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Author(s):	Elizabeth A. DiGangi, Ph.D., D-ABFA, Elizabeth A. Evangelou, MA, Tessa Somogyi, MA, Kevin E. Sheridan, Ph.D., RPA
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Initiation of a Gunshot Wound Trauma Atlas from Human Cranial Bone
Final Summary Overview

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Elizabeth A. DiGangi, PhD, D-ABFA (Principal Investigator)
Elizabeth A. Evangelou, MA (graduate assistant)
Tessa Somogyi, MA (graduate assistant)
Kevin E. Sheridan, PhD, RPA (collaborator)
Department of Anthropology
Binghamton University
4400 Vestal Parkway East
Binghamton, NY 13902

Abstract and Project Purpose

Gunshot wound interpretation, especially of the skull, has been extensively studied in forensic anthropology. Most studies have taken a retrospective approach, whereby information from autopsy reports or forensic anthropology reports are mined for data about predictive patterns. This approach is admittedly problematic due to the number of extrinsic variables present. These variables include factors such as velocity of the projectile, distance of the weapon to the victim, type of firearm, bullet caliber, and bullet construction. In retrospective studies, there is no way to know what many of these variables were, rendering the results less reliable. An experimental approach is therefore more reliable as such variables can be controlled.

Therefore, this project was designed to experimentally control the extrinsic variables of weapon, shooter, distance, caliber, and velocity in a gunshot study on donated human heads. The primary variable being tested was the effect that bullets of two different constructions (hollow point vs. full metal jacket) have on human skulls, and whether the resultant damage could predict bullet type. These different bullet types are designed to either fully penetrate with no fragmentation (full metal jacket) or penetrate and fragment upon contact (hollow point). Analysis of the resultant damage involved quantitative and

qualitative analysis, to include investigations of: diameter, area, and perimeter of the entrance and exit wounds, bone density and cranial bone thickness, bullet type prediction from quantitative and qualitative variables; and on the bullets themselves, analysis of the mass loss upon impact.

Following fracture analysis, all skulls were photographed in detail and an atlas with the photographs and all relevant variable information (velocity, weapon type, bullet type, etcetera) was constructed. This atlas is available upon request by members of the forensic science community to aid practitioners with skeletal gunshot wound interpretation.

Project Subjects

Forty-five donated human heads were obtained from an anatomical gift company, specifically for the purpose of trauma research. Twenty-three individuals were female and 22 were male, with ages ranging from 54 to 90 years old. The heads arrived fleshed and frozen. They were defrosted to room temperature the night prior to the experiment.

Project Design

This project experimentally tested the effect that bullets of two different constructions (jacketed hollow point vs. full metal jacket) have on human skulls. These different bullet types are designed to either fully penetrate with no fragmentation (full metal jacket - FMJ) or penetrate and fragment upon contact (hollow point - JHP). Therefore, we hypothesized that damage caused by hollow point ammunition will be greater, which has implications for fracture interpretation. Heads were divided into four groups, characterized by the type of bullet used and the location of the entrance wound on the cranium (frontal bone or temporal/parietal bone).

A specialized shooting stand was designed to support each head at the height of an average adult male, and each head was secured using a padded wooden vice and luggage straps, so that it could remain in position yet not completely fixed in place. Each head was shot once either in the frontal or parietal/temporal bone region by an expert marksperson, using a revolver with a 1 7/8 inch barrel loaded with 0.38 caliber bullets. Each shot was taken from three yards. Bullet type (jacketed hollow point vs. full metal jacket) was distributed randomly yet evenly between individuals. Twenty-three heads were shot with FMJ bullets and 22 heads were shot with JHP bullets. Following the experiment, heads were x-rayed, CT-scanned, autopsied, and macerated using standard procedures (chemical/enzyme processing or dermestid beetles). After processing, skulls were also evaluated for bone density using dual energy x-ray absorptiometry (DEXA).

Methods/Data Analysis

To determine whether bullet type could be predicted from cranial damage, several analyses were undertaken on the skulls. All statistical analyses were conducted using IBM SPSS software. These are outlined below.

Exit Wounds and Bullet Type

To assess whether bullet type (full metal jacket vs. hollow point) affects whether there is an exit wound for individuals shot in either the frontal bone or temporal/parietal bone, chi-square analysis was used. We analyzed two sets of variables: (1) exit wound presence in the soft tissue dependent on bullet type; and (2) exit wound presence in the bone only (but not the soft tissue) dependent on bullet type.

