An Assessment of the Foundational Validity of Firearms Identification Using Ten Consecutively Button-Rifled Barrels

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ABSTRACT

Using ten consecutively reamed and button-rifled Thompson/Center Arms G2 Contender barrels, fired bullets were collected and 50 comparison test kits distributed to firearm examiners in three countries, including 21 states within the United States. Of the 66 enrolled participants, 44 returned results. Each test kit was comprised of 15 open-set comparisons. Five questioned bullets from each test kit were damaged by being fired into one each of glass, drywall, sheet metal, wood, and Kevlar to replicate damage seen in casework. Participants were unaware that the test kits they were asked to compare were comprised of bullets from consecutively manufactured barrels. Test kits were coded to establish a declared study with double-blind elements. Participants were asked to simply compare the provided knowns to questioned samples, using their laboratory's policies and procedures to include any quality control measures, and render a result. Allowing participants to use their standard operating procedures examines the entire system and gives insight into realistic error rates that could be expected in real casework. The false identification rate was observed to be 0.455 ± 0.139% (1/220) while the false elimination rate was 1.82 ± 0.555% (8/440), both at the 95% confidence interval. The overall total error rate was found to be 1.36 ± 0.414% (9/660) for 660 total comparisons.

Introduction

The foundation of firearms identification is that every firearm can potentially leave its own individual marks on fired ammunition components, whether it is a bullet or a cartridge case. No two firearms yet found will leave marks having the exact same depth, contour, orientation, and relative position. This is due to the way the firearm is manufactured. The worst-case scenario for firearm examiners is a comparison between consecutively manufactured firearms parts due to the greatest potential for subclass carry-over **[1]**. Subclass characteristics are features that may be produced during manufacture that are consistent among items made by the same tool in the same approximate state of wear. These features are not determined prior to manufacture and are more restrictive than class characteristics. The potential danger of subclass characteristics is that, when these marks are present in a firearm and are then transferred by that firearm to fired ammunition components, they could be mistaken for individual characteristics by the firearm examiner unless a careful evaluation of the working surface(s) in question has been conducted. For this reason, validation studies are often designed using a set of consecutively manufactured parts. It is important to test the limits of examiners using the most challenging conditions for the method evaluated, in order to get a true picture of error rates. The method being evaluated in this study is pattern matching of striations on bullets fired through sequentially reamed and button-rifled barrels. If the marks deposited on the fired bullets are uniquely identifiable then trained examiners should be able to accurately distinguish which barrels the bullets were fired through.

The individuality of marks is based on the principle of chip formation and the built-up edge of the cutting tool. As the blade of a cutting tool contacts a metal workpiece to remove material, the metal is building up on the edge of the blade. This material removed from the workpiece can become cold-welded to the surface of the cutting blade and thus become the new pseudo-cutting surface of the blade. These built-up edges of metal break off at random intervals resulting in microscopic defects on the surface of the workpiece that are individual. It is also important to note that the built-up-edge is constantly changing as more metal breaks off and is replaced. The surface of the workpiece is not flat, but rather covered in small ridges of metal that break off as the bulk of material becomes too much for the blade to continue to hold. The density of the metal workpiece and its crystalline structure play a part in determining the rate and extent of chip formation due to the built-up edge **[2]**. If the metal of the workpiece is very dense or hard, such as tungsten, then the crystalline structure is brittle, and the metal will fragment into small discontinuous chips; however, if the metal is soft, such as aluminum, then

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chips may take the form of long ribbons, known as continuous chips. The built-up edge also depends on the speed, surface area of the blade, friction, and rake angle **[3]**.

The rake angle is the angle at which the blade contacts the workpiece. If the rake angle of the blade is perpendicular to the workpiece, then there is higher friction which results in chatter. Chatter between the workpiece and the blade will leave microscopic imperfections on the metal workpiece. If the rake angle is changed to slightly greater than parallel to the surface of the workpiece, then the blade will ride along the workpiece with less friction and less chatter. This results in a smoother workpiece, but metal will still build and break off from the built-up edge of the blade. Another factor that leads to individuality is that the cutting tool changes over time as the tool wears. The remnants of the built-up edge left on the workpiece typically take the form of a burr or rough spot on the metal's surface. In firearms, this burr will contact fired bullets and scratch them in an individual fashion. Barrels are fixed tools so these scratches, or striations, will be in the same orientation, depth, and relative position for subsequent firings until something happens to change these marks (e.g., wear of the surfaces in the bore).

