (1984b) has used fracture patterns to determine direction of fire. He maintains that the linear fractures associated with typical exit sites terminate at the preexisting linear fractures produced by the entering bullet, supporting an earlier premise of Gonzales et al. (1954) that fracture patterns produced by the passage of a missile travel faster than the bullet. In addition, Smith et al. (1987) assert that radiating linear fractures as well as concentric heaving fractures can be used to determine direction of fire. They argue that radiating fractures associated with entrance defects are longer and are not arrested by preexisting fractures. Likewise,

> heaving fractures, if present, have more generations and longer radii than exit associated fractures...Exit fractures show radial and heaving fractures of lesser magnitude, and may be arrested by preexisting fractures... (Smith et al. 1987:1421)

generated by the entrance wound.

d. Entrance and exit defects to extremities

Detection of gunshot trauma on long bones and especially irregular bones can be a much more difficult process. Smaller bones, cancellous bone, and bone affected by degenerative diseases can shatter on impact, bearing little resemblance to the typical trauma site. In such cases where damage from a bullet is suspected, radiographs taken of the area can confirm the existence of radiopaque particles left by the slug's path.

Entrance defects on the distal end of bones are smooth and clean or "drill hole" in appearance while those on the shafts are generally comminuted (Belkin,1978; Huelke and Darling, 1964; La Garde, 1916) (Figure 7). Huelke and Darling (1964) conducted a study of bone fractures produced by bullets of the femur and tibia in both dry and cadaver bones. They observed that metaphyseal and diaphyseal fracture patterns differed greatly. Projectile trauma to the diaphyses in cadaver specimens differed from dry bone specimens in that there were numerous fractures surrounding the exit with little or no fragmentation around the exit in dry bone. The "drill hole" defect was apparent on both cadaver and dry bone entrance sites.

Shaft impacts of both dry and cadaver specimens were comminuted with "butterfly" fragments produced bilaterally (Figure 8). Huelke and Darling (1964) attribute the variation in fracture patterns between bone metaphyses and diaphyses to the different types of bone found in these two areas. Because the distal end is mostly composed of cancellous bone with only a thin layer of cortical bone the kinetic energy is better able to dissipate within the spongy area. This produces less destruction than in more compact cortical bone found in diaphyses which generate more deformation. La Garde (1916) was the first to document "butterfly" fractures in the diaphyses of cadaver specimens.