Bone Mineral Density and Cranial Bone Thickness

To evaluate how bone mineral density affects the propagation of radiating fractures and the overall level of cranial fragmentation as well as assessing how cranial vault thickness affects the size and morphology of gunshot entrance and exit wounds, we used the bone density scan data and measurements of bone thickness, as well as the lengths of the radiating fractures.

Bone thickness was measured using spreading calipers within 5 mm of the entrance and exit wounds. Radiating fracture lengths were measured in millimeters using a Scale Master digital plan measuring tool. Fragmentation of the skull was assessed by sorting individuals into four categories based on degree of fragmentation. Shape of the entrance and exit wounds was assessed using the circularity function in the image processing program ImageJ. A Pearson product moment correlation was conducted to evaluate whether bone density and bone thickness are useful in predicting three outcomes of gunshot trauma: (1) radiating fractures; (2) entrance and exit wound area, perimeter, and circularity; and (3) degree of fragmentation.

Area and Perimeter of Entrance Wounds

To determine the effect of the different bullet constructions on the size (area and perimeter) of cranial entrance and exit wounds, we virtually collected area and perimeter data using the “wand (tracing)” tool in the image processing program ImageJ from digital photographs of the skulls. T-tests were used to assess if there were significant differences in the area and perimeter of entrance and exit wounds by bullet type. Five variables were analyzed: (1) area of the entrance wound; (2) perimeter of the entrance wound; (3) area of exit wound; (4) perimeter of exit wound; and (5) exit-to-entrance wound area ratio.

Entrance and Exit Wound Diameter

Minimum diameters of entrance wounds and maximum diameters of entrance and exit wounds were measured in millimeters using digital sliding calipers. Maximum diameter measurements were the widest points on the margins of the entrance or exit defect. Independent sample t-tests with significance set at 0.05 were run in SPSS to compare bullet constructions by maximum or minimum diameter for shots to the frontal bone or parietal/temporal bone. A subsequent ANOVA test was run to assess how minimum entrance wound diameter was affected by both shot location (frontal or temporal/parietal) and bullet construction.

Bullet Mass Loss

To determine whether the bullets fired into the heads underwent differential deformation based on bullet type and shot location, we weighed bullets following recovery, and mass loss was measured as 130 grains (the original bullet weight of each bullet type) minus the weight of each recovered bullet. Thirty-one bullets were recovered total, and were nearly evenly distributed between FMJ (n=16) and JHP (n=15). Bullets impacting the frontal bone numbered 18, while bullets impacting the temporal/parietal bones numbered 13. Damage to each bullet was quantified as mass loss measured in grains. The relationship between loss of bullet mass, impacted bone, and bullet type were analyzed via univariate ANCOVA in SPSS.

Bullet Type Prediction from Quantitative and Qualitative Variables

Entrance wounds, exit wounds, and resultant fractures were examined both endocranially and ectocranially. Three observers independently scored all 45 crania. Quantitative data were collected on the minimum and maximum diameter of the entrance and exit wounds. Qualitative data included evaluation of bevel characteristics such as its relative size to the wound and whether bevel margins were smooth or crushed, wound shape (i.e., oval, round, or irregular), presence of circumferential delamination around wound margins, and the degree of any cranial fragmentation.

Given missing values from the qualitative data due to not every cranium having an exit wound and to maximize the sample size number of frontal shots (n=24) and parietal/temporal shots (n=21), only the quantitative data were analyzed here. Logistic regression was used to create a diagnostic test of the quantitative data to include sensitivity (i.e., ability to pick up true positives), specificity (i.e., ability to pick up true negatives), and accuracy; with the jacketed hollow point as the referent bullet.

Project Findings

Exit Wounds and Bullet Type

Full metal jacket bullets were found to exit both the bone and soft tissue in both locations (frontal and temporal); while jacketed hollow points were found to not differ significantly in their exit patterns when the individual was shot in the frontal. However, jacketed hollow points were found to not exit the soft tissue in the temporal-only and pooled samples.