There are many different ways to produce rifled barrels. Some processes may be unique to one manufacturer, but many are ubiquitous within the firearms industry. The generalized process is as follows: Barrels begin as a cylinder of bar stock. A center hole is then rough cut using a deep hole drill, also referred to as gun drilling, that is slightly under final diameter for the bore. The last 0.001 to 0.002 inches of the bore is removed by one of the common pre-rifling operations discussed in the next section. This process is used to clean up the rough-cut processes and to enlarge the bore diameter to the final dimensions. Some manufacturers forgo pre-rifling operations and others incorporate this step with the rifling process itself, such as hammer forging.

The pre-rifling process used has a great deal to do with the way individual characteristics are engraved on fired bullets. For instance, honing tends to leave very fine detail on fired bullets whereas reaming leaves more pronounced detail. Individual characteristics are deposited on the bullet as a result of contacting microscopic burrs and rough spots in the barrel left behind by these pre-rifling processes. For this reason, it is important to review some of the pre-rifling and rifling processes in common use **[4, 5, 6, 7]**.

<u>Pre-Rifling Processes</u>

Honing

Honing is the process of applying a high grit sanding compound or drum to the bore of the barrel. The drum is spun while it is moving up and down through the barrel. This results in a very smooth finished surface. A cast of a honed barrel would show fine cross-hatched marks. Fired bullets from honed barrels typically have very fine individual characteristics **(Figure 1)**.

Figure 1: An example of honing marks found in a Colt pistol

Reaming

Reaming is a process where a multi bladed cutting tool is used to remove small amounts of metal. This expands the diameter of the bore to final dimensions as well as produces a smoother surface finish than rough cutting processes used prior. The reaming tool is tapered such that the center of the tool is the largest diameter and is what contacts the bore of the barrel. As the reaming tool wears, more of the blade will contact the bore. Reaming marks are typically readily visible during visual examination of barrels. A cast of a reamed barrel would show coarse concentric rings perpendicular to the long axis of the bore **(Figure 2)**.

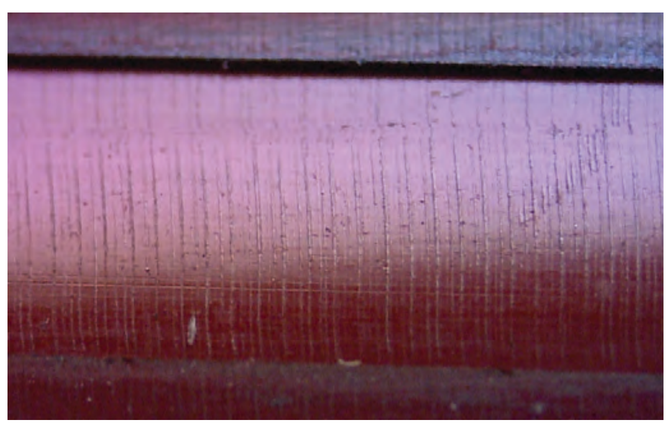

Figure 2: An example of reaming marks found in a Thompson/Center Arms pistol

Burnishing/Ballizing

Burnishing is a process by which pressure is applied to cold work metal and forces the high areas into the low areas. Button rifling that uses a second stage lobe to swage may be considered a form of burnishing. Ballizing is a method of burnishing in which a steel ball is forced under high pressure down the bore of a barrel to smooth out the surface of the land to create a fine finish. This process may be performed before or after rifling **(Figure 3)**.

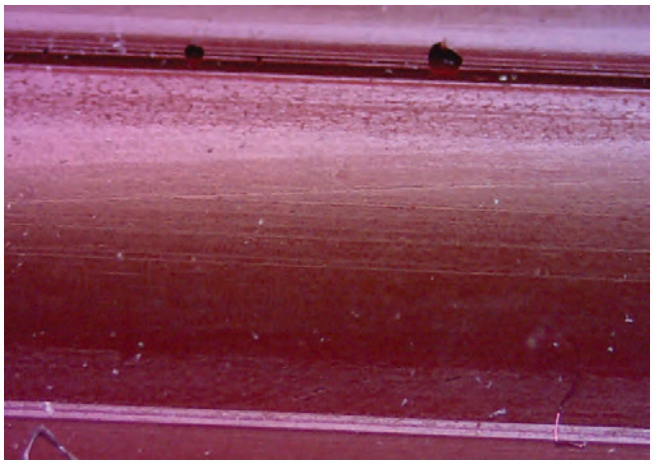

Figure 3: An example of burnishing marks found in a Sig Sauer pistol

<u>Rifling Processes</u>

Hammer Forging

In hammer forging, the rifling is not cut from the bore but rather the metal is shaped around a mandrel. The mandrel, often made of tungsten carbide, has the predetermined rifling characteristics ground into it. The mandrel is inserted into the finished bore of the barrel and force is applied to the outside of the barrel by a set of opposed hydraulic hammers. These hammers pound the bore of the barrel to the shape and contours of the mandrel. The mandrel is then pulled out of the barrel leaving behind rifling. Polygonal rifling is often created using the hammer forging method **(Figure 4)**.