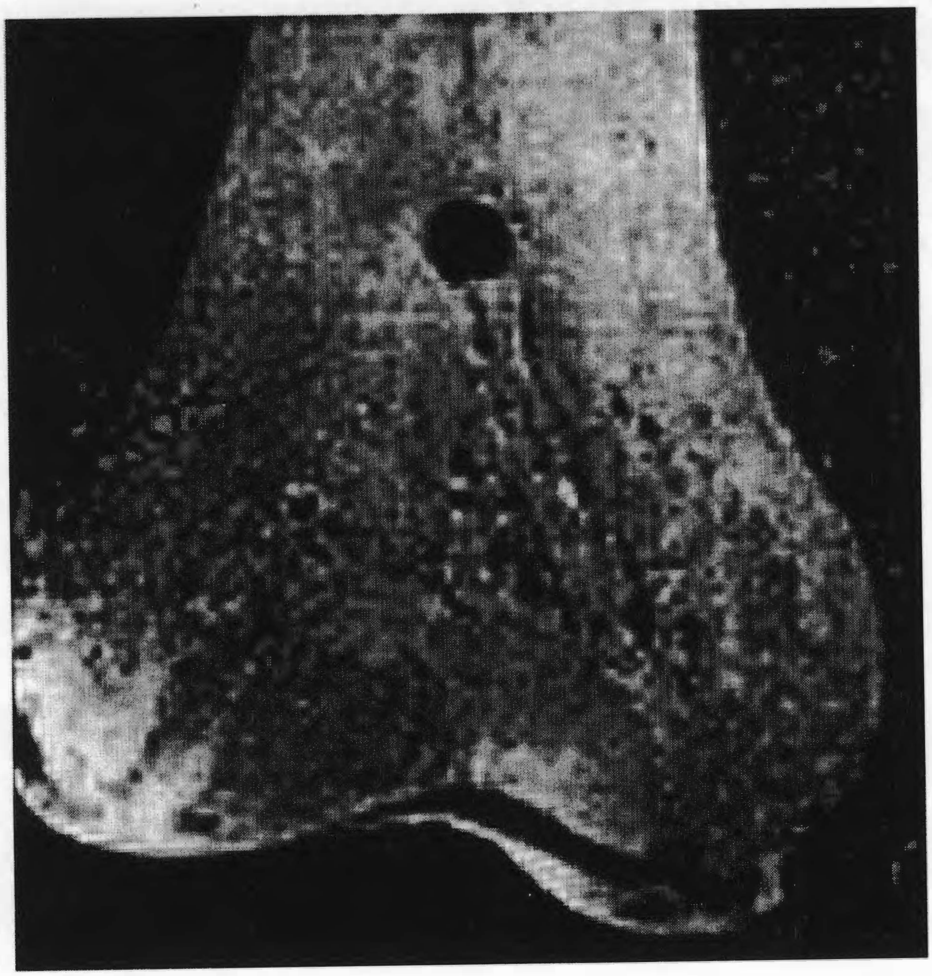


Figure 7. Entrance defect in a distal femur resembling a drill hole.
Source: B. Ragsdale *Gunshot Wounds: A Historical Perspective*. Military Medicine 149:307, 1984.

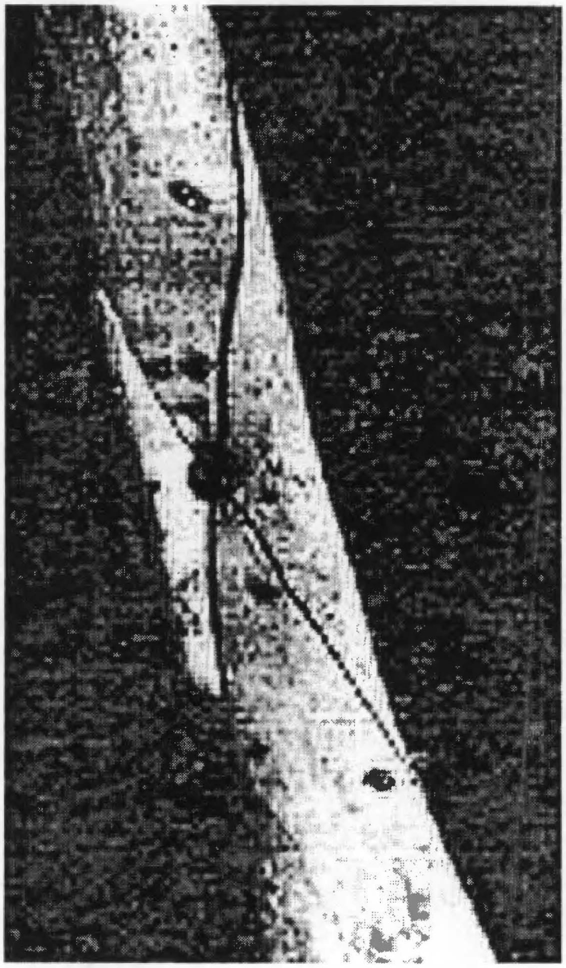


Figure 8. "Butterfly" fracture of tibia.
Source: L. La Garde *Gunshot Injuries, 2nd ed.*. New York: William Wood and Company, 1916.

CHAPTER III

STATEMENT OF PURPOSE

The purpose of this study is to correlate cranial entrance defect diameter to caliber size. Hence,

$H_O: \mu_1=\mu_2=\mu_3=\mu_4$.

There is no significant variation in the minimum diameter of cranial entrance defects which is explained by caliber, while the test hypothesis

$H_R: \mu_1<\mu_2<\mu_3<\mu_4$

is that there is significant variation in minimum diameter of the cranial entrance defect which increases with size of the caliber.

CHAPTER IV

MATERIALS AND METHODS

a. Materials

The sample was 60 specimens obtained at autopsy from the McCormick collection housed at the Regional Forensic Center, Johnson City, Tennessee. These were collected by William F. McCormick, M.D., Deputy Chief Medical Examiner, State of Tennessee. Additionally, thirteen specimens were included from the William F. McCormick, M.D. collection donated and curated by the Forensic Anthropology Center, University of Tennessee, Knoxville. Finally, a specimen collected from Dr. Sandra K. Elkins, Knox County Medical Examiner and Forensic Pathologist at the University of Tennessee Medical Center, Knoxville, was included to provide 73 specimens for statistical analysis (see Table 1).

The criteria for inclusion in this study were known caliber. The calibers considered for this inquiry were .22, .25, .32, and .38. The sample is divided into: thirty-seven specimens of .22 caliber, five of .25, six of .32, and twenty-five of .38 which also include .380 caliber projectiles (see Table 2).

To obtain the minimum diameter of the projectile, measurements of outer table entrance sites at their

Table 1. Summary of sample (N = 73).

Sample	N
Regional Forensic Center, Johnson City, TN	59
Forensic Center, Knoxville, TN	13
UT Medical Center, Knoxville, TN	1

Table 2. Composition of sample (N = 73).

