Firearm Bullet Performance: Phase II, Live-Fire Experimental Study for Archaeological Interpretation©

Douglas D. Scott, Joel Bohy, Nathan Boor, Charles Haecker, Peter Bleed, Patrick Severts, and William Lees

With support from the Lamar Institute

July 3, 2019

(Revised March 20, 2024)

Table of Contents

List of Figures

Acknowledgements

This live-fire experiment is a follow-up or second phase to the November 2016 colonial fowling piece and musket live-fire experiments we reported in 2017. It could not have been undertaken without the cooperation and aid of many individuals. We are extremely grateful to co-author Nathan Boor of Aimed Research for his advice and expertise as well as good company during the field experiments. Nathan provided the high-speed camera set-up that enabled us to collect not only muzzle velocities but also incredible imagery that immeasurably added to our data interpretation.

We are very grateful to Rita and Daniel Elliot and the Lamar Institute for their financial support. Their grant offset some travel costs and allowed for Nathan Boor's participation.

Nancy Williams, Caroline Robinson, as well as Carol and Tom Shanahan not only aided in the live-fire experiments but provided significant logistical support that is sincerely appreciated. Mary Jane Balicki was an avid supporter and assisted during the shoot. We are grateful to Joanna Baxter for providing accommodation for several of the participants. We owe a sincere debt of gratitude to Doyle Hagler, Glenn Garner, and Tony Blocher for their support and assistance with the logistics and shooting efforts.

Introduction

Experimental archaeology has emerged as a rigorous approach to the study of material reflections of human behavior. It has a rich history in the field of archaeology which has largely focused on understanding technological processes affecting environmental and cultural adaptations in the prehistoric past (Coles 1973; Flores 2011; Millson 2011; Shillito et al. 2014). This is an increasingly refined field that lets archaeologists develop insights and methods for making behavioral interpretations of things in the archaeological record. Among the critics of experimental archaeology is Lin et al. (2018) who argue that there is a need for greater emphasis on hypothesis development and variable control to establish what they refer to as *"sound referential linkages upon which constructive analogic inferences about the past can be built."*

We largely agree that more rigorous studies need to be developed to achieve those lofty goals in all areas of archaeological research. Our experimental archaeology efforts focus on the exterior ballistic performance of projectiles and how experimental bullet impact data can inform conflict archaeology studies or any archaeological investigations of sites where firearms residue is found.

To study firearms, archaeologists need to design and carry out appropriate experiments and draw on technical methods developed by firearm examiners, engineers, and physicists. Recent battlefield archaeological investigations have given new impetuous to identifying the rifling characteristics of historic rifled firearms, the external ballistic capability of such firearms, and the combat efficiency of such arms. The goal of this study was to collect information on the ballistic capability of late-eighteenth and mid-nineteenth century rifled firearms. In addition, a smoothbore colonial-era Dragoon pistol was fired, and additional tests of a colonial-era fowling piece with nine buckshot were conducted. This study is a follow-up to experimental work done on colonial smoothbore fowling pieces and muskets dating to the American Revolution-era (Scott et al. 2017).

The results of this live-fire experiment with colonial, Revolutionary War, and American Civil War firearms add to the investigation of late pre-modern gun use and enhance our previous work on colonial-era firearms (Scott et al. 2017). To determine what happens when large-caliber lead balls, shot, and conical bullets were used in combat or hunting we observed impacts of experimentally fired projectiles into ballistic gelatin, an accepted tissue simulant with end coverings to simulate clothing of the era, and into a sand backstop. Projectile deformation associated with varied ranges were catalogued. The results of these experiments will permit archaeologists to better interpret recovered projectiles.

The study goals were to collect data and conduct live-fire experiments with high-quality faithful reproductions of typical and common colonial and Revolutionary War-era weapons and an original Pattern 1853 Enfield rifled musket. The study activities were designed to benefit several audiences:

1) Those interested in the history of firearms.

2) Re-enactors who will use the information in creating more authentic presentations.

3) Professional historians, archaeologists, and interpreters who either deal with firearms or how firearms were used; and

4) Firearm examiners can use the information to exclude historic bullets and cartridges that are sometimes found on crime scenes from consideration and/or correctly assess black powder and reproduction firearms that are sometimes used in shooting incidents today.

The live-fire experiments were designed to capture information on flintlock and percussion firearm performance and capabilities that will benefit the goal audiences in their understanding and interpretation of archaeologically recovered spherical and conical lead balls. To achieve these objectives, we designed the experiments to collect data on:

1) The velocity, range, and ballistic performance of common spherical lead balls of the type used in the colonial-era.

2) Factors that could cause variation in ball impact; and

3) How deformation of lead balls can be linked to velocity, impact range, and target media.

4) To continue the earlier study by focusing on the exterior performance of the famed conical hollow based Minié ball or bullet.

This report is generously illustrated for the simple purpose of providing the reader with illustrations of weapon types, bullets, bullet deformation, and methods. The extensive use of figures is, we believe, important to visualize and make clear the complex elements of firearms exterior and terminal ballistics that would result in a far wordier presentation otherwise.

Principles of Firearms Exterior Ballistics; Background to the Study

Exterior ballistics is the study of the performance of a bullet after it leaves the gun. As Lucien Haag (2006:214-215) observes there is a difference in what a ballistician and a forensic scientist, or for our purposes an archaeologist, is seeking in studying bullet performance. The forensic scientist or conflict archaeologist is seeking to reconstruct a shooting incident or event based on residual physical evidence, the artifact, and knowledge of one or more types of firearm ammunitions' ballistic properties and performance.

Essentially all firearms send a projectile toward a target in a like manner (Garrison 1993; Hueske 2006). The target is determined to be at a certain range, and there is a line of sight between the shooter and the target. When the bullet is fired from the firearm it has a line of departure, a bullet flight path, and an angle of fall which are affected by various physical forces, initial velocity, gravity, air resistance, wind direction, elevation, temperature, barometric pressure, and relative humidity. Each of these factors can be accounted for in one or more ballistic formulae that are used to calculate, with reasonable accuracy, how far the bullet will go before reaching a terminal velocity and return to earth. Likewise, formulae exist to calculate how much energy as foot pounds or joules, or kinetic energy a bullet will have at various ranges (Warlow 2005:130-134). These data become important to understanding bullet capability to incapacitate or kill, or what may happen to a bullet that is an under or overshot. Knowing this basic information allows the archaeologist to understand better the pattern of bullet deformation observed on a battle site, the patterns in which bullets are found, and better interpret an artifact assemblage.

External ballistics for post-1900 firearms and bullets are relatively well known and is the continuing subject of analysis as new smokeless gun powders and conical bullets are developed. Datasets on external ballistics and bullet performance are limited for the soft lead spherical balls and cylindro-concodial bullets of the preceding centuries, especially the spherical lead ball. A great deal of lore and apocryphal information exists on the ranges and performance of these historical bullets. There are good summaries of test shooting, largely at pine boards and thick catalogs or telephone books (Mattoo 1969; Cayton 1984; Fadala 1988; Osborne 1977a, b; Herring 1971; 1972a, b, c), to determine bullet penetration at various ranges that were conducted in the nineteenth century and well into the twentieth century. This data is of limited value to modern researchers. Thus, it becomes necessary to conduct firsthand live-fire research with a variety of weapons under controlled experimental conditions to ascertain the behavior of spherical bullets and other projectiles that will enhance our understanding of lead bullet behavior of the pre-1900-era.

Components of the Live-Fire Experiment

The live-fire experiment used common types of French & Indian War and Revolutionary War Flintlock firearms as well as a Civil War rifled musket. Other components of the experiment included the firing range, consideration of the black gunpowder used as a propellant, standardization of the lead balls, the construction of authentic-style cartridges, and the methods of data collection.

Firearms Used in the Experiment

Two flintlock shoulder-fired firearms, one flintlock pistol, and one American Civil War-era rifled musket were used in the live-fire experiment (Figures 1, 2, 3, and 5). The rifled musket is an original firearm, the others are high-quality reproductions of original firearms. One colonial flintlock, a copy of a .62-caliber Thomas Earle-made fowling piece, represents the type of weapon used by many colonial minute and militiamen and was the subject of buckshot and patched ball firing. One British Pattern 1756 long land musket, aka Brown Bess, in .76-caliber, represented the standard British infantry firearm used in the French & Indian War as well as the American Revolution. The Brown Bess was also used in a double ball load experiment. A .60-caliber Dragoon pistol is a typical colonial-era sidearm and was used to determine velocity and bullet deformation for a flintlock pistol. A .61-caliber colonial rifle was fired with both patched and unpatched balls to determine rifle velocity and whether patching fabric was impressed into the ball during firing. An original British Enfield Pattern 1853 (P-53) English contract percussion rifled musket represented a common firearm used by both sides during the

Figure 1. Thomas Earle fowling piece being fired during the 2016 live-fire experiments.

Figure 2. Colonial rifle at the bench being set for a shot.

Figure 3. Flintlock Dragoon pistol set for a shot.

Figure 4. British Pattern 1742 Long Land musket during the 2016 live-fire experiments.

Figure 5. Enfield Pattern 1853 rifled musket ready for firing.

American Civil War was fired to determine the external ballistic performance of Minié balls (hollow-based conical bullets).

The experimental firing was conducted over a three-day period, November 12-14, 2018, near La Grange, Georgia. The weather conditions were less than optimal, with rain and high humidity a factor in the experiment. November 12 was employed as a preparation day due to heavy rain conditions that precluded firing and setting up the high-speed camera component. The live-fire was held on November 13 and 14 in light rain and humid conditions, ranging from 70% to 86%, on both days. Local temperatures were in the low 50s degrees Fahrenheit, and the barometric pressure hovered around 30 inches Hg both days. The humid and wet conditions created realistic field conditions experienced by soldiers of the era which added to the experimental work but hampered some recording efforts. Smoke from the black powder tended to "hang" in the dense air conditions limiting some velocity data collection since the bullet could not be seen in the high-speed camera imagery.

Firing Range

For this study a wood framed target rack was placed 100-yards downhill from the shooting position. Due to the constant rainy conditions firing was done from a covered porch area that provided protection for the camera set-up, and kept the shooter, weapons, and powder dry (Figure 6). High-speed videography on the 100-yard range was set up to capture muzzle velocity. A shooting bench was constructed to provide a stable base for consistent shooting. While demonstrating accuracy was not the goal of the live-fire experiment, the bench and target provided a stable aiming point for all shots. Just to the front of the sand backstop a target stand with a man-sized silhouette target provided a defined aiming point. The target frame was constructed of 4x4 inch treated pine lumber with a sheet of fiberboard as a target backing.

Figure 6. Camera and shooting area set up on the covered porch which was required due to inclement weather conditions.

A second range of 30 yards in length had been established for use in firing at ballistic gelatin (Figure 7). The range was established with safety as the priority. It was set up in a ravine with a large sand and clay-based backstop with rising ground behind that provided additional safety factors. A tarpaulin was placed on the backstop to track projectile point of entry and improve bullet recovery time. The high-speed camera was adjacent to the target to capture bullet velocity and performance as it entered the tissue simulant.

Figure 7. The 30-yard range with pop-up shelters for the shooter and in the background for the high-speed camera.

Due to the inclement weather conditions pop-up shelters were erected at the shooting position and down range and to one side for the camera. The ranges are located on private property with limited access, thereby providing access control for personal and equipment and ensuring a safe shooting scene.

One team member was designated as range safety officer, with all other shooting team participants also remaining vigilant. After firing the weapon was cleared and a recovery team proceeded down range to recover the projectile. When a flintlock had a hang fire or flash in the pan occurred, the weapon was held in place for a count of 30 seconds, the pan cleaned and re-primed, then an attempt made to fire the weapon again. The range was declared clear only when the weapon was successfully discharged.

After each firing a metal detector sweep of the backstop was conducted to expedite the locating of the fired projectile and to keep the sand free of potential hazards. Just to the front of the sand backstop a target stand with a silhouette target provided a defined aiming point.

Black Gunpowder Propellant

In this study, we used Swiss FFg black gunpowder as the priming and propellant charge in all weapons. Only the charge weight was varied among the guns fired and for purposes of achieving lower velocities for shooting into tissue simulant. Dodd (2006:31) defines black powder as:

> "Black powder, by its very nature, is a true explosive. The smallest of sparks is sufficient to effect ignition. On ignition, a large quantity of bluish-grey smoke is generated and a characteristic sulfurous residue is deposited on both the weapon and the shooting hand. The Chinese are credited with its discovery and the discovery of the explosive properties of the mixture of substances we know as traditional gun powder — sulfur, charcoal, and saltpeter (potassium nitrate). It is suggested that gun powder may have been used in the manufacture of fireworks well before its application to firearms and warfare. Only the manufacturing process has been refined over time."

The origin of black gunpowder is still debated in academic circles, but it is largely agreed to have originated in China in the eleventh century and spread to Europe by the late-thirteenth or early-fourteenth centuries (Buchanan 1996). The first black powder was hand mixed and is referred to as serpentine powder (Hall 1996:87-88). The black gunpowder used in this study is much more refined and is referred to as corned gunpowder. Corning, the wetting of the dry mixture, stamping, and glazing, as well as other manufacturing processes, began in the mid-1400s and largely supplanted serpentine powders by about 1550. The corning process was refined over time, but for all practical purposes corned black gunpowder was the only type used in the New World after the mid-1500s (Hall 1996; Tascón et al. 1996; Howard 1996). The Swiss® brand corned black gunpowder used in our experiments is among the best at producing reliable and replicable results in comparisons with other black gunpowders and black powder substitutes manufactured today for sporting purposes (Haag 2001; 2012).

Historically, the amount of black gunpowder used in various weapons in the eighteenth and early nineteenth centuries varied substantially. The variation in charges is discussed in detail in our previous report (Scott et al. 2017).