Button (Swaging)

Button rifling, or swage rifling, is the most commonly used method to date **[4]**. This method is similar to hammer forging in that no metal is cut from the barrel; however, it differs from hammer forging in that the barrel is not shaped around it. The button, again often made of tungsten carbide, has the rifling characteristics ground into it and is slightly oversized to that of the bore. Considerable force, around 2,500 pounds, is applied to the button to push it down, or pull it through, the barrel (2019 Correspondence with Smith & Wesson). As the button travels down the barrel the metal is displaced into the shape of the rifling. The force surpasses the plastic deformation point of the metal and the barrel retains the shape of the rifling once the button is removed **(Figure 5)**. Generally, marks observed on fired bullets from button rifled barrels are a result of the pre-rifling process.

Broach

Broach rifling uses a long rod with several cutting blades attached. Moving from one end of the rod to the other the cutting blades increase in diameter until the final desired bore diameter is reached. This is called a gang broach. The cutting blades have raised and lowered cutting surfaces to cut the lands and grooves in one pass. As the gang broach is pulled through the barrel, metal is shaved incrementally from the bore until all cutting blades have passed through and the final diameter is reached **(Figure 6)**. Some manufacturers use bore broaching as a pre-rifling process, particularly in double broached barrels. In these instances, a broach is used to cut the grooves and clean the surface of the lands. This results in

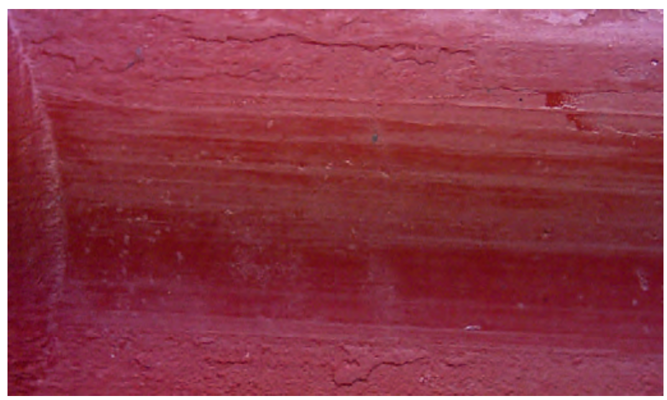

Figure 4: An example of a hammer-forged land found in a Glock pistol

Figure 5: An example of a button rifled land found in a Bryco Arms pistol

parallel broach marks down the lands as well as the grooves.

Although the pre-rifling process used has much to do with the deposition of individual characteristics on fired bullets, it is important to note that it may not be the only source of individual characteristics. The remnants of other machining processes, such as porting, drilling gas ports (in gas-operated firearms), and crowning, may also contact the bullet, creating individual characteristics. This is especially true if the crowning tool is piloted and contacts the rifling at the muzzle. Although each barrel will leave the factory with individual characteristics, they may become even more unique with the addition of wear from normal use and abuse over time.

Figure 6: An example of a broached land found in a Beretta pistol

Once bullets are fired and engraved with these individual characteristics, they may incur damage as a result of striking a target. This is common in casework and as such contributes to the difficulty of bullet comparisons. Damage to the bullet can result in foreshortening and partial or complete obliteration of the individual characteristics; however, identification is often still possible with damaged bullets depending on what area and to what extent the bullet is damaged **[8]**. It is important to conduct validation studies using specimens for comparison that are representative of casework.

Materials and Methods

<u>Materials</u>

Smith & Wesson produced ten consecutively manufactured Thompson/Center Arms G2 Contender barrels for use in this study **(Figure 7)**. These barrels started as ten steel bar stock blanks. The blanks were numbered by the manufacturer one through ten and were machined in numerical order throughout the manufacturing process. The blanks then underwent a deep hole drilling process to rough cut a hole that would become the bore of the barrel. The barrels were then consecutively reamed with the same reaming tool. This tool was at the end of its production life, which is approximately 400 barrels. Following the reaming process, the barrels were each cast to examine the microscopic reaming marks before rifling.