This analysis revealed that bullet construction (hollow point vs. full metal jacket) has no significant relationship with presence of an exit wound in bone or soft tissue and bone, when fleshed heads are shot in the frontal bone, and revealed that full metal jacketed bullets generally perform as expected, in that the majority exited the bone and soft tissue. At the same time however, the performance of the hollow points was more complex than expected. The hollow points *did not* perform as expected for those individuals shot in the frontal - they exited both the bone and external soft tissue. However, in the temporal-only and pooled samples, these bullets *did* perform as expected and generally did not pass through the external soft tissue, only the bone.

Bone Mineral Density and Cranial Bone Thickness

Significant results using the Pearson product moment correlation test at an alpha of .05 included the relationship between bone mineral density (BMD) and total length of exit wound radiating fractures ($p=.029$); BMD and average length of exit wound radiating fractures ($p=.031$); BMD and maximum length of exit wound fractures ($p=0.019$); and BMD and degree of fragmentation ($p=.001$). In terms of bone thickness, significant results included the relationship between bone thickness and entrance wound perimeter ($p=.028$); entrance and exit wound-adjacent bone thickness and entrance wound circularity ($p=.033$) and degree of fragmentation ($p=.030$).

These results indicate that BMD has more of an effect on the propagation of radiating fractures and the degree of fragmentation of the skull than it does on the size or the shape of entrance and exit wounds. In our sample, bone density did not have a significant effect on the size or shape (area, perimeter, and circularity) of entrance wounds. The results of the bone thickness tests indicate that bone thickness has an effect on entrance wound size and shape as well as on the degree of fragmentation, but not the propagation of radiating fractures. The results of these tests also demonstrated that entrance bone thickness and exit bone thickness were closely correlated, yet interestingly were significantly correlated with slightly different variables. Entrance wound thickness was correlated with entrance wound perimeter, whereas exit bone thickness was not correlated with entrance wound perimeter. All other correlations with entrance wound thickness were shared with exit wound thickness, though the correlations with entrance wound thickness were stronger than those with exit wound thickness. As hypothesized, bone mineral density significantly impacts the degree of cranial fragmentation in the event of gunshot trauma.

Area and Perimeter of Entrance Wounds

Significant results using the independent samples t-test at an alpha of .05 included the relationship between the two bullet types and entrance wound area ($p=.001$) as well as perimeter (p=.001). However, the tests examining these variables for exit wound area and perimeter were not significant. In addition, results of the paired samples t-test comparing the area of the exit wounds to the area of the entrance wounds were significant (p=0.001). Finally, results of the independent samples t-test comparing the two bullet types for exit wound area relative to entrance wound area were not significant.

As expected, there was a significant difference in the size of gunshot entrance wounds by bullet construction with jacketed hollow points producing larger entrance wounds. Unexpectedly, these bullet constructions did not produce significantly different-sized exit wounds. Also as expected, exit wounds were consistently larger than entrance wounds; however, there was not an exit-to-entrance wound size ratio that was unique to either bullet construction.

Entrance and Exit Wound Diameter

Significant results of the independent samples t-test at an alpha of .05 included the comparison of the two bullet types with the maximum diameter of entrance wounds (pooled sample [p=.002] and frontal [p=.018] and temporal/parietal [p=.001] separated out). The comparison of the bullet types to maximum diameter of the exit wounds were not significant.

In terms of minimum diameter, the analysis using ANOVA demonstrated that on average, impacts from JHP bullets created larger entrance wounds than did FMJ bullets (p=.001), irrespective of shot location. Overall, FMJ shots were very similar when shot locations (i.e., frontal vs. temporal/parietal) were compared, but JHP shots were significantly different when shot locations were compared, with JHP bullets to the frontal bone producing average minimum entrance diameters 1.79 mm larger than did JHP bullets to temporal/parietal bones (p=.006). As expected, these data demonstrate that JHP ammunition produces gunshot entrance wounds with larger maximum diameters than FMJ ammunition. However, the same pattern with the differences in maximum diameter measurements were not present for the exit wounds.

Bullet Mass Loss

Using ANCOVA, the results indicate a significant relationship between mass lost and target bone on the skull ($p=0.039$). In contrast, bullet type (FMJ vs. JHP) showed no significant relationship with mass lost ($p=0.429$). The combined effect of target and bullet type showed no significant relationship ($p=0.668$). The differential degrees of bullet mass loss between skeletal elements suggests that this figure may be used as a metric for associating fired bullets with damage to skull elements of differing thickness. At lower levels of mass loss (>1.3 grains), distinction between frontal and temporal damage would not be possible, since the ranges of mass loss overlap at these levels. At greater levels of mass loss, bullets are more likely to be associated with hits to the frontal bone. In general, this supports the hypothesis that thickness has a significant influence on the degree of damage to bullets striking bone.