We chose to use a 110 grain black powder charge in the 75-caliber gun including the priming charge as it most closely approximates and is consistent with the known charges in surviving Revolutionary War cartridges for the 100-yard firing experiments. For the fowling piece we chose to use an 85 grain powder charge including the priming charge. The colonial rifle powder charge was 80 grains. The Dragoon pistol charge was 60 grains, as was the charge for the P-53 Enfield. We also used reduced charges to lower the muzzle velocity when firing at ballistic gelatin to capture the bullet in the gelatin. Powder measures showed only a .1-gram variation in weight among any given charge size.

Lead Spherical Balls and Minié Balls Used in the Experiment

Information on the diameter and weight of balls from the Revolutionary War musket and fowling piece comes largely from the archaeological record. This issue is discussed in detail in our previous report (Scott et al. 2017).

The spherical balls used in the live-fire experiment are commercially cast soft lead bullets (Figure 8). All the balls were weighed, and the diameter measured during the preparation work. Each ball was numbered with an indelible marker so that the original diameter and weight could be compared to the fired diameter and weight. The same was done with the Minié balls (conical hollow based bullets) intended for use in the Enfield P-53 musket.

Figure 8. Unfired examples of the bullets used in the experiment. L. to R., .282-inch buckshot, .530-inch ball, .580-inch ball, .60-inch ball, .69-inch ball, .58-inch Minié ball with wide skirt base, and .58-inch Minié ball with narrow skirt base.

The experimental spherical ball weights show a minimum of 1.5 grain (.1-gram) to a maximum of 4.6 grain (.3-gram) weight variation. The measured ball diameters also showed very little variation, being about .001 to .003-inch among all the balls measured. They have far less variation in weight and diameter than any of the published historical ball diameters or weights or for reported archaeological specimens. The balls are less than bore size which is typical of the era as less than bore sized to allow ease of loading, especially after multiple rounds were fired which caused black powder fouling in the bore. The common term for this is windage.

Minié balls were of two types. The first type was from the Log Cabin brand. It has a wide ring around the base. Many of the bullets had a void in the hollow base suggesting low quality control when they were cast. The bullets proved to be inaccurate when fired. A second conical Minié ball type, a more typical 3-base ring type, was used in most of the 30-yard firing work.

Cartridges and Cartridge Paper

Prior to the live-fire experiments Joel Bohy and Patrick Severts rolled a series of cartridges in each of the calibers to be used following eighteenth and nineteenth century guides on cartridge construction (Figures 9, 10). Proper weight laid paper in a trapezoid shape was rolled around a wood former. A ball or nine buckshot were placed in one end, the top twisted closed and the former removed. The appropriate powder charge for the caliber was then poured into the other end of the cartridge, then the paper was twisted closed, and the excess laid paper folded over to form a tail. Linen twine was then wetted and tied below the ball or ball and buck to hold the bullet in place. Finally, a ball point pen was used to mark the completed cartridge with the name of the gun and ball size.

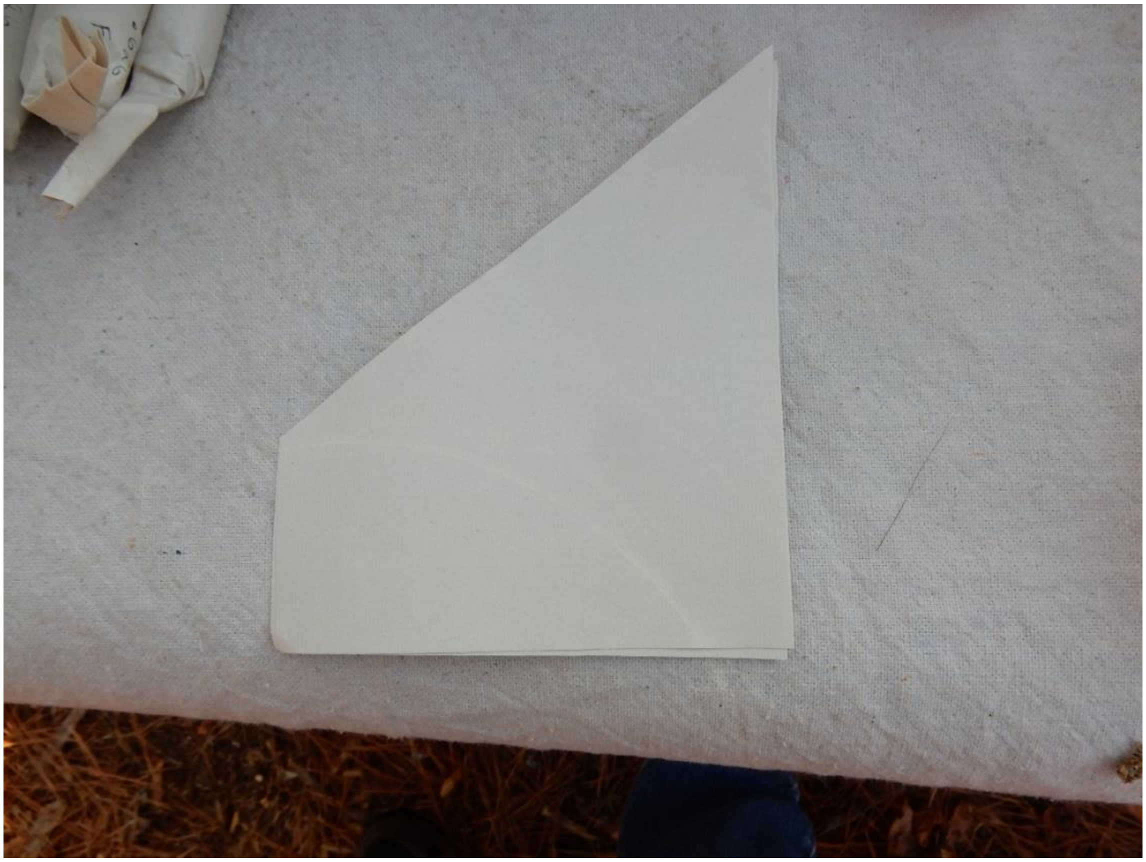

Figure 9. Laid cartridge paper cut to standard form and ready for rolling cartridges.

Figure 10. Patrick Severts and Joel Bohy rolling cartridges in preparation for the experimental firing.

Live-Fire Experiment

The live-fire experiments were conducted on November 13-14, 2018. Each firearm was loaded for the experimental firings by a single individual. Each firearm was fired in multi-shot strings by the same individual. The guns were fired from a bench rest, not to achieve accuracy for each shot, but to enable the use of high-speed videography to capture the ball as it emerged from the muzzle as well as record initial muzzle velocity.

Nathan Boor of Aimed Research® provided and operated a Phantom V611® high-speed camera that was calibrated for each shot string. The camera recorded imagery at approximately 6,900 frames per second in raw format. For each shot string, the gun was placed on the bench and the height from muzzle to ground surface was recorded. Each shot had the bullet diameter and weight recorded. Also recorded were the weight of the propellant charge, the calculated muzzle velocity, temperature, wind speed, humidity, and barometric pressure. Weather data was recorded using the Ballisticarc© program by Geoballistics with an attached WeatherFlow© anemometer installed on an iPhone X.

Weather throughout the live-fire event was rainy with recorded temperatures in the mid-50s degrees Fahrenheit with humidity between 70% and 86%. It was cold and wet.

Shots were fired at a range of 100-yards using a man-sized head and torso silhouette target mounted on a 4x4 treated pine frame. On November 14 shooting was confined to firing the fowling piece, rifle, Dragoon pistol, and the P-53 Enfield at blocks of Clear Ballistic® gelatin at a 30-yard range with a sand and clay backstop.

After each shot was fired two to three team members moved down range with metal detectors to search for and recover the fired ball. Metal detectors employed included a Minelab CTX 3030®, a Minelab E-TRAC®, and a Fisher F75®. Recovered bullets were bagged separately and labeled with the gun type, shot number, ball diameter, muzzle velocity, date, and any other relevant information.

The live-fire experiment resulted in the firing of 74 spherical or conical balls and 63 buckshot. The breakdown for each caliber fired by number of shots fired with recoveries are noted, and total number of balls recovered per caliber.

9 - .530-inch patched balls were fired in the Thomas Earle fowling piece – 7 known shot sequences recovered, one not recovered, and one unknown shot attribution recovered – recovery 8 balls = 89%.

7 - .580-inch balls were fired (2 in the colonial rifle and 5 in the Dragoon pistol) – 7 known shot sequence recoveries – recovery 7 = 100%.

12 - .60-inch balls were fired in the colonial rifle – 9 known shot sequence recoveries – total recovery = 75%.

4 - .69-inch balls were fired in two shot sequences in the Pattern 1756 musket –3 balls recovered = 75%.

22 - .577-inch conical bullets fired from the P-53 Enfield – 11 known shot sequence recoveries – 3 unknown attributions – total recoveries 14 = 63%.

18 - .282-inch buckshot was fired in two separate shots in the Thomas Earle fowling piece – 2 recovered with unknown attribution- total recoveries 2 = 11%.

Total ball and buckshot fired 72 - Total known recoveries 43 = 60%   Total unknown recoveries 6 = 8%. Total recovery 49 = 68% Ball and bullet recovery = 76% Buckshot recovery = 11%.

Thomas Earle Fowling Piece - .62-caliber, was fired on each of the two days of shooting. Five shots were fired on the first day with no misfires in the wet weather. The load was 85 grains of FFg Swiss black powder. Three shots were fired with .530-inch diameter balls, each patched with bed ticking .019-inch-thick (Figure 11). Two shots were fired using nine .282-inch diameter buckshot in each round. Six shots were fired on the second day using 65 grains of powder and patched .530-inch balls. No misfires occurred.

Figure 11. Spherical balls marked and prepared for firing with greased cotton bed ticking patches.

The purpose of firing the fowling piece with patched balls was to determine if the patch fabric weave would be impressed into the body of the ball during firing. Nine .530-inch balls (numbered 19-25) were fired with patching. Balls 20 and 25 were not recovered or not identified as to shot number. Velocities ranged from 550 f/s to 1160 f/s depending on the powder charge for six of the nine shots. Velocity could not be recorded for three shots. All balls exhibited impact scarring for their individual velocities consistent with the 2016 experiments with the same fowling piece (Scott et al. 2017). Black powder stippling, as well as sand, soil, and wood impact scarring (Figures 12, 13) was evident on all the recovered balls. No patch fabric impressions were observed on the recovered balls regardless of their fired velocity.

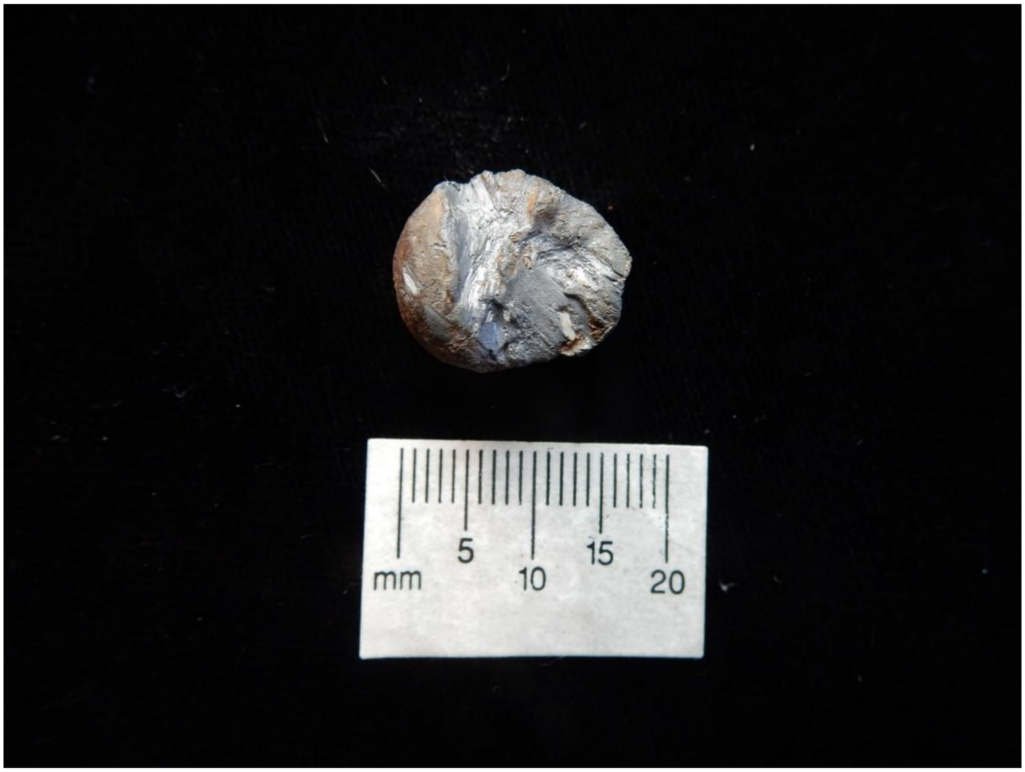

Figure 12. Impact scarring from striking the wood target frame. The damage is extensive, and some wood grain is visible on the scars, as well as wood fragments embedded in the ball.

Figure 13. Examples of black powder stippling observed on fired balls.

The purpose of the buckshot firing was to follow up on the 2016 experiments of firing buck and ball in the fowling piece (Scott et al. 2017). This experiment used nine uncontained buckshot of .282-inch diameter. The powder charge was poured down the barrel, then a paper wad was rammed in, followed by nine buckshot, and a paper over wad was seated. This experiment builds on the work of Dr. Lawrence Babits who conducted a series of live-fire experiments to determine the accuracy of buck and ball loads at different ranges. He conducted the experiments over several years with French and U.S. regulation muskets (Babits 2002). His report used documentary sources and compared them to his live-fire experiments. He found that the ball was reasonably accurate out to 100 yards, but the buckshot rarely hit the target at that range. Buckshot would hit an intended target at 25 to 30 yards, but beyond that range it was largely a matter of coincidence if a buckshot hit its intended target.

In this experiment each buckshot pellet was labeled with a sequential number with an indelible marker. The intent was to recover the buckshot and record the location of each recovered shot. Velocity was recorded for several pellets in each shot. For Shot 1 velocity was recorded for seven pellets (740, 690, 570, 450, 655, 275, 225 f/s respectively). Eight of the nine pellets had their velocity recorded for Shot 2 (625, 625, 545, 510, 475, 265, 275, 120 f/s respectively). Pellets traveling under 300 f/s are unlikely to have caused wounding beyond bruising. Approximately one third of the pellets in each shot were recorded within three feet to four feet of the muzzle with a velocity of less than 300 f/s.

