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Caliber Estimation from Cranial Entrance Defect Measurements

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ABSTRACT: Caliber estimation from entrance defects has long been rejected by forensic scientists. This appears to be a consequence of soft tissue perspective of forensic pathologists. 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 consisted of 73 specimens obtained at autopsy (thirty-seven of .22 caliber, five of .25, six of .32, and twenty-five of .38).

To test the strength of the relation between caliber, minimum diameter, and maximum thickness Pearson correlation coefficients were conducted. The strongest relationship was observed between caliber and minimum diameter. A relationship between minimum diameter and maximum thickness was also observed. To test the null hypothesis that the mean minimum diameter is not significantly different between calibers an analysis of variance procedure was performed. The ANOVA yielded a strong relationship between dependent variable minimum diameter and caliber. Multiple regression analysis measuring the association between minimum diameter, caliber, and maximum thickness was also conducted. The Pr > F .0001 suggests that the overall model is significant.

Discriminant functions and canonical variables were obtained. Classification was first performed by using two values small and large calibers. The large caliber group consisted of .38, while the small caliber group included .22, .25, and .32. The correct classification rate using crossvalidation for large caliber is 86.96%, and 93.33% for the group small caliber. A narrower classification was also performed by using three values, .23 caliber (.22 and .25 calibers grouped), .32, and .38 as the criterion variable groups also using minimum diameter and maximum thickness as predictors. The correct classification rate using crossvalidation is 82.02% for .23 caliber, 73.94% for .38 caliber, and 16.67% for .32 caliber defects. The discriminant functions can be used with appropriate caution to classify observations into groups defined by caliber using minimum diameter and maximum thickness as the predictors. Caution is suggested when attempting to estimate caliber from defects that are not produced from the perpendicular entrance of a bullet.

KEYWORDS: forensic science, forensic anthropology, cranial gunshot wound defect, bullet caliber, physical anthropology

Law enforcement agencies and medical examiner facilities are increasingly using 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 forensic pathologists perspective. This is especially true with regard to soft tissues. The general opinion of most forensic scientists is that caliber of the bullet cannot be determined from the diameter of the entrance wound (1). However, cadaver studies of pistol-shot wounds of the head by Phelps (2) revealed that "the wound of entrance is usually not very much larger than the ball, and may thus absolutely determine caliber."

This research involves re-examining some standards established by forensic pathologists from a forensic anthropologic 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 1100 feet per second will be considered low-velocity weapons (after 3,4). 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 4,5), progress in research methods and the development of a standardized reference of measurement would aid gunshot wound aspects of forensic investigation.

The amount of tissue damage is determined by the amount of kinetic energy lost by the projectile in the body (6–9). 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. Thus, the wounding capacity of a missile striking bone will be greater than in soft tissues (10, 11). In addition, cancellous bone will experience less damage than the more compact cortical bone (12–15).

The purpose of this study is to correlate cranial entrance defect diameter to caliber size. The null hypothesis is that there is no significant variation in the minimum diameter of cranial entrance defects which is explained by caliber, while the test hypothesis is that there is significant variation in minimum diameter of the cranial entrance defect, which increases with size of the caliber.

Materials and Methods

Sample

The sample was 59 specimens obtained at autopsy from the William F. McCormick collection housed at the Regional Forensic Center, Johnson City, 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.

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Portions of the work were submitted to the following:

"Estimating Caliber from Cranial Entrance Wound Measurements." Paper submitted to American Academy of Forensic Sciences, 1996 Annual Meeting, Nashville, TN.

"Handgun Caliber Estimation from Cranial Entrance Defects" Poster submitted for American Association of Physical Anthropologists, 1996 Annual Meeting, Durham, NC.

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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.

The criterion for inclusion in this study was 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.

Measurements

Cranial bones considered in this study were frontal, parietal, temporal, and occipital. To obtain the minimum diameter of the projectile, measurements of outer table entrance sites at their 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.

Statistics

Several statistical tests were conducted using the SAS system at UTCC Vax (after 16). A univariate analysis for summary statistics to calculate the means 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).

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 (17).

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.