Caliber	Race	Sex	N	Mean Age	Std Dev
.22	White	Male	30	44.633	21.626
.22	White	Female	7	47.752	15.752
.25	White	Male	5	44.6	16.149
.32	White	Male	4	9.0	26.356
.32	White	Female	2	57.5	26.162
.38/.380	White	Male	18	53.444	16.136
.38/.380	White	Female	4	35.75	10.012
.38	Black	Male	2	41	18.384
.380	Black	Female	1	18	.

narrowest point defined by a circular margin were taken. Furthermore, maximum cranial defect diameters, as well as minimum and maximum cranial thickness measurements were collected when possible. To obtain the most precise measurements possible a Helios dial caliper calibrated to the nearest tenth of a millimeter was used. The bore diameter for each caliber is shown in Table 3.

b. Methods

Several statistical tests were conducted using the SAS system at UTCC Vax (after Schlotzhauer and Littell, 1987). A univariate analysis for summary statistics to calculate the means, variance, and standard deviations for the different calibers and maximum thickness was conducted. Also, correlation analysis to measure the strength of the relation between the variables, caliber, minimum diameter, maximum diameter, and maximum thickness was obtained.

A one-way analysis of variance (ANOVA) was performed to test the null hypothesis that the mean minimum diameter is not significantly different among calibers and to determine how much of the variation observed in the minimum and maximum diameters is due to differences in calibers and not random error. The ANOVA procedure compares the means of the response variables (minimum and maximum diameters) for various combinations of the classification variables (caliber).

Table 3. Bore diameters for .22, .25, .32, .38 caliber bullets in millimeters.

Caliber	Bore diameter (caliber)2.54 X 10 = mm
.22	5.588
.25	6.35
.32	8.128
.38	9.652

A multiple regression analysis was also applied to test the null hypothesis that there is no significant variation in minimum diameter explained by caliber. The multiple regression measures the association between two or more independent variables to estimate the dependent variable. In this study minimum diameter was treated as the dependent variable, caliber as an independent variable, and maximum thickness as an independent variable. The General Linear Model was used to perform the multiple regression analysis (Ott, 1988).

Independence between the variables sex and type (homicide or suicide), caliber size (small or large) and sex, and caliber size and type will be tested by conducting a Chi-square test. A Chi-square tests the hypothesis of independence by calculating a test statistic and comparing it to a critical value to produce a p-value (Schlotzhauer and Littell, 1987).

In addition, a discriminant function analysis was conducted to classify observations into groups defined by caliber using minimum diameter and maximum thickness as the predictors. To reduce bias the crossvalidation method, which treats n-1 out of n observations, was applied to obtain the discriminant functions. Classification was first performed by using two values, small and large calibers as the class variable. The large caliber group was comprised of .38, while the small caliber group includes .22, .25, and

.32. A finer classification was also performed using three caliber values .23, which groups .22 and .25 calibers, .32, and .38 as the class variable also using minimum diameter and maximum thickness as predictors. Canonical variables, linear combinations of predictor variables that summarize between-class variation were also derived.

CHAPTER V

RESULTS

a. Summary statistics

Summary statistics for minimum and maximum diameter and maximum thickness for the different calibers are presented in Tables 4, 5 and 6. The means and ranges for minimum diameter and maximum thickness for the different calibers are illustrated in the side-by-side box and whisker plots (Figure 9 and Figure 10). Extreme outliers are evident in both the .22 and .38 calibers.

b. Correlation analysis

The strengths of the relationships between caliber, minimum diameter, maximum diameter, age, sex, race, minimum thickness, and maximum thickness were tested by conducting a Pearson correlation coefficients (Table 7). The strongest relationship was observed between caliber and minimum diameter (r=.75223; P<.0001). The P< .0001 is a strong indication that the true sample correlation is not 0, thus rejecting the Ho: Rho=0. A strong relationship was also observed between caliber and maximum diameter (r=.60554; P<.0001), though, not as strong as the relationship between caliber and minimum diameter suggested by a lower r-value.

Table 4. Summary statistics for minimum diameter by caliber. (N=73)

Caliber	N	Mean	Std Dev	Variance	Minimum	Maximum
.22	37	6.759	1.273	1.623	5.6	11.5
.25	5	6.72	0.661	0.437	6.0	7.5
.32	6	8.666	1.521	2.314	6.6	10.9
.38	25	11.004	2.329	5.427	8.7	17.4

Table 5. Summary statistics for maximum diameter by caliber. (N=70)

Caliber	N	Mean	Std Dev	Variance	Minimum	Maximum
.22	37	8.486	2.228	4.966	5.9	16.7
.25	4	8.575	1.639	2.689	6.3	10.0
.32	6	10.771	2.370	5.619	7.0	15.0
.38	23	12.877	3.423	11.717	9.4	22.0

Table 6. Summary statistics for maximum thickness by caliber. (N=68)

Caliber	N	Mean	Std Dev	Variance	Minimum	Maximum
.22	34	5.873	1.946	3.789	2.5	10.5
.25	5	4.5	1.193	1.425	3.1	5.8
.32	6	5.6	2.735	7.48	1.0	8.0
.38	23	5.521	2.234	4.991	2.0	10.4