Surprisingly, only two pellets were recovered during the metal detecting. The heat of firing and travel down the bore erased the numbers placed on the pellets. One was recovered about 50 yards from the 100-yard target and the other was found in the backstop. The one recovered at 50 yards and had several contact marks on the body. These facets indicated the buckshot was part of the shot column. It had some banding around the body indicating compression or upsetting when it was fired. The buckshot found in the backstop was partially flattened and had several contact facets.

British Pattern 1756 Long Land Musket - .76-caliber, was fired twice on November 13 at 100 yards using a 110 grain powder charge in each shot. The gun was loaded with two .69-inch balls in each shot to simulate a double load known to have been used on occasion by the British in the eighteenth-century for close range volley fire. Parkman (2017:62-65) discusses multi-ball loads in his work on seventeenth and eighteenth-century firearm experimental firing.

The general belief that two spherical balls fired in a smoothbore musket possessed an advantage against massed troops at ranges of less than 300 yards was well established in the eighteenth and nineteenth centuries (Secretary of War 1856:111). Experiments with the new Model 1855 rifled musket firing two and three spherical balls were found to give satisfactory results for accuracy up to the 200-yard range at which it was tested. The test was conducted at 100, 150, and 200 yards. At 100 yards for five shots with three balls all 15 balls hit within a five-foot square area. At 150 yards 14 balls hit within a five and one-half foot high and six and one-half-foot wide area, and at 200 yards 13 balls struck in an area of six feet high and 11 feet long (Secretary of War 1856:112).

One of the few historical accounts of double ball load use in combat comes from the 1759 Battle of Quebec on the Plains of Abraham. General James Wolfe had ordered his soldiers to charge their muskets with two balls each in preparation for the engagement (Reid 2003:74-75). Chartrand (1999:88), citing a journal entry by Captain John Knox, serving with the 43rd Foot, wrote that as the French came within range, the regiments *"gave them, with great calmness, as remarkable a close and heavy discharge as I ever saw."*

There is one account regarding using a double ball or brace of balls load directly relating to the Boston Massacre. Edward Craft's account (Bowdoin and Warren 1770:67) of the same evening at another Boston location recalled speaking to a British soldier who told him *"his orders were, when the party came from the guard house by the fortification, if any person assaulted them, to fire upon them, every man being loaded with a brace of balls."*

Based on Craft's deposition, some suppose the British officers ordered their troops to load with double balls prior to the Boston Massacre in 1770. The assumption was that the number of casualties could not have occurred with only standard single ball charges. Sivilich's (2018) analysis of two lead balls attributed to the Boston Massacre in the Massachusetts Historical Society (the only two artifacts attributed to the event known to be in existence) demonstrated they were fired in British musket caliber weapons and struck at moderate to high-velocity. One ball allegedly passed through the arm of bystander Edward Payne and embedded in a door post. The second ball passed through a shutter and was recovered in the back wall of his house.

The live-fire experiment research question was simply: would a double ball load have the velocity to do the type of damage reported at Quebec and are the two balls found in Edward Payne's house consistent with a double ball load?

The live-fire experiment had .69-inch balls 18a and 18b loaded on a 110-grain black powder charge, less 15-grains for priming, for one shot and balls 17a and 17b loaded in a similar manner for the second shot. For the first shot at 100 yards, the top ball was traveling at a velocity of 678 f/s and the bottom ball at 260 f/s within three feet of the muzzle. Ball 18a, which was the bottom ball was recorded at 260f/s, was not recovered. Ball 18b, the top ball, was recovered in the 100-yard backstop. It showed black powder stippling on one face and some sand scarring from impact into the backstop. The ball was not significantly deformed. It would rank 1 on the ball deformation index (Scott et al. 2017) indicating a low-velocity impact.

The second shot, using balls 17a on the bottom and 17b on the top, was also loaded using a similar black powder charge (Figure 14) and two .69-inch balls. The musket misfired once but discharged the second time. Ball 17a, the bottom ball, had a velocity of 300 f/s at three feet from the muzzle, and the top ball, 17b, a velocity of 670 f/s at the same distance. Ball 17b was recovered in the 100-yard backstop. It had sand and dirt scarring but little deformation, scoring a 1 on the bullet deformation index. Ball 17b had a ramrod mark on one face and some black powder stippling on the opposite side. It had some sand and dirt scarring from impact in the ground about 40 yards in front of the target. It also scored 1 on the deformation index.

The recorded velocity of the bottom most balls was 260 and 300 f/s. Those velocities are below the threshold of a lead bullet's capability to do significant damage to a person or embed in a media.

Figure 14. Double ball load, 17a and 17b showing slight deformation from contact in the barrel on firing.

like wood. The fact ball 17a did not even strike the target but was found some 40 yards in front of it emphasizes its diminished velocity and ballistic characteristics.

The two top balls were both recorded at moderate velocities for a Brown Bess musket. Their initial velocities are similar to a single ball load as observed in previous experiments using the same type of gun powder and 110-grain charge (870-1215 f/s). This experiment's results are consistent with Mogish's (1990) findings in a fatal case where a black powder multi ball load resulted in death. The bottom ball acted as cue ball in pool pushing the other ball out at the cost of a loss of kinetic energy to the bottom ball.

The premise of a double ball load being capable of inflicting serious damage at short ranges only holds true for the top ball. The bottom ball may have had the capability to bruise or perhaps break the skin of a human, but the velocity was not fast enough to cause serious wounds. The premise of lethality for a double ball load is partially rejected.

Flintlock Dragoon pistol - .60-caliber, was fired five times using .580-inch balls rolled in cartridges using 60 grains of black powder. Three shots were fired on November 13 with Shots 12, 49, and 50 at the 100-yard target. Two shots were fired on November 14 at 30 yards into gelatin, Shots 11 and 13. The purpose of the pistol experiment was to determine muzzle velocity and down range performance.

No data was recorded for two shots, 13 and 49. Shots 12 and 50 fired at 100 yards had a recorded velocity of 330 f/s and 430 f/s respectively at three feet from the muzzle. The three shots fired at 100 yards were all recovered in the backstop. Shots 12 and 49 exhibited ramrod marks, black powder stippling, and sand and soil impact scarring despite the low travel velocity. Shot 50 exhibited banding around the ball from compression and traveling down the pistol bore as well as black powder stippling and some very light soil and sand impact scarring.

Shot 11, at 30 yards, had a recorded velocity of 433 f/s. The ball was recovered about 12 inches into the ballistic gelatin block. Shot 13 was fired at the gelatin block from 12 feet. No velocity data was recorded for this shot. The ball struck the simulated uniform cloth covering the end of the gelatin block, marking it with a black spot. The ball bounced back toward the shooter and was recovered about 12 yards from the target. Both balls fired at the gelatin exhibited black powder stippling but little to no impact scarring or deformation.

All five pistol fired bullets scored 1 to 1.5 on the bullet deformation index.

Colonial Flintlock Rifle - .61-caliber, was fired eight times on November 12 at the 100-yard target and six times on November 13 at the 30-yard target. The bullet used was a .60-inch diameter with 80 grains of black powder for the 100-yard firing and 60 grains for the 30-yard firing. The purpose of the experiment was to determine velocity with and without patching and ascertain if patched bullets were impressed with the fabric weave during firing. Another aspect of the live-fire was to determine the degree and detail of rifling impressions impressed on the ball during firing.

Rifle shots 2, 5, and 6 were fired on the 100-yard range with a .60-inch ball with no patching. No observable velocity data was recorded for these shots. Ball 5 was not recovered. Ball 2 exhibited a low-velocity impact with some soil and sand impact scarring. Very slight rifling impressions were evident. Ball 6 also exhibited a low-velocity impact with some sand and impact scarring. No rifling impressions were evident.

Rifle shots 1, 4, and 7 were fired with a .02-inch-thick greased bed ticking patch. Bullets 1 and 4 were not recovered but had recorded velocities of 1195 f/s and 1320 f/s respectively. Bullet 7 was recovered. Its recorded velocity was 1230 f/s. There is no evidence of patching fabric impression, but there is light compression banding with faint rifling impressions on the bullet body as well as soil and sand impact scarring. Black powder stippling is evident.

Bullets 19a and 20a are .580-inch diameter balls. We reduced the ball size in order to use a thick cloth patch. Both were fired on the 100-yard range with a .02-inch-thick greased bed ticking patch with 80 grains of black powder. Bullet 19a had a recorded velocity of 1150 f/s and 20a a velocity of 820 f/s. Both bullets were recovered and both exhibited compression banding with faint or light rifling impressions along with sand and soil impact scarring. Bullet 19a also exhibited black powder stippling.

Bullets 3, and 8 were fired at 30 yards at the ballistic gelatin as patched balls using the .02-inch-thick bed ticking Figure 15). Bullet 9 was fired without a patch at the same target. Bullet 3 had two observable velocities, the first at 1078 f/s in front of the target. The ball passed alongside the gelatin block but did not strike it. As the ball passed from camera view the velocity was recorded as 1042 f/s. The ball lost 36 f/s in 32 inches of travel at 30 yards from the gun muzzle. Bullet 3 exhibited no rifling or fabric impressions. The bed ticking patch was recovered. It is slightly charred with the ball outline clearly visible, but no rifling impression are evident. The bullet did exhibit a medium to high-velocity impact, 2.5 on the bullet deformation index, with soil and sand impact scarring.

Bullet 8 had a low initial velocity of 726 f/s in front of the target with a last observed velocity of 350 f/s as it passed low under the gelatin stand. The observed loss of velocity in 32 inches was 376 f/s. There is no evidence of fabric or rifling impressions. It exhibits a 1 on the bullet deformation index with little impact scarring.

Bullet 9 was fired without a patch as a control. Unfortunately, there was no observable velocity data. The bullet exhibits black powder stippling but no rifling impressions. It is a 2 to 2.5 score, medium to high-velocity impact, on the bullet deformation index. It exhibits flattening on one side and significant sand and soil impact scarring.

After firing bullets 3, 8, and 9 with little accuracy and no rifling impression evident it was concluded the bullets were undersized for the colonial rifle bore diameter. Bullets 61-1, 61-2, and 61-3 were employed. These bullets are greater than .60-inch in diameter but less than the bore diameter of .61-inch. Bullet 61-1 was patched with a thin, .014-inch thick, modern pressed fiber patch. The bullet entered the gelatin at 855 f/s striking the simulated colonial uniform cloth and passing through 32 inches of gelatin, exiting at 218 f/s. This is a loss of 637 f/s in 32 inches of travel in the gelatin. The bullet exhibited no evidence of the patch weave impression but did have faint rifling impressions as well as strong impressions of the colonial uniform cloth weave. The bullet exhibits little to no impact deformation (Figure 16).

Bullet 61-2 used a modern elastic polymer fabric as a patch that was .026-inch thick. There was no observable velocity data. The bullet passed to the left of gelatin and was recovered in the backstop. There is no evidence of the patch fabric impressions, but some faint rifling impressions are evident. There is minor soil and sand impact scarring but little to no bullet deformation.

Figure 15. Rifle ball 3 and the recovered bed ticking patch. The ball was deformed on striking the target. No rifling or fabric impressions are evident on the ball. No ball fired with a patch was found to have any fabric impressions.

Figure 16. The colonial rifle ball 61-3 on the left exhibits compression banding and rifling impression. Rifle ball 61-1, right, exhibits fabric impressions from passing through the simulated colonial uniform cloth. No impressions of patching fabric were observed.

Bullet 61-3 was also patched with polymer fabric. It struck the gelatin at 913 f/s, clipping the lower edge. The bullet passed under the gelatin and had a last observable velocity of 382 f/s. The bullet lost 531 f/s of velocity in 32 inches of travel under the gelatin. There is no observable patch fabric impression, and only very faint rifling impressions (Figure 16). There is very minor bullet deformation with some slight sand and soil impact scarring.

The experiment's results indicate that patch fabric impressions are not likely to be present when fired from rifled firearms. Fabric impressions are created when a bullet hits a cloth covered target. The patches seem to be burned away during the powder combustion cycle in this experiment at least. Additional experiments with near bore-sized balls with a patch of appropriate thickness are warranted to determine if the lack of patch fabric impressions is because of the size of the ball we used.

British Pattern 1853 Enfield Rifled Musket - .577-caliber, four shots were attempted at the 100-yard range (31, 33, 47, and 48) and eighteen shots at the 30-yard range with two different bullet types and three different powder charges. The purpose of this experimental set was to determine the range of bullet velocity and overall conical bullet performance.

The standard shoulder-fired arm of the American Civil War used by both Union and Confederate forces was the rifled musket. The most common caliber used was the .58-caliber, or .577-caliber Minié ball. Originally developed in France by Claude Minié, it became the first widely accepted hollow based conical bullet adopted for military use. Extensive experimentation was conducted by the French, British, and United States armies, as well as others, in the mid-1850s with the Minié style bullet (Hawes 2004). Many other conical bullet designs were evaluated with most western European countries and the U.S. adopting one form or another of the Minié ball (Secretary of War 1856).

The U. S. Army adopted the .58-caliber Minié ball in 1855. Experiments with the elongated hollow based bullet began in 1852 and resulted in the army experimenting with an optimal rifling configuration of five land and grooves. This was based on the concept that there should be an odd number of grooves in the bore, such that a groove would be opposite a land. The odd number of land and grooves was believed to create less deformation in the bullet as it was rammed home in loading and firing. The pitch or twist of the rifling was right with one turn in 72 inches. Both the twist direction and rate were believed to provide the best external ballistic performance required by the military for tactical use in combat deployments in use in the mid-nineteenth century.

The five land and groove with right-hand twist suggested by the 1852 experiments was changed to a three land and groove configuration with a right-hand twist as a result of additional experiments in 1854 and 1855. The .58-caliber musket charge of 60 grains of black musket powder was also established by experimentation (Secretary of War 1856:85-109).