In addition, bias was tested by conducting a paired difference t-test to test the mean difference between observations for minimum diameter, maximum diameter, and maximum thickness measurements ($N = 18$). The average difference for minimum diameter, maximum diameter, and maximum thickness measurements were not significantly different from zero, respectively (T = 1.6088, Pr > .1261; T = −1.2093, Pr > .2431; T = −.1019, Pr > .9200). A correlation analysis to measure the strength of the relation between first and second measurements for the variables minimum diameter, maximum diameter, and maximum thickness was also conducted. A strong relationship between first and second measurements for all variables was observed ($P < .0001$). Paired t-test and correlation analysis results are presented in Table 1.

Results

Summary Statistics

Summary statistics for minimum and maximum diameter for the different calibers are presented in Tables 2 and 3.

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

TABLE 1—*Paired t-test and correlation results to test for bias. (N = 18).*

	Diff	Std Dev	Pr>	r
Mindiam	1.6088	0.4981	0.1261	0.9801
Maxdiam	−1.2093	0.4482	0.2431	0.9929
Maxthick	−0.1019	0.9245	0.9200	0.8995

TABLE 2—*Summary statistics for minimum diameter by caliber in millimeters. (N = 73).*

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

TABLE 3—*Summary statistics for maximum diameter by caliber in millimeters. (N = 70).*

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

TABLE 4—*Pearson correlation coefficients.*

	Caliber	Mindiam	Maxdiam	Maxthick
Caliber	1.0000	0.7522	0.6055	−0.0571
	0.0000	0.0001	0.0001	0.6440
Mindiam	0.7522	1.0000	0.8172	0.2793
	0.0001	0.0000	0.0001	0.0211
Maxdiam	0.6055	0.8172	1.0000	0.1788
	0.0001	0.0001	0.0000	0.1477
Maxthick	−0.0571	0.2793	0.1788	1.0000
	0.6440	0.0211	0.1477	0.0000

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

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 ANOVA for the dependent variable maximum diameter generated similar results with a Pr > F .0001 and R-square .373380.

Multiple Regression

The Pr > F .0001 indicates that the overall multiple regression model is significant (Table 5). 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 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.

Discriminant Function Analysis

The canonical discriminant scores are presented in Table 6. The first canonical correlation, CAN1, .786024 is considerably larger than the CAN2 correlation .004241. The correlation between minimum diameter and the first canonical 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 (−0.050 245) 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.

TABLE 5—*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.

The degree of differentiation between caliber was measured using Mahalanobis D^2 (Table 7). 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 presented in Table 8. 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.

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 9. 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 93.33 percent for the group small caliber (Table 10).

The raw discriminant function coefficients and constant for small and large calibers are presented in Table 11. 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.

Discussion and Conclusion

This investigation examined the relation between minimum entrance diameter, cranial thickness, 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. 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 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 bone thickness will also increase the size of the wound.

The discriminant functions extracted enable 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 7 mm and maximum thickness of 5 mm, the linear

TABLE 6—*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.

TABLE 7—*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

*.23 = .22 and .25 calibers grouped.
† $P < 0.01$.

TABLE 8—*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.

discriminant function to classify the observation into large and small groups would be used (refer to Table 11).

$Y = -10.42456 + 1.55328(7) - 0.62673(5) = -2.68525$. The negative ($-2.68525$) value that falls close to the small group means 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. (18), where bullets that passed through an existing fracture also caused the bullet to produce a wound smaller than the caliber.

A classification system based on cranial location (such as, frontal, temporal, parietal, occipital) would be valuable. However, a larger sample is needed to divide the study into cranial location. In addition, perhaps distinguishing between bullets that are relatively the same size (such as, .357, 9 mm, .38) would also be interesting. For example, a wound generated by a .357 would be expected to be much larger than either a 9 mm or .38, because the .357 can produce muzzle velocities surpassing 1500 feet per second as compared to the 9 mm which averages 1100 feet per second, whereas the typical muzzle velocity for a .38 is between 865 to 915 feet per second (19). 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 (20). 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 . . ." (1) (such as a 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

TABLE 9—*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					

TABLE 10—*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 11—*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

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.

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ERRATUM

In the article "Caliber Estimation from Cranial Defect Measurements" J Forensic Sci 1996 Jul;41(4):629, second column, second line in second paragraph, "al" was inadvertently omitted from the word "anthropological."