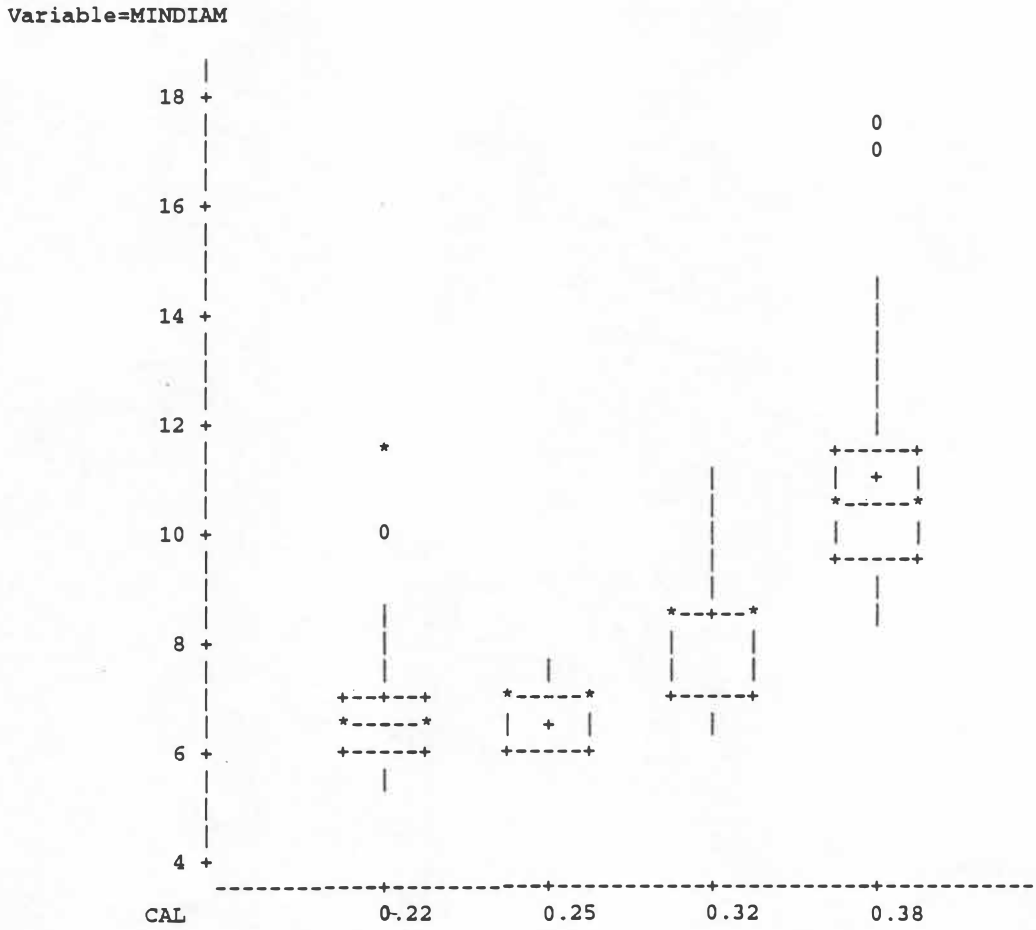


Figure 9. Means and ranges for minimum diameter.
* and 0 denote values that are outliers. + indicates the mean.