Both a .69-caliber Minié ball for altered (rifled) Model 1842 muskets and .54-caliber Minié ball for the Model 1841 Mississippi rifle were adopted along with the new Model 1855 rifled musket in .58-caliber. The Model 1841 rifle was to be reamed and rebored to .58-caliber.

Bullet penetration experiments were completed at the same time as the final Minié ball design was accepted. The .58-caliber elongated ball of 500 grain weight and propelled by 60 grains of black musket powder was found to have excellent penetration by standards of the day. The standard penetration measurement was to place groups of one-inch-thick pine boards separated by one and one-half inches of space at different ranges. The .58-caliber Minié ball was found to penetrate 11 boards at 200 yards, 6 1/3 boards at 600 yards, and 3 ¼ boards at 1000 yards. In comparison, the .69-caliber Minié ball penetrated 10 ½ boards at 200 yards, 6 1/3 boards at 600 yards, and 3 ½ boards at 1000 yards. The .58-caliber altered Model 1841 rifle penetrated 9 ½ boards at 200 yards, 5 2/3 boards at 600 yards, and 3 boards at 1000 yards. The ordnance officers testing the weapons found these results to be entirely satisfactory for combat weapons (Secretary of War 1856:102).

The British also conducted bullet penetration experiments for their weapons, including the P-53 Enfield rifled musket. Their tests employed a stand that had twenty- 18-inch square 1/2-inch-thick elm boards spaced 1-inch apart. One reported penetration experiment using standard service cartridges resulted in the Enfield bullet passing through 11 boards, although the range is not reported (Hawes 2004:82-83).

Initial muzzle velocities obtained by Musket Ballistic Pendulum ranged from 896 f/s to 936 f/s with a mean velocity of 914 f/s for the altered Model 1841 rifle, and 858 f/s to 989 f/s with a mean velocity of 963 f/s for the Model 1855 rifled musket (Secretary of War 1856:105). The .69-caliber smoothbore musket was found to have an initial muzzle velocity of 949 to 971 f/s with an average mean velocity of 954 f/s (Secretary of War 1856:106).

Army test firing proved that the .69-caliber and .58-caliber Minié balls were effective projectiles. In controlled tests accuracy was good for the anticipated combat conditions, mass volley fire, of the era. Hitting a target, regardless of range, is determined by many factors, weather conditions, quality of the gun powder, and the ability of the shooter. In test conditions most of the variables could be controlled as opposed to actual combat conditions. A good example of shooter ability can be seen in rifled musket practice reported by the Navy following the Civil War using the .69-caliber Plymouth rifled musket, Sharps and Hankins carbines, and .44-caliber Whitney and Colt Army revolvers. USS *Unadilla* reported a small-arms drill in 1868 with the Plymouth rifle at 50 yards. There were 21 hits on the target out of 120 fired, or 17.5% hits. The ship's company also fired Whitney and Colt Army revolvers at 35 yards of 36 and 12 rounds, respectively with only four hits on the target each, or 11% and 33% respectively.

USS *Franklin* reported an 1868 small arms practice for Plymouth rifles also at 40, 50, and 60 yards. At 40 yards of 354 rounds fired only 43 hit the target, at 50 yards for 207 rounds fired only 13 were target hits, and at 60 yards of 215 rounds fired 32 were target hits. This results in 12%, 6.2%, and 15% respectively. The ship's company also fired Sharps and Hankins carbines at the same drill. The range was 40 yards and out of 140 rounds fired 35 struck the target (25%).

The general complaint against the Plymouth rifle was its weight and inaccuracy (McAulay 2017:13). The low target hit rate likely reflects those complaints but the poor performance with revolvers and the Sharps and Hankins firearms more likely reflects the lack of marksmanship ability among the men manning the ships.

McAulay (2017:17) reports on USS *Brooklyn*'s small arms drill with the Plymouth rifle in 1872 that the ship's company fired 480 rounds with the expenditure of 650 percussion caps. This is nearly a 25% wastage of percussion caps. Whether caps were lost or failed to function is not stated. During the 1871 Korean expedition the landing force that captured the Korean forts expended 3,000 rounds of .69-caliber Plymouth rifle rounds and some 12,000 musket caps (McAulay 2017:20). This is a 4 to 1 ratio of caps lost or expended to each round fired, a very high percussion cap usage rate for a combat action.

The live-fire experiments undertaken in moderately adverse weather conditions produced mixed results. Three shots (31, 47, and 48) were fired at the 100-yard range. The Minié balls used had a deep hollow cavity, with several bullets showing voids or bubbles deep in the cavity, the result of improper casting. Each shot was fired using 60 grains of black powder. The velocity of bullet 31 was 955 f/s, bullet 47 was 1130 f/s, and bullet 48 was 1340 f/s. None of these bullets were recovered. Bullet 33 failed to properly seat in the barrel during loading and was pulled using a

Figure 17. Pulled and fired Minié balls used in the experiment. The bullet on the left seated improperly and was pulled from the rifled musket with a ball screw. The center and right bullets are typical of fired bullets with rifling impressions evident and significant impact damage to the side from being in yaw when it impacted.

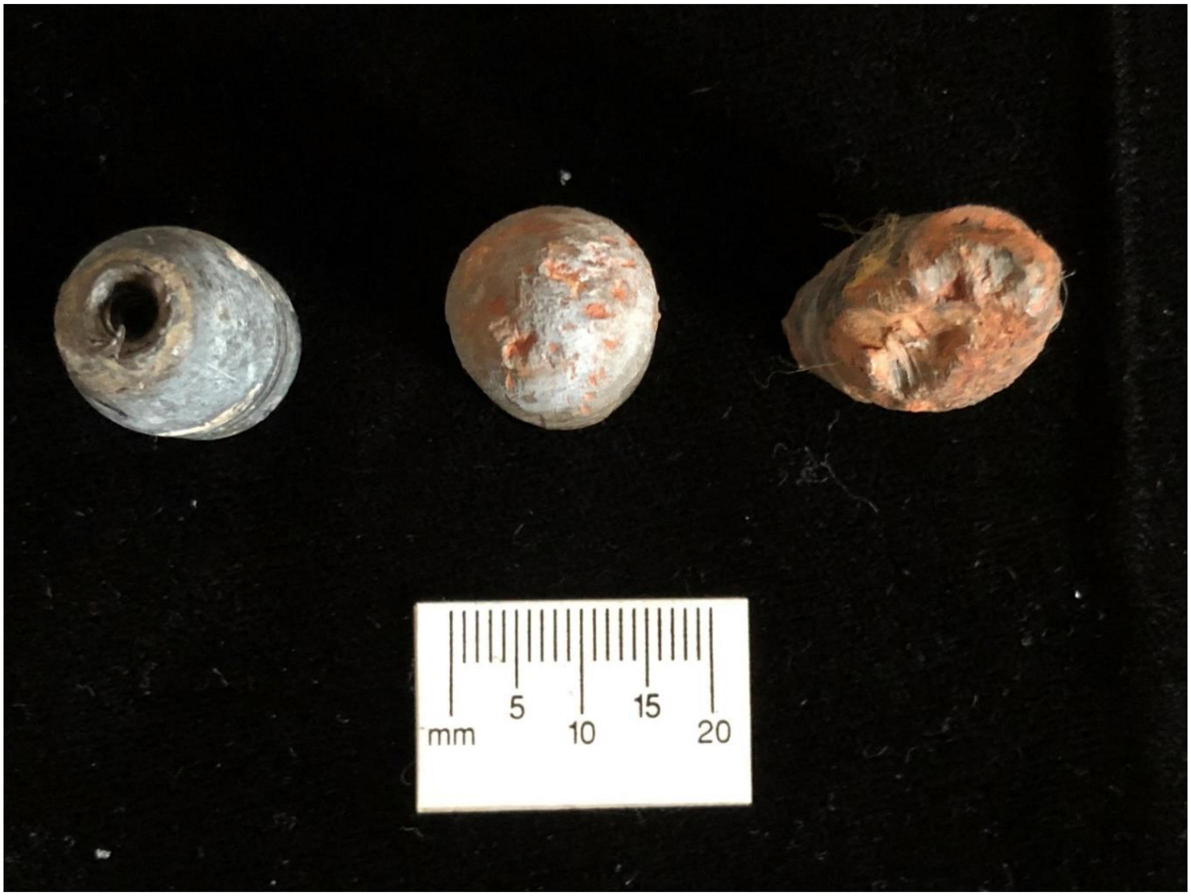

Figure 18. Nose view of the pulled and fired Minié balls used in the experiment. The bullet on the left exhibits the standard characteristic of being pulled. The center and right bullets are typical of fired bullets with nose damage from a stable bullet impact, and significant impact damage to the nose and side from being in yaw when it impacted.

ball screw (Figures 17, 18). The coincidental need to pull this bullet successfully replicated the screw hole and marks of the bullet body found in archaeological examples of pulled bullets. The reason for the poor bullet seating appears to be an issue with a pitted rifle bore near the breech end of the barrel. This also may have contributed to the poor shot accuracy experienced during the live-fire experiments.

At the 30-yard range eighteen shots were fired at the ballistic gelatin. The first seven used the same bullet type (wide skirt) used at the 100-yard firing. The powder charge was reduced to 50 grains of black powder for bullets 29, 30, 34, 38 in an attempt to capture the bullets in the gelatin. This was unsuccessful, and the powder charge was reduced to 40 grains for bullets 37, 44, and 46. All the bullets fired with less than 60 grains of black powder were in yaw (aka tumbling) when they either hit or passed by the gelatin blocks (Figure 19).

The 50 grain powder charge shots resulted in bullet 29 reaching a velocity of 1035 f/s before the bullet entered the gelatin. It passed through 16 inches of gelatin and exited at 802 f/s in yaw. The bullet exhibited strong rifling impressions and nose and side impact damage. Bullet 30 had no

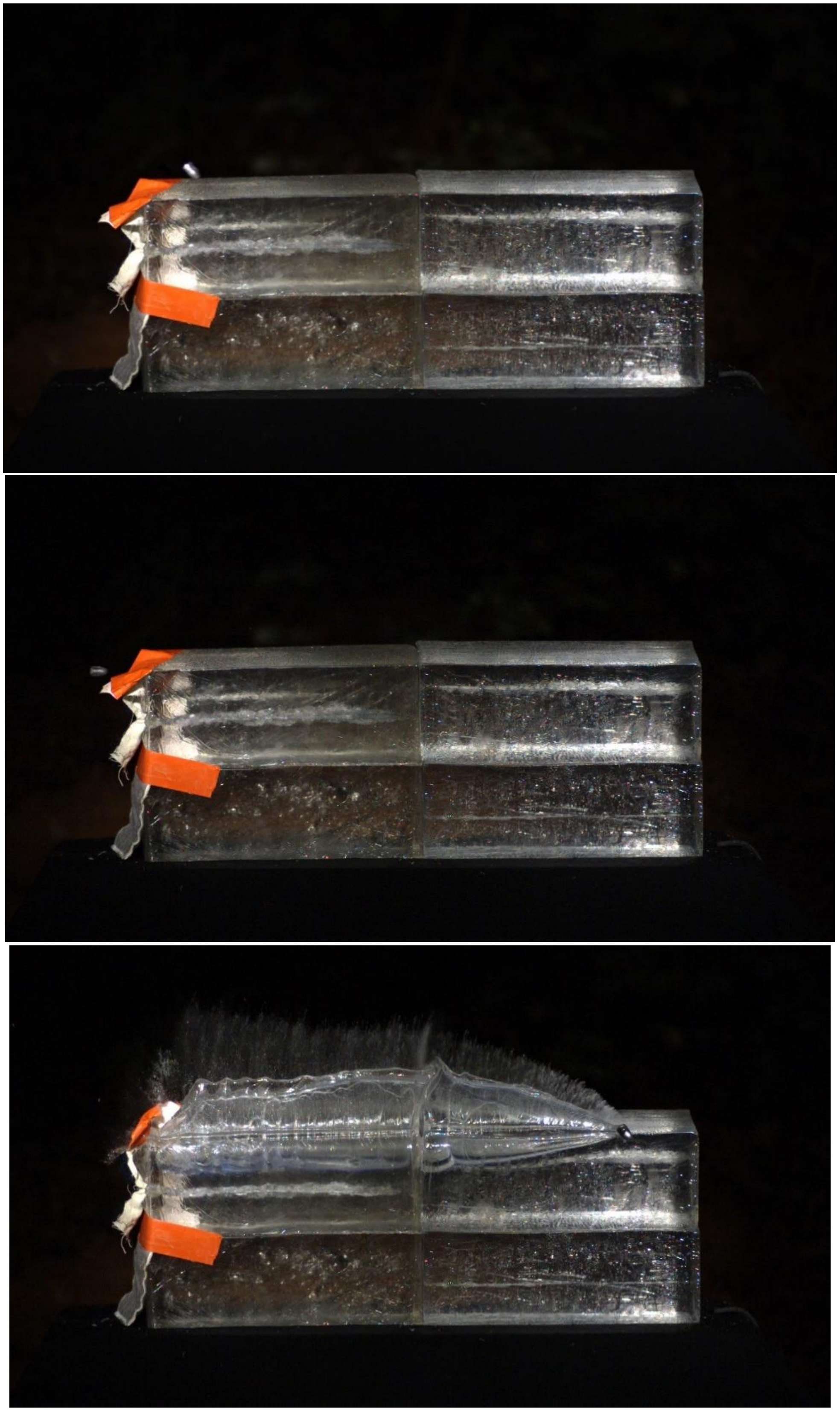

Figure 19. Enfield shot 44 destabilized above the gelatin blocks and shot 67 was stable on entry into the gelatin and destabilized on exit as seen in the bottom two images.

observable velocity data but was recovered in the backstop. Rifling impressions were evident and there was slight nose damage and some soil and sand impact damage on the bullet body.

Bullet 34 reached a velocity of 1135 f/s before entering the gelatin block. It passed through one 16-inch block and exited in yaw at 655 f/s for a loss of 480 f/s. The bullet was not recovered. It may be one of the three Minié balls recovered several weeks later.