Bullet Type Prediction from Quantitative and Qualitative Variables

For entrance wounds to the frontal bone, a cut point of 11.0 mm minimum diameter had a 90.9% sensitivity, 84.6% specificity, and 87.5% accuracy in determining the bullet type, with the jacketed hollow point entrance more likely to be above 11 mm ($p<.001$). For entrance wounds to the parietal/temporal bone, a cut point of 9.5 mm minimum diameter had 100% sensitivity, 80% specificity, and a 90.5% accuracy in determining bullet type with the jacketed hollow point entrance more likely to be above 9.5 mm ($p<.0001$).

These results indicate that for .38 caliber bullets, entrance wound diameter at different locations on the cranium is a very strong predictor of bullet construction, with jacketed hollow points creating a larger entrance wound overall.

Conclusions

To determine whether bullets of different constructions could be estimated or determined from cranial gunshot trauma, we conducted several tests on multiple variables including size and shape of entrance and exit wounds, length of radiating fractures, presence of exit wounds in bone and soft tissue, and the effect of bone mineral density and bone thickness. We also examined the amount of mass lost of the bullets that were used in the experiments. The most substantial finding is that bones struck by JHP and

FMJ ammunition of the same caliber can be distinguished based on the diameter of the entrance wound, with wounds caused by JHP bullets being significantly larger. We hypothesize this is due to the petals of the bullet expanding upon contact. In addition, this analysis confirmed that exit wounds are almost always larger than entrance wounds. Further, we found that BMD has more of an effect on the propagation of radiating fractures and the degree of fragmentation of the skull than it does on the size or the shape of entrance and exit wounds, meaning that bullet type can be estimated irrespective of the individual's bone density.

Implications for Criminal Justice Policy and Practice in the United States

The NIJ Forensic Science Technology Working Group Operational Requirements for the past several years has outlined multiple research needs within the forensic sciences. One of these in particular calls for greater understanding of the modeling of injuries:

> *Further research studies on force measurement, fracture mechanics and modeling of injuries (to include bone tissue and soft tissue) to improve accuracy of trauma analysis and quantify error rates associated with trauma interpretation.*
> (From: http://www.nij.gov/topics/forensics/documents/2015-forensic-twg-table.pdf)
> Page 9; accessed 1.23.16.

The proposed study contributed to this research goal, in that it initiated an understanding of whether two different bullet constructions for bullets designed to either stay intact upon impact or fragment upon impact result in measurably different fracture patterns on the human skull, when other major extrinsic variables are controlled for. This knowledge in part contributed to a separate research goal, that of creating a cranial gunshot wound trauma descriptive and photographic atlas. This purpose behind this atlas is to ultimately improve skeletal gunshot trauma interpretation. This atlas is available upon request to interested members of the forensic science community.

While the current consensus is to not attempt to estimate variables such as bullet caliber from skeletal remains (Berryman et al., 2012), this is largely due to the large number of extrinsic variables that are unknown during the traditional or skeletal autopsy. These variables include factors such as velocity, distance of shooter to victim, caliber (sometimes unknown if the bullet is not recovered), firearm type, etcetera. Our ultimate goal was to control for each of these variables experimentally to generate knowledge about the impact each variable has when the others are controlled for. Practitioners who refer to the atlas will be able to have a better understanding of gunshot wound injury by simplifying the picture via limiting of confounding variables. While a number of research papers and books exist with photographs and descriptions of gunshot wounds (e.g., DiMaio, 1999; Kimmerle and Baraybar, 2008), the injuries depicted were not created experimentally, meaning that a number of the extrinsic variables that interacted to create the final injury pattern are unknown.

The knowledge this project generated, namely, that distinct bullet constructions leave different signatures on human bone fills in a hole in our knowledge of the effect of this variable on cranial gunshot trauma. Providing practitioners with some indication of whether differing bullet constructions contribute to distinct injury modeling further contributes to efforts to build upon our ability to reveal information from the skeleton.

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