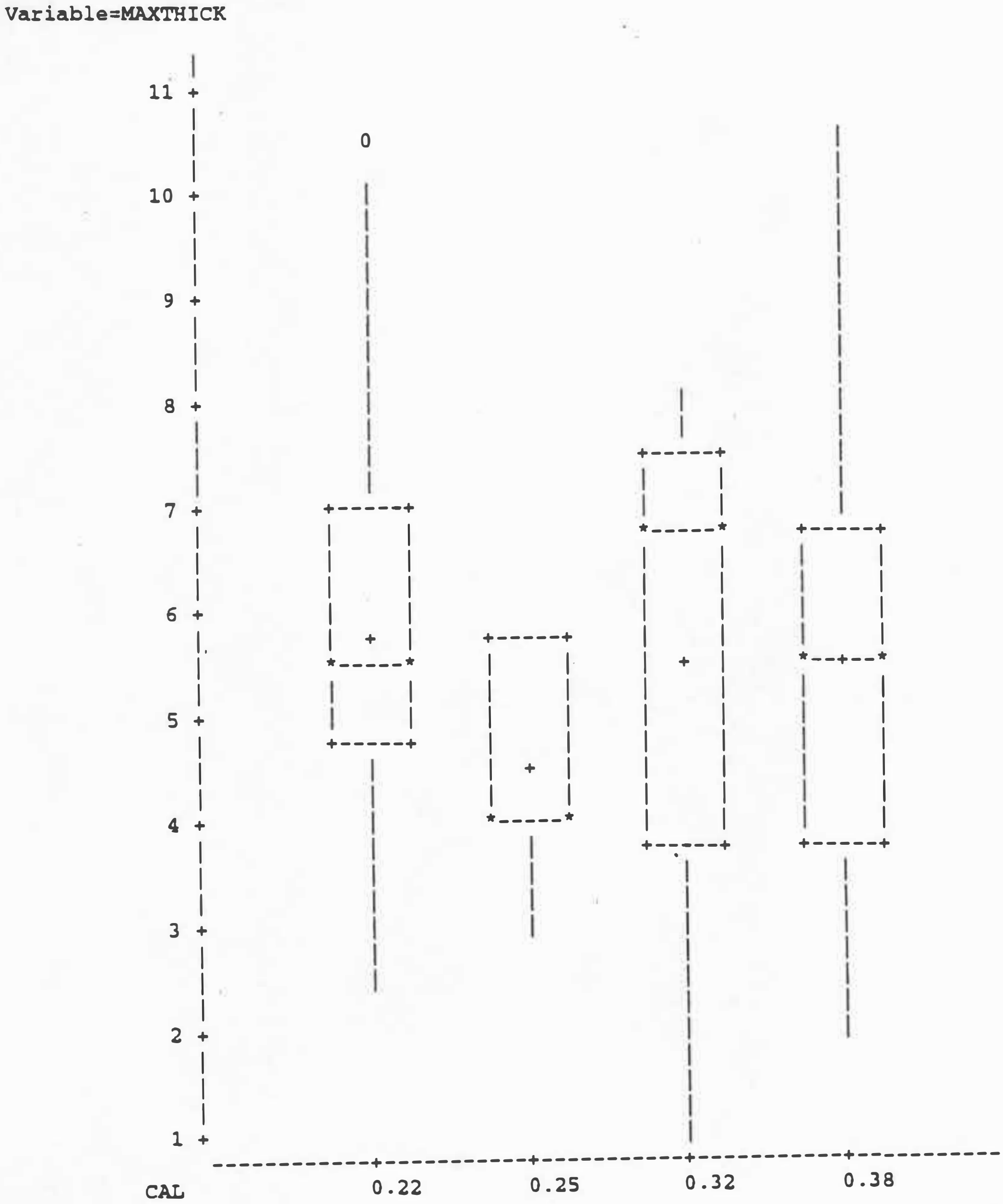


Figure 10. Means and ranges for maximum thickness.
0 denotes outliers. + indicates the mean.

Table 7. Pearson Correlation Coefficients.

	caliber	mindiam	maxdiam	maxthick
caliber	1.0000 0.0000	0.7522 0.0001	0.6055 0.0001	-0.0571 0.6440
mindiam	0.7522 0.0001	1.0000 0.0000	0.8172 0.0001	0.2793 0.0211
maxdiam	0.6055 0.0001	0.8172 0.0001	1.0000 0.0000	0.1788 0.1477
maxthick	-0.0571 0.6440	0.2793 0.0211	0.1788 0.1477	1.0000 0.0000

The first row = r-values. Second row = p-values.

A relationship between minimum diameter and maximum thickness was also observed (*r*=.27929; Pr >.0211).

c. Analysis of variance

The analysis of variance procedure yielded a strong relationship between the dependent variable minimum diameter and caliber size. The Pr > F .0001 and R-square .561266 indicate the mean minimum diameter is significantly different between calibers. The post hoc tests for difference between calibers with 95% confidence intervals are presented in Table 8.

The ANOVA for the dependent variable maximum diameter generated similar results with a Pr > F .0001 and R-square .373380. The post hoc tests for difference between calibers with 95% confidence intervals are presented in Table 9.

d. Multiple regression

The Pr > F .0001 indicates that the overall multiple regression model is significant. However, the interaction is not significant indicated by a Type III sums of squares Pr > F 0.7819. When the interaction is removed, the Pr > F .0001 indicates that maximum thickness is significant. Both independent variables, caliber and maximum thickness, are significant with Pr > F .0001, respectively. The equation for the model should be used to extrapolate minimum diameter from known caliber and maximum thickness

Table 8. ANOVA. T tests for caliber comparisons for minimum diameter at the .05 level are indicated by *.

Caliber Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit	.05 Level Significance
.38-.32	0.974	2.4458	3.9442	*
.38-.22	3.2890	4.1985	5.1080	*
.38-.25	2.6110	4.3258	6.0406	*
.32-.38	-3.9442	-2.4458	-0.9474	*
.32-.22	0.3179	1.7526	3.1874	*
.32-.25	-0.1625	1.8800	3.9225	
.22-.38	-5.1080	-4.1985	-3.2890	*
.22-.32	-3.1874	-1.7526	-0.3179	*
.22-.25	-1.5321	0.1274	1.7868	
.25-.38	-6.0406	-4.3258	-2.6110	*
.25-.32	-3.9225	-1.8800	0.1625	
.25-.22	-1.7868	-0.1274	1.5321	

R-square 0.561266, Pr > F 0.0001

Table 9. ANOVA. T tests for caliber comparisons for maximum diameter at the .05 level are indicated by *.