Bullet 38 reached 974 f/s missed the target and was recovered in the backstop. Strong rifling impressions were evident. There was minor nose impact deformation with some sand and soil scarring around the bullet nose.

The bullets fired with a 40 grain black powder charge were 37, 44, and 46. Bullet 37 reached a velocity of 877 f/s striking the edge of the gelatin and exiting in yaw at 616 f/s. The bullet exhibits a clear ramrod mark (a concentric ring below the nose) with slight nose deformation and sand and soil scarring around the nose. Rifling impressions are strong on the bullet.

Bullet 44 shot high as it was in yaw. It reached a velocity of 812 f/s. The bullet exhibits rifling impressions and has a ramrod mark around the nose. There is sand and soil scarring on the bullet side and the skirt base is flared outward.

Bullet 46 had no observable velocity data. The bullet hit and embedded in a wooden stake used as part of the target setup. The nose was split and largely lost, the base skirt is dented inward in one area, and there is sand and soil scarring on the body. Rifling impressions are clear.

Due to the poor bullet performance a different Minié ball type was substituted for the next eleven shots, bullets 65-75. These bullets appeared to be more consistently cast with no observable defects or voids and are characterized by a narrow skirt when compared to the first bullet set.

Using the new bullet variety two shots were fired, bullets 65 and 66, using 40 grains of black powder. There was no observable velocity data on bullet 65 nor was it recovered post shot. It may be one of three recovered after the shoot. Bullet 66 reached a velocity of 953 f/s and was observed in the high-speed footage in yaw. The recovered bullet has lightly impressed rifling marks. There is some nose damage and some sand and soil scarring on the bullet nose.

Bullet 66 achieved a velocity of 1210 f/s as it entered the gelatin block. It exited the block in yaw at 428 f/s. This is a loss of 782 f/s. The bullet was recovered and exhibited rifling impressions, a ramrod mark, and some sand and soil scarring on the bullet body. No fabric impressions are visible on the bullet nose where it struck the simulated Civil War uniform cloth before entering the gelatin block.

The remaining shots used a 60 grain black powder charge, the standard charge for a rifled musket. All shots using the standard charge were stable until they hit the gelatin or some other media. Experiments in the 1850s concluded the 60 grain charge was optimal, and such was proven true by the live-fire experiments.

Bullet 67 was stable as it entered the gelatin block at 1210 f/s. It destabilized and exited the gelatin at 428 f/s after approximately 20 inches of travel through the gelatin (Figure 19). This is a loss of 782 f/s. Rifling marks and the ramrod mark are clear on the bullet, but no cloth weave imprint is discernable. There is slight sand and soil impact scarring to the bullet body.

Bullet 68 had no observable velocity data and was not recovered.

Bullet 69 reached a velocity of 1196 f/s and struck the edge of the gelatin block, where it still retained a velocity of 1112 f/s. The recovered bullet has clear rifling impressions, a ramrod mark with some sand and soil impact scarring. Cloth threads were found on the bullet just below the nose. No fabric impressions were noted.

Bullet 70 reached a velocity of 1210 f/s but missed the gelatin block. The recovered bullet exhibits rifling impressions, a ramrod mark, and sand and soil scarring on the side as well as the base skirt being dented inward.

Bullet 71 also reached 1210 f/s and passed through the gelatin. It exited at 451 f/s. The recovered bullet is mushroomed but still retains rifling marks and has sand and soil scarring impact marks.

Bullet 72 struck the gelatin block at 1205 f/s and exited at 748 f/s. The bullet was not recovered immediately after the shot.

Bullet 73 struck the gelatin block at 1260 f/s and passed through 32 inches of gelatin, exiting at 1240 f/s. The bullet was not recovered.

Bullet 74 had no observable velocity data. The recovered bullet exhibits rifling impressions and a ramrod mark. There is slight nose impact damage and some sand scarring on the body and base skirt. The base skirt is slightly crushed by impact. The bullet appears to have been in yaw at the time of impact with the backstop.

Bullet 75 traveled at a velocity of 1220 f/s as it entered the gelatin. It immediately began tumbling and exited the gelatin at 330 f/s. The recovered bullet exhibits rifling marks and has some nose deformation as well as a dented and crushed base skirt. Sand and soil impact scarring is evident.

General observations on Minié ball performance are consistent with the reported historical research. The bullets are not stable in flight with 40 or 50 grain black powder charges. The bullets are in yaw within a short distance after leaving the muzzle. The bullets sustained a stable flight with the 60 grain charge until they struck the gelatin or another media. They were immediately destabilized upon striking media. Side and base impact damage was reasonably consistent on the recovered bullets and is consistent with recovered archaeological material. We believe the side and base impact damage is consistent with the bullet being in yaw at the time of impact.

Weber and Scott's (2006) research on comparisons of fired percussion caps showed that individual tool marks from the hammer and cone are preserved on percussion caps. The work used experimental firing and archaeological artifacts to identify the minimum number of firearms at an event based on comparisons of fired percussion caps. The Pattern 1853 Enfield was first dry fired (no powder charge or bullet) with an original Union Metallic Cartridge Company musket cap, then dry fired with a modern German made musket cap to continue this research.

Live firing used the German musket cap. Each fired cap was collected and bagged with a shot number identifier.

The caps were compared under 40X magnification on an American Optical Universal Comparison Microscope. Of the 24 fired caps seven were so severely damaged by firing as to be unsuitable for microscopic comparison. These were excluded from further study. The remaining seventeen all retained adequate individual or partial unique individual characteristics to state they are consistent with being fired by the same firearm or could not be excluded. Those that were excluded are shots: 3, 44, 60, 67, 69, 72, and 74. Those that retained partial individual characteristics and could not be excluded are shots: 30, 48, 65, 70, 73, and 75 (Figure 20).

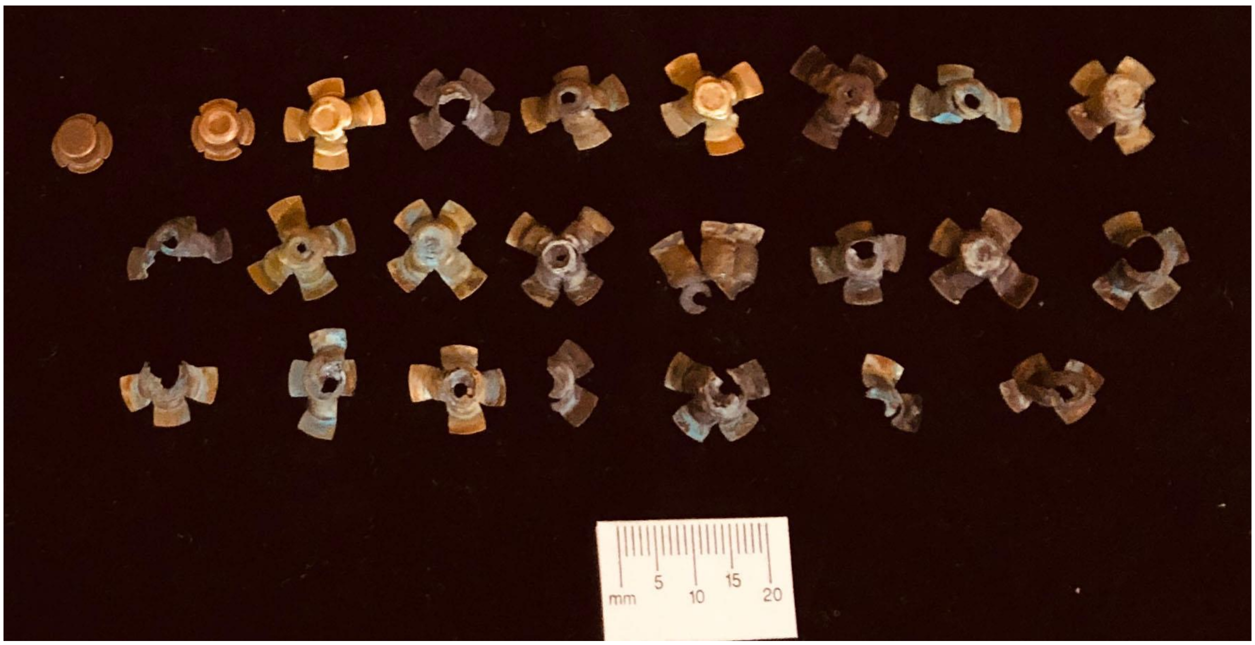

Figure 20. All recovered percussion caps used in the live-firing. Top row, l to r; unfired original UMC musket cap, dry fired UMC musket cap, modern German dry fired musket cap, fired German musket caps - shots 3, 29, 32, 33, 37, 30 and 38; middle row – shots 44, 46, 47, 48, 60, 65, 66, and 67; bottom row – shots 69, 70, 71, 72, 73, 74, and 75.

Results of Live-Fire Experiment and General Observations

The live-fire experiment collected a significant amount of controlled data on muzzle velocity, bullet penetration, and bullet deformation complimenting and enhancing the results observed during the 2016 live-fire experiments (Scott et al. 2017).

Laid Cartridge Paper Observations

The laid paper cartridges were largely fully combusted during firing as was observed in the 2016 study. The high-speed video confirms that cartridge paper did not fully combust in the barrel during firing, but numerous fragments were expelled with the gases, and most combust before reaching the ground. Fragments of laid cartridge paper are clearly seen in the videos being expelled down range from the barrels. Incompletely consumed cartridge paper pieces were found 15 feet to 30 feet down range from the shooting bench.

Tissue Simulate Live-Firing Results

Tissue simulants are materials that approximate the density of human tissue and approximate the penetration resistance of soft tissue (Boackle 2011). Bullets fired into tissue simulants create a temporary and a permanent wound cavity that mimic actual wound trauma reasonably well (MacPherson 1994:63-78). The temporary cavity can be observed using high-speed videography. The permanent cavity is what remains after the bullet passes through or is captured in the tissue simulant. A variety of studies demonstrate that tissue simulants meeting the standard BB penetration test (MacPherson 199:74-75) achieve dynamic equivalence which can then be used to model wound trauma. When a spherical ball enters the tissue simulant at a given velocity the gelatin begins to deform as a response to strain forces acting upon it. The gelatin deforms elastically until it reaches a critical point where it ruptures and then rebounds to near its original position. The strain forces caused by the bullet diameter, mass, and velocity create an elastic response in the gelatin that creates a wound track or cavity that expands with the initial strain and then contracts leaving a visible but small wound track.

Forensic pathologists and others have done extensive study and experimentation on projectile interaction with soft tissue. The main feature that contributes to the severity and extent of the wound is the size of the temporary wound cavity. The cavity size is directly related to the amount of kinetic energy lost by a projectile as it travels through tissue. Kinetic energy possessed by a projectile is not the determining factor in wound severity, but rather it is the amount of energy loss. DiMaio (2016:151-152) identifies five primary factors of energy loss that are directly related to wound severity: 1) bullet shape, 2) angle of yaw at the time of impact, 3) change or deformation of the bullet area in its passage through tissue, 4) construction of the bullet itself, and 5) biological characteristics of the tissue being impacted.

DiMaio (2016:152) discusses two types of wound tracks produced by a projectile, permanent and temporary wound tracks. As a bullet moves through tissue it is pushed aside creating a temporary cavity that undulates between 5 and 10 milli-seconds before settling into a permanent bullet or wound track. The size of the temporary wound cavity is directly related to the loss of kinetic energy, or the absorption of energy by the surrounding tissue. Temporary wound cavities can be as much as 11 to 12.5 times the diameter of the projectile. Human tissue can absorb a certain amount of kinetic energy, but at some point, the ability of the tissue to absorb the energy is exceeded, and tissue damage occurs. Organs can undergo partial or complete destruction, bone can be shattered even if not struck directly, and vessels may rupture. Essentially what is happening is the elasticity of bone, organs, vessels, muscle, and other tissue is exceeded and damage occurs.

The live-fire experiment used Clear Ballistic® gelatin obtained from Clear Ballistics®. Clear Ballistic gelatin meets the FBI and NATO protocols for testing terminal ballistics of human tissue simulants. The protocol standard states that an acceptable calibrated gelatin must have a steel BB (.177-inch or 4.5mm in diameter) shot at 590 f/s (180 m/s) at 10 feet (3.04m) come to rest between 1.73 and 1.8 inches (4.4 and 4.6cm) into the gelatin.

The Clear Ballistics' blocks are 6x6 inches square and 16 inches long. Two blocks were placed end to end and aligned creating a 32-inch-long area of gelatin. A roughly 6x6 inch square of cloth, meant to simulate the thickness and weight of average colonial or Civil War-era clothing, was placed on the front of the lower blocks (Figure 21). A third block was set on top of the first block to provide additional weight and increase the target area. Civil war uniform cloth was placed on this block when the Pattern 1853 Enfield was fired.

Figure 21. Simulated uniform cloth squares placed on the front of the ballistic gelatin. Top, Union overcoat, blouse, and shirt fabric; middle row, Confederate blouse and shirt fabric and Union blouse and shirt fabric; bottom row, colonial uniform coat, waistcoat, and shirt fabric, and Union trouser fabric.

The colonial cloth squares were made up of broadcloth followed by a piece of serge to represent a coat and lining. Behind these was another piece of broadcloth and a piece of serge to represent a waistcoat and lining. The final piece of cloth was a square of linen representing a shirt. The cloth was replica fabric that is the same weight and weave of known historic cloth constructed of similar materials (Potter and Hanson 2014; Moore and Haynes 2003; Brown 1999; Kidwell and Christman 1974).

The Civil War cloth consisted of four different configurations. One square simulated a Union overcoat or great coat cloth over a Union jacket or blouse with a liner, and domet flannel shirt material. A second square omitted the overcoat cloth and used only the blouse flannel, liner, and domet flannel shirt material. The third square simulated kersey trouser cloth, and the fourth square simulated a Confederate uniform Jean cloth with cotton cloth liner, and flannel shirt material. Cloth thickness was recorded for each cloth type.

The colonial rifle, .61-caliber, was fired six times at the gelatin blocks. Only one ball struck the gelatin and was captured. The ball has distinct and clear colonial cloth impressions. We believe we used balls that were too small to effectively grip the rifle's land and grooves, thus rendering it largely inaccurate for target shooting. Additional experiments are planned to correct this issue.

The Dragoon pistol, .60-caliber, was fired twice at the gelatin blocks. One ball did strike the colonial cloth on the block but did not have sufficient velocity to penetrate the cloth. The ball bounced off the cloth leaving a black mark. No fabric impressions were observed on the ball surface.

The Thomas Earle fowling piece, .62-caliber, was fired with two sizes of cloth-patched balls at the gelatin blocks. The fowling piece was fired five times with no hits in the gelatin.

The Enfield Pattern 1853 percussion rifled musket, .577-caliber, was fired 18 times at the gelatin blocks. Most of the shots were in yaw as they approached the gelatin. Six shots entered the gelatin, passing through the Civil War simulated uniform cloth. Three other shots struck the side of the gelatin blocks, grazing the side. No clear fabric impressions were observed on the nose or body of any of the recovered Minié balls.

Comparison between a smoothbore musket bullet passing through ballistic gelatin blocks and the conical Minié ball through the same media type in yaw shows dramatic difference in wounding effect (Figure 22). The differences confirm the DiMaio (2016:151-152) factors of energy loss that are directly related to wound severity. In this case the bullet shape, angle of yaw at the time of impact, and change or deformation of the bullet area in its passage through tissue. The high-speed video comparison between the spherical ball and conical bullet in yaw dramatically demonstrates the severe wounding effect of large-caliber conical bullets of the type used in the American Civil War. Those wounding effects are discussed and illustrated in the six-volume treatise, *The Medical and Surgical History of the War of the Rebellion* published by the Office of Surgeon General in the 1880s. This modern experimentation using high-speed videography clearly records the cause and nature of those effects.

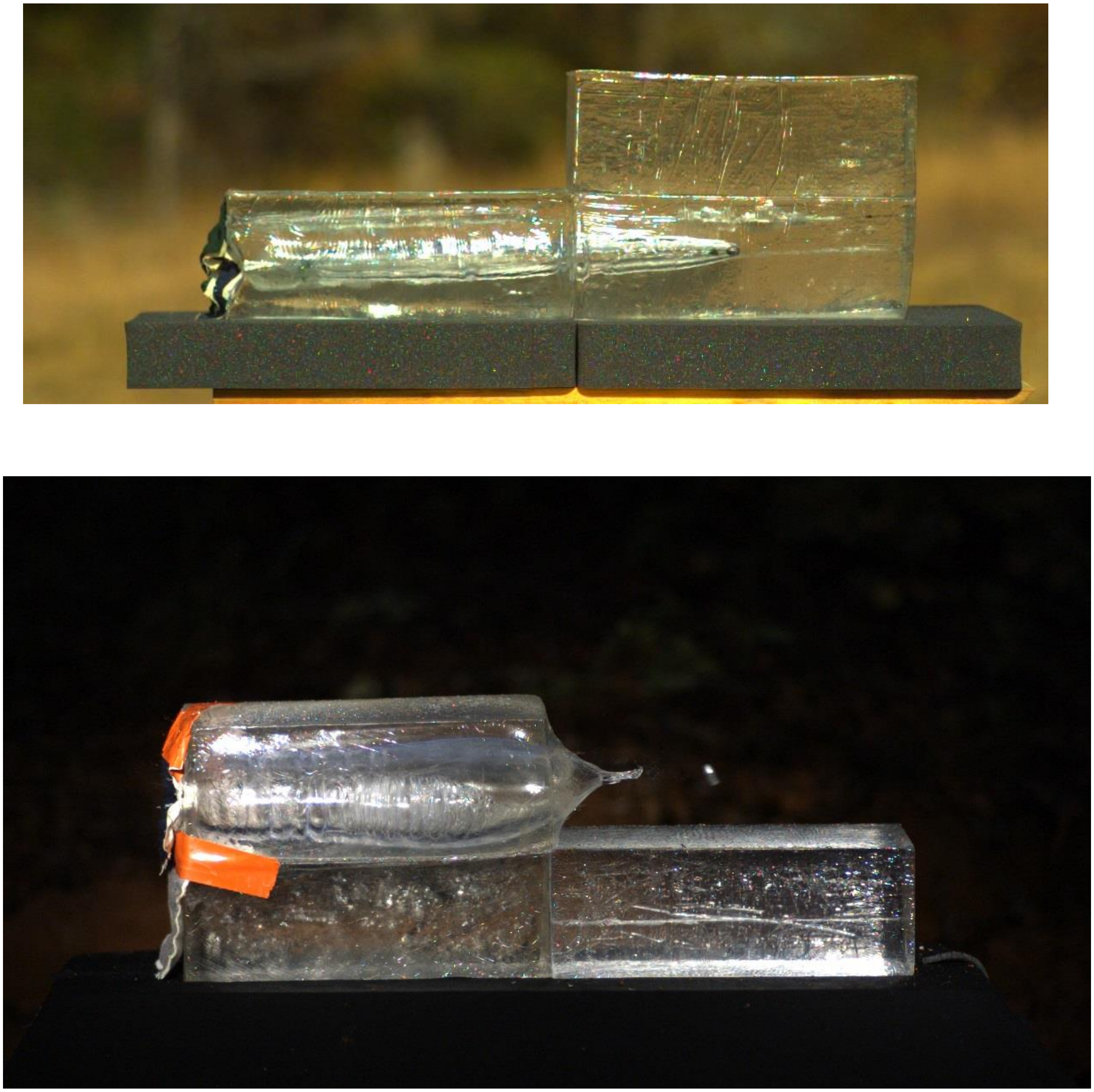

Figure 22. The top image illustrates a .626-inch diameter spherical ball fired from a .68-caliber French Model 1763/1766 smoothbore musket traveling at 785 f/s passing through a ballistic gelatin block compared to a .576-inch diameter Minié ball fired from an Enfield Pattern 1853 rifled musket, .577-caliber, entering the gelatin block at 1135 f/s and exiting in yaw at 655 f/s. Note the difference in the cavitation produced by the higher velocity conical bullet. The extent of cavitation is more than twice that of the spherical ball. This image dramatically demonstrates the significantly different potential wounding effect of high-velocity conical bullets compared to lower velocity spherical balls of a larger caliber.

Ball Penetration and Deformation

The dynamics of bullet penetration in any media are complex and dependent on velocity at the time of impact, the density of the media it strikes, and drag or resistance on the bullet during flight. Miller and Bailey's (1979:449-463) study of drag drawn from eighteenth and nineteenth-century cannon firing sources demonstrated that with the development of the 1868 Bashforth chronographic instrument, reasonably accurate velocity and drag measurements were attainable. They also found the earlier ballistic pendulums (ca. 1787 and ca. 1839) were less accurate than the Bashforth chronograph, but still produced reasonable data. Using modern data and mathematical formulae they created drag models for spheres ranging in velocity from Mach 0.3 to Mach 2.0. Their basic research is incorporated into the ballistic models employed in this study.

Likewise, bullet deformation is dependent on the same issues. MacPherson (1994) studied and modeled bullet penetration as related to incapacitation from wound trauma. Bullet penetration in any substance, be it soil, wet or dry wood, or human tissue, is dependent on several factors including the energy it has when it strikes a substance. This is kinetic energy, and here we express it as foot/pounds (ft-lbs.). A soft lead bullet traveling at a velocity has mass (weight), speed, and stored but dissipating energy as it fights resistance or drag. The object or media the bullet strikes, if soft, transfers the kinetic energy of the bullet in the form of heat, if hard the bullet is deformed to some degree or another as a function of the laws of thermodynamics. The force that results in bullet deformation is simply Newton's Third Law of Motion; for every action there is an equal and opposite reaction. There is no absolute direct correlation to bullet deformation since kinetic energy and damage is not due directly to energy absorption, but to the amount of force per area on the bullet and media. Bullets behave according to physical laws, and by knowing the velocity, mass (weight), and other variables bullet deformation and penetration can be mathematically modelled (MacPherson 194:11-14). Modern ballistic calculators take these variables into account when calculating muzzle velocity, changes in velocity over time, air resistance (drag), and gravity, to determine bullet speed loss over distance and drop from the angle of the firearm muzzle relative to the ground surface.

In penetration studies, the terms low and high velocity have specific definitions. Low velocity is considered to be a bullet traveling at 300 f/s or less, while high velocity is considered to be a bullet traveling at 600 f/s or more (MacPherson 1994:74-77). For all practical purposes all charges fired in the arms in this experiment achieved high-velocity as used in penetration and wound trauma studies.

Bullet penetration and expansion or deformation is modelled using the principles of fluid dynamics. Bullets expand more in higher density fluids and less in lower density fluids. Lower density fluids include water, tissue, tissue simulants, and experiments have shown that bullets penetrate and expand or deform in consistent ways in these lower density situations (MacPherson 1994:122-125; Fackler 1988:555-557).

Bullets yield or deform in response to the force applied on them. A ball striking a hard, strong solid (e.g. rock, hard woods, etc.) will deform at relatively low velocities because the hard and rigid surfaces produce large forces on the bullet (Kerkhoff et al. 2015; Mattijssen et al. 2016).

The diameter of the bullet and its mass (weight, usually expressed as sectional density) is another factor in the amount of deformation that occurs when a ball strikes a hard or rigid surface. Pure or dead soft lead (not pure in the chemical sense, but with impurities present at such low levels as to not be significant) is very ductile and deforms significantly based on static loading as confirmed in experiments (MacPherson 1994:127) using spherical balls and black powder loads. The experiments show that lead spherical balls show slight deformation at about 690 f/s velocity and increase accordingly at higher velocities when fired into soft fluids like tissue or water (Figure 23).

Lucien Haag (personal communication December 15, 2004) conducted an experiment firing lead spherical balls from modern cartridge pistols and rifles using controlled black powder charges. He fired each shot into a water tank at velocities ranging from 360 f/s to 1026 f/s for .45-inch balls in a pistol and ranging from 1049 f/s to 1529 f/s for .45-inch balls fired from a rifle. His investigation found the higher the velocity the greater the deformation. His lower velocity impacts ranging from 630 f/s to 1026 f/s had virtually no deformation while rounds fired above 1049 f/s to 1138 f/s showed some slight flattening. Recovered balls fired between 1281 f/s and 1336 f/s were showed flattening to nearly half the diameter, while the round fired at 1529 f/s was nearly completely flattened. Haag's experiments largely confirm the work of MacPherson (1994).

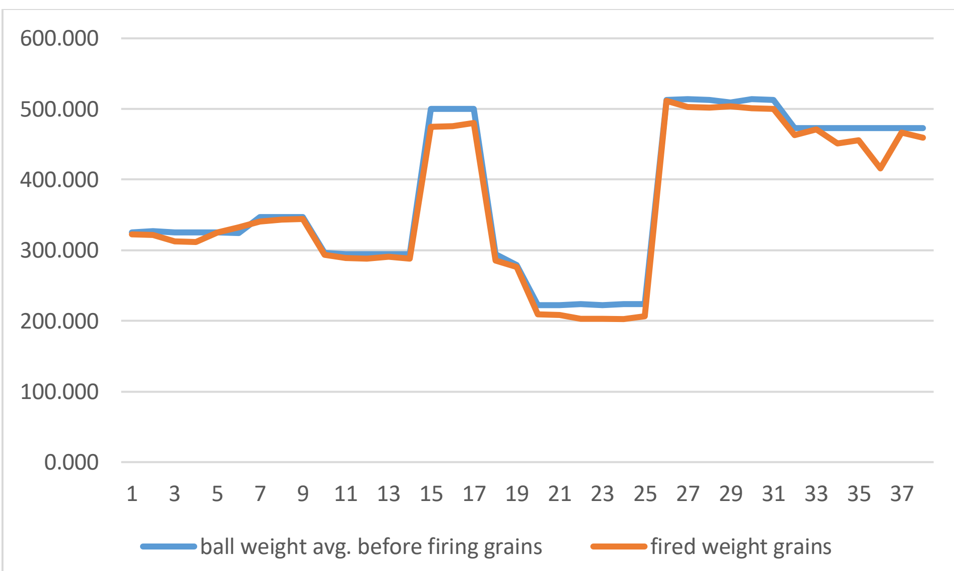

Figure 23. The average weight loss is .3% of the ball weight. The range of weight loss ranged from a high of .9% to a low of .02%. Weight loss is directly correlated with velocity and hardness of the media the bullet struck.

The 2016 live-fire experiments (Scott et al. 2017) confirmed the Haag and McPherson findings. The November 2018 experiments also confirmed those findings. The higher the velocity the greater the deformation on both spherical balls and Minié balls. The smaller balls, .520-inch and .580-inch, showed the least deformation and the larger balls, .69-inch showed the largest deformation at any given velocity, which is consistent with metal yielding functions correlated to the bullet's sectional density (MacPherson 1994:142-143). The same proved true for the conical Minié balls. The issue with them was stability. When stable the bullet nose area suffered the greatest deformation at impact. If the bullet was in yaw (tumbling) on impact, then the bullet side and base skirt were the most deformed area of the bullet.

Lead Bullet Deformation Index

For more than 30 years an intuitive scale based on personal experience with shooting muzzle loading weapons has been used to assign value to impact deformed bullets. The scale is descriptive using Low, Medium, and High-Velocity Impact terms as a means of defining impact deformation (e.g. Scott et al. 1989). An ordinal scale was developed by Foard (2008; 2012) based on idealized diameters of musket balls recovered from archaeological contexts. The 2016 live-fire experiments where bullets fired at known velocities were recovered allowed a new more quantitative-based index scale to be suggested (Scott et al. 2017). While this scale has recognized weaknesses, it does refine and replace the even less precise Low, Medium, and High-Velocity Impact scale that is in common use (e.g. Scott et al. 1989). The validity of the scale was tested in the 2018 experimental firing.