Caliber Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit	.05 Level Significance
.38-.32	-0.1921	2.1058	4.4038	
.38-.25	1.4239	4.3023	7.1807	*
.38-.22	2.9718	4.3904	5.8091	*
.32-.38	-4.4038	-2.1058	0.1921	
.32-.25	-1.1227	2.1964	5.5155	
.32-.22	0.1065	2.2846	4.4626	*
.25-.38	-7.1807	-4.3023	-1.4239	*
.25-.32	-5.5155	-2.1964	1.1227	
.25-.22	-2.6954	0.0882	2.8718	
.22-.38	-5.8091	-4.3904	-2.9718	*
.22-.32	-4.4626	-2.2846	-0.1065	*
.22-.25	-2.8718	-0.0882	2.6954	

R-square 0.373380, Pr > F 0.0001

(Table 10): y=(Intercept+Caliber)+Maxthickx.

The null hypothesis that there is no significant variation in minimum diameter explained by caliber should be rejected. Based on the results of this analysis, the significant difference in the size of the minimum diameter is influenced primarily by the caliber but thickness also influences the size of the minimum diameter.

e. Chi-square test

A Chi-square test was conducted to test for independence between sex and type (homicide and suicide), caliber size (small and large) and sex, and caliber size (small and large) by type (homicide and suicide).
The chi-square for sex and type yielded a *P*-value of .250, which clearly supports the null hypothesis that the variables sex and type are independent. The *P*-value for caliber size and sex is .771 supporting the null hypothesis that the variables caliber size and sex are independent. The *P*-value .584 supports the null hypothesis that the variables caliber size and type are also independent.

f. Discriminant function analysis

The canonical discriminant scores are presented in Table 11. The first canonical correlation, CAN1, .786024 is considerably larger than the CAN2 correlation .004241. The correlation between minimum diameter and the first canonical

Table 10. Multiple regression analysis of minimum diameter on to caliber and maximum thickness.

Source	DF	SS	Pr > F
Model	2	278.5806	0.0001
	DF	Type I SS	Pr > F
Caliber	1	233.2722	0.0001
Maxthick	1	45.2684	0.0001
	DF	Type III SS	Pr > F
Caliber	1	244.3654	0.0001
Maxthick	1	45.2684	0.0001

Parameter	*Estimate	Pr > |T|	Std Error of Estimate
Intercept	-1.28965753	0.1791	0.94956633
Caliber	25.92750275	0.0001	2.59885970
Maxthick	0.39802099	0.0001	0.09269371

*Values obtained without the interaction in the model.

Table 11. Canonical discriminant analysis for .23*, .32, and .38 caliber groups.

	Canonical Correlation	Eigenvalue	Likelihood Ratio	Approx F	Num DF	Den DF	Pr> F
1	0.786024	1.6167	0.38215934	19.7640	4	128	0.0001
2	0.004241	0.0000	0.99998202	0.0012	1	65	0.9728

Total Canonical Structure

	Can1
Mindiam	0.944961
Maxthick	-0.050245

Raw Canonical coefficients

	Can1
Mindiam	0.6480619392
Maxthick	-0.2624563012

Group Means on Canonical Variates

Caliber	Can1
.23*	-1.001920266
.32	0.022332464
.38	1.693082417

*.23=.22 and .25 calibers grouped.

variable is positive (0.944961). The variation observed in minimum diameter is thus positive to caliber size. The correlation between maximum thickness and the first canonical variable is negative (-0.050245) implying that the difference in cranial thickness is weakly related to caliber. The raw canonical coefficients for CAN1 show that the classes differ more widely on the linear combination .6480619393*mindiam-.2624563012*maxthick.

The degree of differentiation between caliber was measured using Mahalanobis D^2 (Table 12). The D^2 between defects produced by .23 and .32 caliber bullets is not significant (F= 2.68623, P<.0758). There is a significant distance between wounds produced by .23 and .38 caliber projectiles (F=51.73158, P<.0001). There is a difference between wounds produced by .32 and .38 caliber projectiles, which is significant (F=6.53994, P<.0026). However, there does appear to be some overlap between calibers produced by the crossvalidation classification which are presented in Table 13. The crossvalidation classification yielded correct classification of 82.02 percent for .23 caliber, 73.94 percent for .38 caliber, and 16.67 percent for .32 caliber defects.