Using the ball deformation data acquired during the live-fire experiment we found they validate the ordinal or nominal bullet deformation rating scale that roughly equates to an approximate velocity range suggested in 2017 (Scott et al. 2017). We emphasize that the **Lead Bullet Deformation Index (LBDI)** scale we propose cannot be used as a one-to-one correlation to absolute velocity and the amount of deformation, rather it is intended to give the user an approximation of the relationship between velocity and deformation. Using the ordinal rating scale model results in a number that can be tested using ANOVA, Regression, or Chi-square tests.

We define the **Lead Bullet Deformation Index** to be:

Based on a mixed qualitative and quantitative set of observations of the fired bullet a rating scale number can be determined. Measurements should include the maximum diameter (diameter A), the thickness or amount of flattening (diameter B), and the minimum diameter that is not in the plane of deformation (diameter C). These data can be plotted and trendlines applied through scatter plots and various statistical regression procedures to observe and refine trends. Qualitative observations of the amount of impact scarring present range from minimal to extreme as to the degree of impact flattening (commonly called mushrooming) the bullet exhibits.

The ordinal scale is:

1. Likely velocity is less than 800 f/s based on little or no visible scarring or flattening. Diameter measurements are essentially consistent for the three measured points on the ball.

2. Likely velocity is between 800 f/s and 1100 f/s based on slight to moderate visible impact scarring, possibly some imbedded residue or negative impressions (sand or rock

inclusions or impressions), and some impact flattening that is less than half the diameter of the ball. Diameter measurements show flattening to less than one half the ball's original diameter or caliber.

3. Likely velocity is greater than 1100 f/s based on significant impact scarring and flattening of ball to becoming totally mushroomed. Measurements should reflect the thickness of the flattening relative to the measured diameter as extreme.

We suggested when there is a question of whether a ball falls in one ordinal range or another that it is appropriate to use a .5 number. An example is that a ball shows some minimal impact scarring, and some moderate flattening would be assigned a 1. However, the measurements in the A and C axes are essentially the same, but the thickness or flattening measurement is notable and could be assigned a 2. We suggest assigning it a 1.5 rating. That data can be used to refine any statistical analysis. We do not endorse any finer intermediate resolution between the numbers as this will only be pure speculation and confuse any statistical analysis.

The scale was applied to the bullets recovered from the 2018 live-fire experiments. The effort duplicated and validated the earlier work. Bullet deformation is clearly equated with velocity at impact (Figure 24). The Lead Bullet Deformation Index does approximate the velocity range within a degree of error.

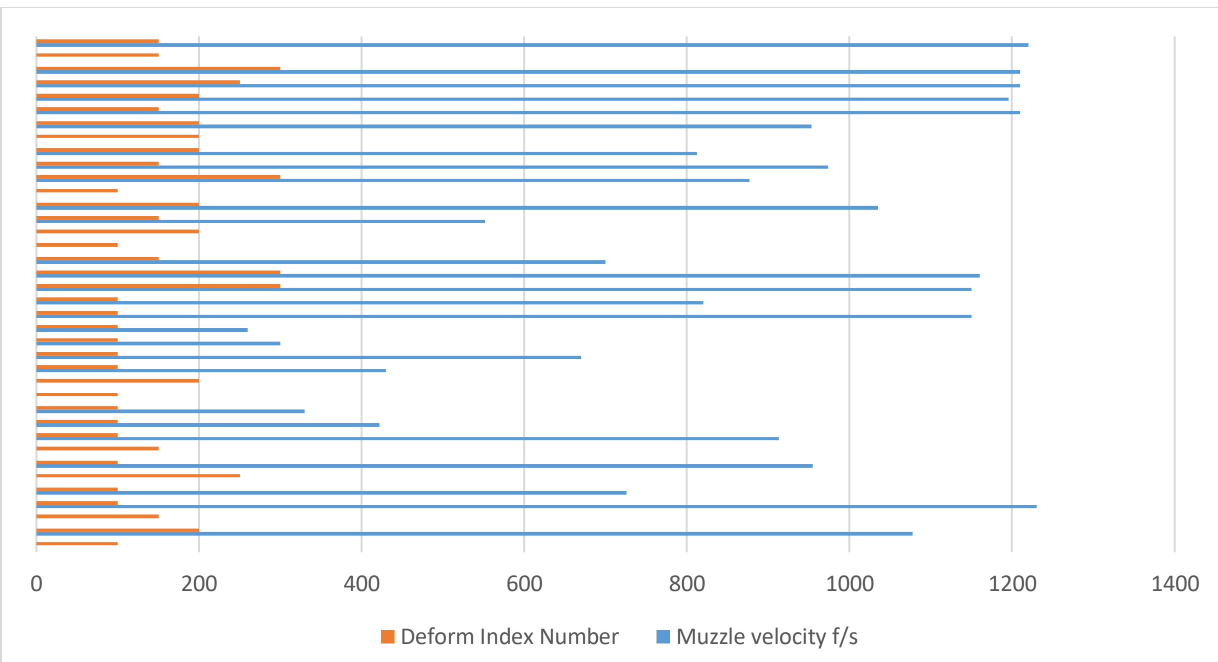

Figure 24. Bullet deformation relative to muzzle velocity. The graph clearly demonstrates that muzzle velocity is correlated with the degree of bullet deformation for the 38 bullets used in the study. What cannot be easily dealt with is the media which the bullet struck, which also influences deformation.

Other Observations

Sometimes balls fired from muzzle loading firearms exhibit a variety of characteristics that can be mistaken for impact deformation. These can be identified and interpreted with careful observation and analysis. Sivilich (2016), Foard (2012), Foard and Morris (2012) and Harding (2012) have observed, described, and interpreted these and other non-impact characteristics on spherical lead bullets from a variety of archaeological contexts. Sivilich was one of the first to use live-fire data to validate interpretations of impact and non-impact marks on fired balls. The current live-fire empirical evidence further verifies and validates the archaeological based descriptions and interpretations as well as those of Sivilich (2016)

The live-fire recovered bullet data confirm characteristics found on balls relate to the loading or the type of load. These characteristics, like ramrod marks from loading the round, or faceting or multiple dimples on one surface, likely indicate a buck and ball round (Figure 25). Another characteristic is a smooth band completely or partially around the ball. The banding effect occurs when a ball is upset in the bore during loading, slightly compressing the bullet. When fired the propellant gases further force the ball against the bore creating the band. It is a tell-tale indication of a ball being fired from a smoothbore gun. Figure 26 illustrates land and groove rifling impressions still observable on impacted Minié balls.

For balls or conical bullets fired in rifled barrels additional characteristics are impressed on the bullets. The obvious marks are the ramrod indentation on spherical balls, and a circular mark around the nose of conical bullets when using a tulip shaped (hollow nose) ramrod. Different ramrod shapes will leave different impressions on the nose of conical bullets that can be used as an aid in identifying the firearm type in use. The ramrod data should be combined with another observable characteristics to reach a conclusion on model or gun type.

Microscopic examination of fired balls can often reveal several other micro characteristics that may aid in identifying the media in which the ball imbedded or passed through. Traces or impressions of wood, soil (e.g. sand or gravel), fabric impressions or fabric adhering to the ball surface, or even bone embedded in the ball, aid in the interpretation of the shooting incident under investigation.

Figure 25. Ramrod marks on spherical balls. Casting sprues are also evident on the first and third balls.

Figure 26. Minié balls fired from the Pattern 1853 Enfield rifled musket. Land and groove impression are evident on the bullet body, as well as Enfield-type ramrod nose deformation incurred during the loading process.

The presence of black powder stippling and ramrod marks are common observations on bullets fired from muzzle loading guns. Forensic pathologists recover bullets from bodies on a regular basis. One aspect of their work involves examination of projectiles for embedded or adhering tissue and foreign material (DiMaio 2016:39-40). Finding and determining what is adhering or has embedded often requires microscopic examination, and the use energy dispersive x-ray

(Scanning Electron Microscope – SEM-EDX). The latter is beyond this study's capability. DiMaio (2016:41-42) describes how black powder firearms projectiles, usually pure lead, or minimally hardened lead, will often have tell-tale peppering on the surface that faced the burning powder when the firearm was discharged. This peppering or black powder stippling is readily observed and can be used as a criterion for determining if the projectile was fired in a black powder firearm. He also notes that other features, such as ramrod or loading lever marks can be found on lead balls. We observed those features on the recovered balls.

Ball Deformation and Determination of Original Caliber

The deformed pure or soft lead spherical ball is particularly noted for being difficult to determine its original nominal caliber in archaeological contexts due to impact. Several formulae have been advanced that use the weight of the deformed spherical ball to calculate its approximate original diameter. Arrowood and Berglund (1980) developed one formula that gave a 99.5% level of confidence when at ± three standard deviations. Daniel Sivilich devised a similar formula (1996; 2009) with only one standard degree of error which has proved quite reliable and replicable. Branstner (2006) attempted to improve the Sivilich formula by recalculating the density of lead and reformulating the Sivilich formula. Branstner devised a table of lead ball diameters based on weights that range from .228-inch in diameter to 1.67-inch in diameter. Sivilich (2016:25-27) revised his formula and included new data on lead density to determine an original caliber more accurately, with only one degree of standard error.

We tested the revised Sivilich formula against the recovered fired balls from the live-fire experiment. We knew the original ball diameter and weight before firing and we weighed the fired balls as well as calculated the fired ball weight loss by caliber and average weight loss for each ball diameter. The weight of the recovered balls was used to test the 2018 Sivilich formula.

The revised Sivilich Formula proved exceptionally reliable and accurate for spherical balls. A regression correlation was run comparing the two data sets. Sivilich's formula tends to overestimate the ball diameter from a few thousandths of an inch to about one-hundredth of an inch or about 1% (Figure 27). The R value was calculated to be .998 with less than one standard error of deviation. The R value is near ideal and proves the Sivilich Formula to be accurate and reliable for calculating the original ball diameter using weight or mass from recovered archaeological specimens. A test was also conducted using the fired conical Minié balls (Figure 28). The Sivilich Formula was never intended to be used in this manner, and the results of the test confirm that the formula should not be used for conical bullets. The test demonstrated the if one uses the Sivilich Formula with conical bullets it will consistently overestimate the bullet diameter by over 8%. To reemphasize the point, the Sivilich formula was *not* designed for conical bullets. It is a very useful tool to predict a fired spherical ball diameter.

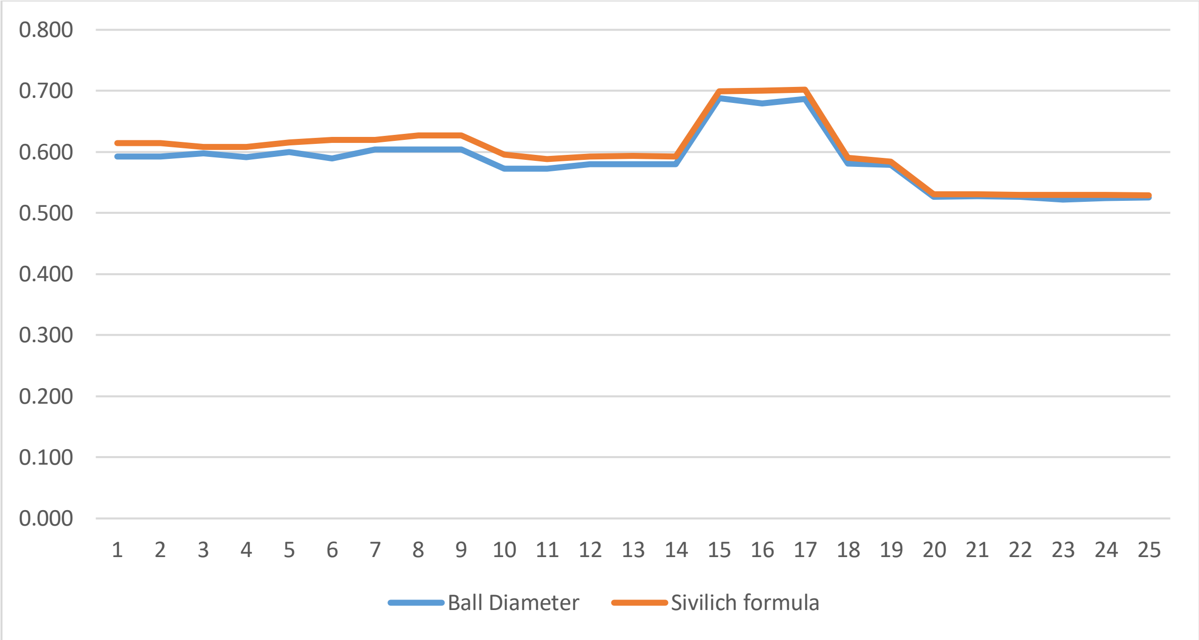

Figure 27. Actual spherical ball diameter compared to the fired bullet weight calculated ball diameter using the revised Sivilich formula. The agreement is above the 90% level, although the Sivilich formula tends to overestimate the bullet caliber by about 1%.