Raw discriminant function coefficients and constants or classification criteria for each caliber group, .23, .32, and .38 were extracted using Y=constant+minimum

Table 12. Mahalanobis D^2 between caliber matrix.

Mahalanobis D^2

Caliber	.23*	.32	.38
.23*	0	1.04931	7.26304
.32	1.04931	0	2.79162
.38	7.26304	2.79162	0

F statistic:

Caliber	.23*	.32	.38
.23*	0	2.68623	51.73158
.32	2.68623	0	6.53994
.38	51.73158	6.53994	0

Prob >

Caliber	.23*	.32	.38
.23	1.0000	0.0758	0.0001
.32	0.0758	1.0000	0.0026
.38	0.0001	0.0026	1.0000

*.23=.22 and .25 calibers grouped.

Table 13. Crossvalidation matrix. Number of observations and percent classified into caliber.

Caliber	.23*	.32	.38	Total
.23*	32	6	1	39
	82.02	15.38	2.56	100.00
.32	3	1	2	6
	50.00	16.67	33.33	100.00
.38	1	5	17	23
	4.35	21.74	73.91	100.00
Total	36	12	20	68
Percent	52.94	17.65	29.41	100.00
Priors	0.3333	0.3333	0.3333	

*.23=.22 and .25 calibers grouped.

diameter*X1+maximum thickness*X2 (Table 14). The linear discriminant functions for estimating caliber from minimum diameter and maximum thickness are presented in Table 15. An observation is classified into a caliber group if the corresponding function produces the largest numerical value.

The discriminant analysis using the two values large (.38) and small (.22,.25, and .32) calibers as the criterion variable groups yielded better results. The canonical discriminant scores for caliber grouped into size, large and small, are presented in Table 16. The canonical discriminant analysis for calibers grouped into size generated similar results to the discriminant analysis which classified them into specific calibers. A positive correlation (.945373) between minimum diameter and the first canonical variate, which suggests that the variation observed in minimum diameter is positive to caliber size was also observed. The negative variable (-.048984) generated by the correlation between maximum thickness and caliber, suggests that the variation in cranial thickness is weakly related to caliber size.

The degree of differentiation measured using Mahalanobis D^2 between wounds produced by small and large caliber is 6.13170, which is a significant difference (F=45.95702, P<.0001). The classification rate using crossvalidation for large caliber is 86.96 percent, and

Table 14. Linear discriminant function coefficients for estimating caliber from minimum diameter and maximum thickness.

Caliber	.23*	.32	.38
Constant	-8.22777	-11.71057	-19.75070
Mindiam	1.95418	2.61767	3.70071
Maxthick	0.54709	0.27143	-0.16021

*.23=.22 and .25 calibers grouped.

Table 15. Linear discriminant functions for estimating caliber from minimum diameter and maximum thickness for .23, .32, and .38 caliber.

.23*:	Y=-8.22777+1.95418(MinDiam)+0.54709(MaxThick)
.32:	Y=-11.71057+2.61767(MinDiam)+0.27143(MaxThick)
.38:	Y=-19.75070+3.70071(MinDiam)-0.1601(MaxThick)

*.23=.22 and .25 calibers grouped.

Table 16. Canonical discriminant analysis for large and small calibers.

	Canonical Correlation	Eigenvalue	Likelihood Ratio	Approx F	Num DF	Den DF	Pr> F
1	0.765350	1.4141	0.41423953	45.9570	2	65	0.0001

Total Canonical Structure

	Can1
Mindiam	0.945373
Maxthick	-0.048984

Raw Canonical Coefficients

	Can1
Mindiam	0.6272770757
Maxthick	-0.2530963309

Group Means on Canonical Variates

Caliber	Can1
Large	1.638679832
Small	-0.837547470

93.33 percent for the group small caliber (Table 17).

The raw discriminant function coefficients and constant for small and large calibers are presented in Table 18. An observation is classified into the group small if the value produced is negative and into the group large if the function produces a positive value.

Table 17. Crossvalidation matrix. Number of observations and percent classified into caliber.

Caliber	Large	Small	Total
Large	20	3	23
	86.96	13.04	100.00
Small	3	42	45
	6.67	93.33	100.00
Total	23	45	68
Percent	33.82	66.18	100.00
Priors	0.5000	0.5000	

Table 18. Linear discriminant function for classifying caliber into groups large and small.

Variable	Coefficients
Minimum diameter	1.55328
Maximum thickness	-0.62673
Constant	-10.42456
Small mean	-3.0659
Large mean	3.0659

CHAPTER VI

DISCUSSION AND CONCLUSION

This investigation examined the relation between minimum entrance diameter, cortical bone thickness of the cranium, and the caliber of the projectile. The strongest correlation was observed between minimum diameter and caliber followed by a correlation with maximum cranial thickness and minimum diameter.

Defects produced by .38 caliber bullets were significantly larger than those produced by either .22 or .25 caliber bullets, results which are comparable to previous studies by Berryman et al., (1994; 1995 in press). Also, corresponding with their study, no significant difference was observed between defects produced by .22 and .25 caliber projectiles. In addition, the mean minimum diameter for wounds produced by .25 caliber bullets were slightly smaller than the .22 caliber means. This inconsistency could be explained by the knowledge that .25 caliber projectiles are generally jacketed and resist deformation, whereas .22 caliber bullets are usually nonjacketed, which allow for more deformation. The difference between .32 and .38 caliber was significant, but not significant between .32 and .25 calibers. However, extreme outliers are evident in both the .22 and .38

calibers. This could possibly be explained by the extreme maximum thickness of the bone at these sites.

Bone thickness at the site of impact was observed to be an important factor in the degree of wound formation. The results of the multiple regression analysis revealed that the difference in defect diameter appears to be explained by not only the caliber of the projectile but also the thickness (cortical) of the bone at the site of impact. The study suggests that the larger the bullet caliber the larger the defect and the greater the cortical bone thickness will also increase the size of the wound.

The discriminant functions extracted enables the forensic scientist to estimate the caliber of a suspect handgun using minimum diameter and thickness cranial measurements. The wider classification into large and small groups produced a higher percentage of correct classifications than a finer classification into groups .23, .32, and .38. For example, to classify an observation with a minimum diameter of 7mm and maximum thickness of 5mm, the linear discriminant function to classify the observation into large and small groups would be used (refer to Table 18):

$Y=-10.42456+1.55328(7)-0.6267(5) = -2.6851$. The negative (-2.6851) value which falls close to the small group mean would classify the observation into the small group. Caution is suggested when attempting to estimate caliber from defects that are not produced from the perpendicular entrance of a bullet, for instance, keyhole wounds, bullets entering along sutures or fractures, a bullet that enters on its side, should be taken into consideration.

A number of the defects produced by .32 caliber bullets were misclassified into either .23 or .38. The small sample size of N=6 and the less than ideal circumstances of several of the cases (defects along sutures, keyhole defects with irregular margins, expansion of the diploë), which yielded measurements smaller than the caliber of the projectile could be accountable for the high misclassification rate for wounds produced by .32 caliber bullets within this particular study. In addition, projectiles that pass through a suture can produce a defect that is smaller than the bullet, similar to observations by Berryman et al. (1995 in press), where bullets that passed through an existing fracture also caused the bullet to produce a wound smaller than the caliber.

This study could be improved with a larger sample, a classification system based on cranial location (i.e., frontal, parietal, occipital), and perhaps distinguishing between bullets that are relatively the same size (i.e., .357, 9mm, .38). For example, a wound generated by a .357 would be expected to be much larger than either a 9mm or .38, because the .357 can produce muzzle velocities surpassing 1500 feet per second as compared to the 9mm which averages 1100 feet per second, whereas the typical muzzle velocity for a .38 is between 865 to 915 feet per second (Marshall and Sanow, 1992). The effects of velocity have been well documented on soft tissue with the result of proving that two projectiles of similar size will produce differing entry sites depending upon velocity with the higher speed projectile producing a much larger defect (Kirkpatrick and Di Maio, 1978). The importance of tissue density is also a well known factor in the degree of wound formation and was further considered in this study in relation to bone thickness. The size of the entrance defect is primarily influenced by the caliber of the projectile, but bone density at the site of impact also affects the diameter of the wound. Many factors such as intermediate targets, "passage of a bullet or pellet through an intermediate object before striking a victim..." (Di Maio, 1985:80)(i.e., glass window) and bullet deformation, are responsible for the size of entrance cranial defects. The possibility of narrowing or eliminating particular calibers would be useful to law enforcement, however.

The area of wound ballistics, especially its effects on hard tissue, is worthy of considerable research. As mentioned, investigations in wound ballistics and their attempts at caliber estimation have been from the perspective of the forensic pathologist whose focus is usually upon soft tissue. Because of the limited inquiries into the response of hard tissue to projectile impact, there is still a large expanse of unanswered questions for the forensic anthropologist and forensic pathologist to pursue. Though an exact caliber determination from cranial measurements is unlikely, refinements of the methods presented in this investigation would provide estimates for those cases in which evidence is not recoverable. Although the collection is small and only a few caliber types are represented, there is sufficient evidence to suggest that a more detailed examination with a wider range of control samples could lead to a standard index of entrance diameter to aid the forensic anthropologist in the identification of caliber size.

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Ann entered Rollins College, Winterpark, Florida, the following fall, and in May 1990, she received the degree Bachelor of Art in Spanish with a minor in Business. Ann later became interested in anthropology and in December 1992, earned a second B.A. in Anthropology from Florida Atlantic University, Boca Raton, Florida.

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