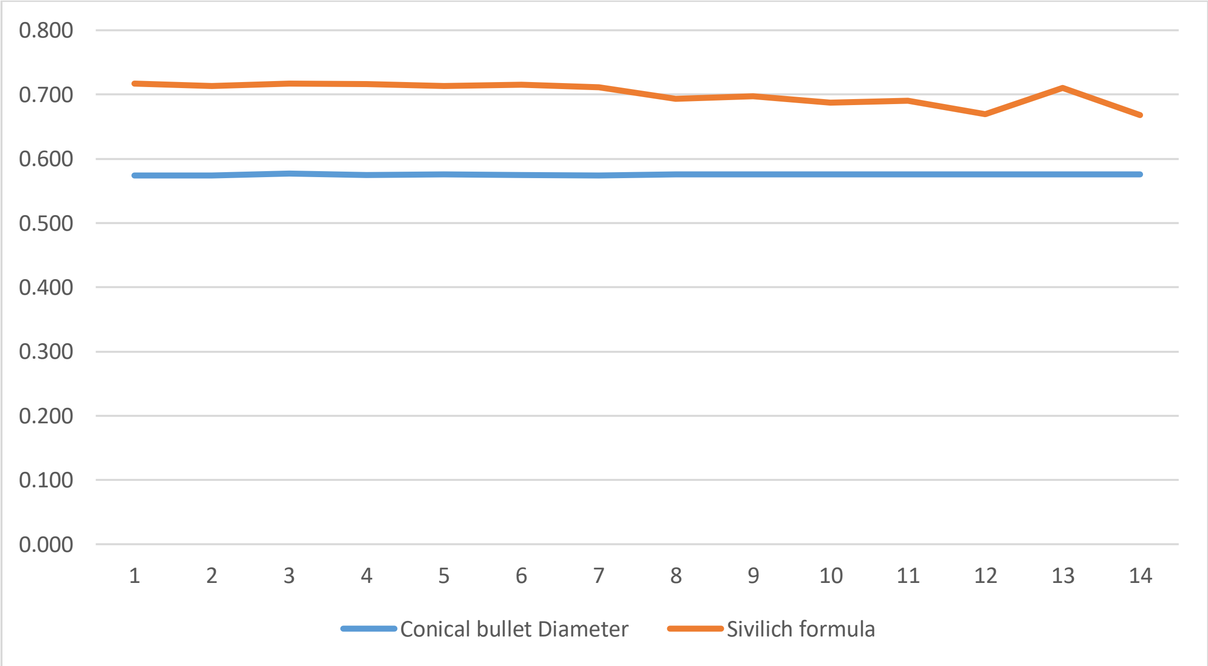

Figure 28. The Sivilich formula is not intended for use on conical bullets. As a test the formula was applied to the Minié balls/bullets used in the November live-fire experiment. As predicted the Sivilich formula is not appropriate for use on conical bullets as it significantly overestimates the original caliber by more than 8%.

Summary and Conclusions

The November 2018 firearms live-fire experiment can be characterized as an unqualified success. The work with rifled firearms, despite severe inclement weather conditions, adds new information to the 2016 experimental work. The intent behind the investigation was to determine the external ballistic bullet performance of a series of smoothbore shoulder and hand-fired guns of the type commonly used during the American Revolution, as well as rifled firearm performance for the same era and the American Civil War. The general premise or research design that drove the experimental investigation was to document the fired ball performance in terms of muzzle velocity, penetration capability, and bullet deformation as it terminated its flight. This study not only recovered bullets fired at different media; tissue simulant, sand, and soil; it also used high-speed videography to determine initial muzzle velocity for each shot. The collected information was analyzed and compared to models of lead bullet external ballistic performance.

Our data exhibits excellent correspondence with ballistic performance models, further validating those models and allowing us to compare our data findings with various data sets. This study revalidated the value of the Sivilich Revised Formula. This validation of the Sivilich Formula is of real value to archaeological investigations.

Another valuable lesson derived from the live-fire experiments is the validation of bullet deformation and a general correlation with velocity. The LBDI we present should have continued testing and validation, but we believe that it has utility as an independent ordinal scale to assess impact deformation on conflict sites. The LBDI assessment can be of use in determining possible firing line distances on battlefields which will expand the archaeological interpretative potential of bullet datasets.

The experimental effort also demonstrated, albeit with a small sample, that cloth impressions on spherical balls originated from passing through uniform cloth. No ball fired with a cloth patch was impressed with the patch weave, although more study is warranted. The lack of cloth weaving impressions on conical bullets is interesting and deserves additional experimental work to validate these observations.

Much of the work we undertook is designed to aid archaeologists in better understanding of potential information yields that can be gained from bullet analysis from archaeological sites. We have focused on conflict sites specifically and the role bullet analysis has in yielding information that expands and enhances their interpretive value. An additional intent in conducting the live-fire experiments is to provide well controlled and defined data to forensic firearm examiners so they may use the information to identity historic firearm types involved in law enforcement cases either by inclusion or exclusion. We believe the data presented here will aid firearms examiners with case work when it involves shooting incidents with smoothbore muzzle loading black powder firearms.

References Cited

Arrowood, Michael C. and James S. Bergland
1980 Classification of Lead Ball: A Mathematical Approach. *Association of Firearm and Tool Mark Examiners Journal 12:40-46*.

Boackle, Mark
2011 The Use of Perma-Gel Testing Medium for Comparison of Terminal Performance of Different Caliber Pistol Calibers. *The Journal of the Association of Firearm and Tool Mark Examiners* 43(2):146-153.

Bowdoin, James, and Joseph Warren
1770 A Short Narrative of the Horrid Massacre in Boston, perpetrated in the evening of the fifth day of March 1770, by soldiers of the 29th regiment, which with the 14th regiment were then quartered there; with some observations on the state of things prior to that catastrophe. Edes and Gill, Boston, Mass.

Branstner, Mark C.
2008 The Problem with Distorted, Flattened, Spent, and Otherwise Mangled Lead Balls: A Simple Remedy. *Illinois Archaeology* 20:168-184.

Brown, William L., III
1999 *Thoughts on Men's Shirts in America: 1750-1900*. Thomas Publications, Gettysburg, Penn.

Buchanan, Brenda J. (ed.)
1996 *Gunpowder: The History of an International Technology*. Bath University Press, UK.

Cayton, John C.
1984 Blackpowder Firearms, Powder Residue, and Ball Penetration. *Association of Firearm and Tool Mark Examiners Journal* 16(4):80-81.

Chartrand, Rene
1999 *Quebec, 1759*. Osprey Publishing, Oxford, UK.

Coles, J.
1973. *Archaeology by Experiment*. Hutchinson University Library, London, UK.

DiMaio, Vincent J. M.
2016 *Gunshot Wounds: Practical Aspects of Firearms, Ballistics, and Forensic Techniques*. CRC Press, Boca Raton, FL (Third edition).

Dodd, Malcolm J.
2006 *Terminal Ballistics: A Text and Atlas of Gunshot Wounds*. Taylor and Francis, New York.

Fadala, Sam
1988 Penetration of Round Ball. *Association of Firearm and Tool Mark Examiners Journal* 20(2):135-139.

Fackler, Martin
1988 Handgun Bullet Performance. *International Defense Review* 21(5):555-557.

Foard, Glenn
2008 Integrating Documentary and Archaeological Evidence in the Investigation of Battles: A Case Study from Seventeenth-Century England. PhD Dissertation, University of East Anglia, East Anglia, UK.

2012 Battlefield Archaeology of the English Civil War. British Archaeological Reports, British Series 570.

Foard, Glenn, and Richard Morris
2012 The Archaeology of English Battlefields. Council for British Archaeology, Research Report 168.

Flores, J. R.
2011. Creating a History of Experimental Archaeology, in Millson, D.C.E. (ed.) *Experimentation and Interpretation: The Use of Experimental Archaeology in the Study of the Past*, pp 29-45. Oxbow Books, Oxford, UK.

Garrison, D. H., Jr.
1993 Shooting Reconstruction vs Shooting Reenactment. *Association of Firearm and Tool Mark Examiners Journal* 25(2):125-127.

Grancsay, Stephen V.
1954 Firearms vs. Armor. In *Gun Digest*, edited by John Ambler, pp 9-11, 15. Gun Digest, Chicago, Ill.

Haag, Lucien C.
2001 Black Powder Substitutes: Their Physical and Chemical Properties and Performance. *Association of Firearms and Tool Mark Examiners Journal* 33(4):313-325.

2006 *Shooting Incident Reconstruction*. Academic Press, New York.

Hall, Bert
1996 Gunpowder and Early Gunpowder Weapons. In *Gunpowder: The History of an International Technology* edited by Brenda J. Buchanan, pp 121-136. Bath University Press, UK.

Harding, D. F.
2012 *Lead Shot of the English Civil War: A Radical Study*. Foresight Books, London

Herring William G.
1971 Ballistics for Muzzle Loaders, Part 1. *Muzzle Blasts* 33(4):12-13.

1972a Ballistics for Muzzle Loaders, Part 2. *Muzzle Blasts* 33(5):6-7.

1972b Ballistics for Muzzle Loaders, Part 3. *Muzzle Blasts* 33(7):6-7.

1972c Ballistics for Muzzle Loaders, Part 4. *Muzzle Blasts* 33(9):5-7, 28.

Hawes, Arthur B.
1859 *Rifle Ammunition, being Notes on the Manufactures connected therewith, as conducted in The Royal Arsenal, Woolwich*. W. O. Mitchell, London (reprint 2004, Thomas Publications, Gettysburg, PA).

Howard, Robert A.
1996 The Evolution of the Process of Powder Making from an American Perspective. In *Gunpowder: The History of an International Technology* edited by Brenda J. Buchanan, pp 3-24. Bath University Press, UK.

Hueske, Edward E.
2006 *Practical Analysis and Reconstruction of Shooting Incidents*. Taylor and Francis, New York.

Kerkhoff, Wim, Ivo Alberink, and Erwin J. A. T. Mattijssen
2015 An Empirical Study on the Relation Between the Critical Angle for Bullet Ricochet and the Properties of Wood. *Journal of Forensic Sciences* 60(3):605-610.

Kidwell, Claudia B., and Margaret C. Christman
1974 *Suiting Everyone: The Democratization of Clothing in America*. National Museum of History and Technology, Smithsonian Institution Press, Washington. D.C.

Lin, Sam C., Zeljko Rezek, and Harold L. Dibble
2018 Experimental Design and Experimental Inference in Stone Artifact Archaeology. *Journal of Archaeological Method and Theory* 25:663-688.

MacPherson, Duncan
1994 *Bullet Penetration: Modeling the Dynamics and the Incapacitation Resulting from Wound Trauma*. Ballistic Publications, El Segundo, CA.

Mattijssen, Erwin J. A. T., Ivo Alberink, Suzanne D. Brouwer, and Wim Kerkhoff
2016 The Influence of Wood Grain on the Bullet's Ricochet Behavior. *Journal of Forensic Sciences* 61(3):765-772.

Mattoo, B N.
1969 Shot Penetration from Ballistic Data. *Journal of Forensic Sciences* 14(4):521-527.

McAulay, John D.
2017 *Rifles of the United States Navy and Marine Corps, 1866-1917*. Mowbray Publishing, Woonsocket, RI.

Miller, Donald, and Allan Bailey
1979 Sphere Drag at Mach Numbers from 0.2 to 2.0 at Reynolds Numbers Approaching 10^7. *Journal of Fluid Mechanics* 93:449-464.

Millson, D. C. E. 2011. Experimentation and Interpretation: *The Use of Experimental Archaeology in the Study of the Past*. Oxbow Books, Oxford, UK.

Mogish, Nicholas M.
1990 Unusual Effects of Discharging Multiple Lead Balls from a Black Powder Firearm. *Association of Firearm and Tool Mark Examiners Journal* 22(2):206-207.

Moore, Robert J., Jr., and Michael Haynes
2003 *Lewis and Clark: Tailor Made, Trail Worn: Army Life, Clothing, and Weapons of the Corps of Discovery*. Farcountry Press, Helena, Mont.

Osborne, Jack
1977a Round Ball Ballistics. *Muzzle Blasts* 38(5):4-5

1977b Round Ball Ballistics (Calculating Trajectory). *Muzzle Blasts* 38(6):17

Parkman, Colin J.
2017 Experimental Firing and Analysis of Impacted 17th-18th Century Lead Bullets. PhD Dissertation, University of Huddersfield, Huddersfield, West Yorkshire, UK.

Potter, Gail Debuse and James A. Hanson
2014 *Clothing and Textiles of the Fur Trade, Volume 4 of The Encyclopedia of the Trade Goods of the Fur Trade*. Museum of the Fur Trade, Chadron, Neb.

Reid, Stuart
2003 *Quebec 1759: The Battle that Won Canada*. Osprey Publishing, Oxford, UK.

Scott, Douglas D., Richard A. Fox, Jr., Melissa A. Connor, and Dick Harmon
1989 *Archaeological Perspectives on the Battle of the Little Bighorn*. University of Oklahoma Press, Norman.

Scott, Douglas D., Joel Bohy, Nathan Boor, Charles Haecker, William Rose, and Patrick Severts
2017 Colonial Era Firearm Bullet Performance: A Live Fire Experimental Study for Archaeological Interpretation. https://Adademia.edu.

Secretary of War
1856 *Reports of Experiments with Small Arms for the Military Service*. A. O. P. Nicholson Public Printer, Washington, DC. (reprint undated by Dean S. Thomas, Arendtsville, PA.)

Shillito, L. M., Fairnell, E. and Williams H. S. 2014. Experimental Archaeology. *Archaeology Anthropology Science*, Vol 7 1-2.

Sivilich, Daniel M.
1996 Analyzing Musket Balls to Interpret a Revolutionary War Site. *Historical Archaeology* 30(2):101-109.

2009 What the Musket Ball Can Tell: Monmouth Battlefield State Park, New Jersey. In *Field of Conflict: Battlefield Archaeology from the Roman Empire to the Korean War*, edited by Douglas Scott, Lawrence Babits, and Charles Haecker, pp 84-101, Potomac Press, Washington, DC.

2016 *Musket Ball and Small Shot Identification: A Guide*. University of Oklahoma Press, Norman.

Sivilich, Daniel and Joel Bohy
2018 Musket Balls from the Boston Massacre: Are they Authentic? Paper presented at the 10th Biennial Fields of Conflict Conference, Pequot Museum, Mashantucket, CT. Accessed online May 27, 2019: https://bravodigs.org/historical-research/.

Tascón, Ignacio González, Juan Carlos Jiménez Barrientos, Dolores Romero Muñoz, and Amaya Sáenz Sanz
1996 Black Powder in Mining – Its Introduction, Early Use, and Diffusion Over Europe. In *Gunpowder: The History of an International Technology* edited by Brenda J. Buchanan, pp 205-218. Bath University Press, UK.

Warlow, Tom
2005 *Firearms, the Law, and Forensic Ballistics*. CRC Press, New York.

Weber, Kent P., and Douglas D. Scott
2006 Uncapped Potential: Applying Firearms Identification Procedures in the Analysis of Percussion Caps. *Historical Archaeology* 40(3):131-143.