The ten barrels were then consecutively button rifled using the same carbide button that was at the start of its life **(Figure 8)**. A button can rifle several thousand barrels before it is replaced. These barrels were rifled and chambered in .357 Magnum caliber. This caliber was chosen for its interchangeability with

Figure 7: Thompson/Center Arms G2 Contender pistol

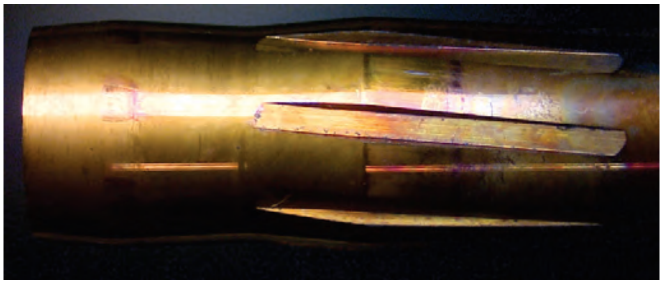

Figure 8: Two stage button used to consecutively rifle barrels 1-10

.38 Special caliber cartridges. In the rifling process, a carbide button, with a negative of the desired rifling characteristics ground into it with a diamond wheel, is forced down the bore of the newly reamed barrels with 2,000 to 2,500 pounds of force. The grooves of the button are deep enough that the lands it creates never contact the bottom and do not pick up the parallel grind marks. The button is slightly larger than the inner diameter of the bore. This process displaces or swages the metal of the barrel into the final dimensions of the desired rifling. Rather than cutting the rifling in, this forces the metal to surpass its yield point.

Elastic deformation describes how metal will bend back in response to a force, once the force is no longer applied. Button rifling overcomes this by the button being larger than the desired rifling so that elastic deformation gives way to plastic deformation. Plastic deformation begins to occur at the point at which the metal will no longer bend back and recover, despite the removal of the stress or force. This point where elastic deformation becomes plastic deformation is known as the yield point. With plastic deformation, the metal will retain the shape of the rifling that was ground on the button. The rifling characteristics for these barrels were eight lands and grooves with a right-hand twist. Following button rifling from the chamber to the muzzle, the barrel will bell out at the end. This bell exists because of the outward force of pulling an oversized button through the smaller diameter bores. Therefore, the muzzle end is cut off to remove the bell and the outer diameter of the barrels are turned to their final dimension. With this process, 1.5 inches of muzzle bell is removed. This reduces the overall length of the barrel from 13.5 inches to 12 inches.

Following turning the outer diameter, the barrels undergo a chamber reaming operation. This operation expands the diameter of the chamber to Sporting Arms and Ammunition Institute (SAAMI) specifications for .357 Magnum caliber chambers **[9]**. Chamber reaming also tapers the throat creating a gradual transition from the chamber to the height of the lands in the rifling.

The last machining operation performed is crowning of the muzzle. Smith & Wesson uses a piloted crowning tool to machine a small amount of material from the muzzle. The pilot of this tool is 0.5 inches long and rides on the lands in the barrel. Roughly 0.025 inches of material is removed from the muzzle in this process. The rifling of Contender barrels abruptly terminates at the crown; there is no gradual radius to the crown, but rather a recessed table that ends flush with the rifling.

Three types of ammunition were tested for their ability to pick up individual characteristics: PMC, American Eagle (Federal), and Winchester .38 Special caliber cartridges. PMC Bronze .38 Special caliber full metal jacket (FMJ) 132 grain ammunition was selected for its consistency of marking and 2,500 cartridges were obtained (lot 38G-1093). Using this ammunition, each barrel was test fired into a horizontal water tank to collect the bullets undamaged for comparison. Each barrel underwent a 20-test fire break in period. After the break-in period the bullets were found to reproduce individual characteristics consistently.

Test Kit Design

Fifty test kits were created with fifteen comparison sets per kit **(Figure 9)**. Each of the fifteen sets was comprised of two known bullets and one questioned bullet. The participants were offered the two known bullets to establish reproducibility of the individual characteristics. Participants were then asked to compare at least one of the known samples to the questioned sample.

Each test kit was comprised of ten true identifications and five true eliminations. Of the five true eliminations three were between consecutively manufactured barrels, one was from non-consecutive barrels, and one was a class elimination on land and groove impression measurements. Using the consecutively manufactured barrels, excluding barrels #7 and #10 due to damage during manufacturing, ammunition was test fired into a horizontal water tank and bullets collected in batches of fifty per barrel. This ensured that known samples were within fifty test fires of one another to assist in reproducibility. Class elimination samples were collected from three firearms outside of the ten consecutive barrels. These firearms were RG, Charter Arms, and Arminius .38 Special caliber revolvers. The class characteristics of these elimination firearms were the same as the ten barrels produced by Smith & Wesson with the exception of the land and groove impression widths. These widths had a difference of approximately 0.020, 0.010, and 0.005 inches for the RG, Charter Arms, and Arminius revolvers, respectively.

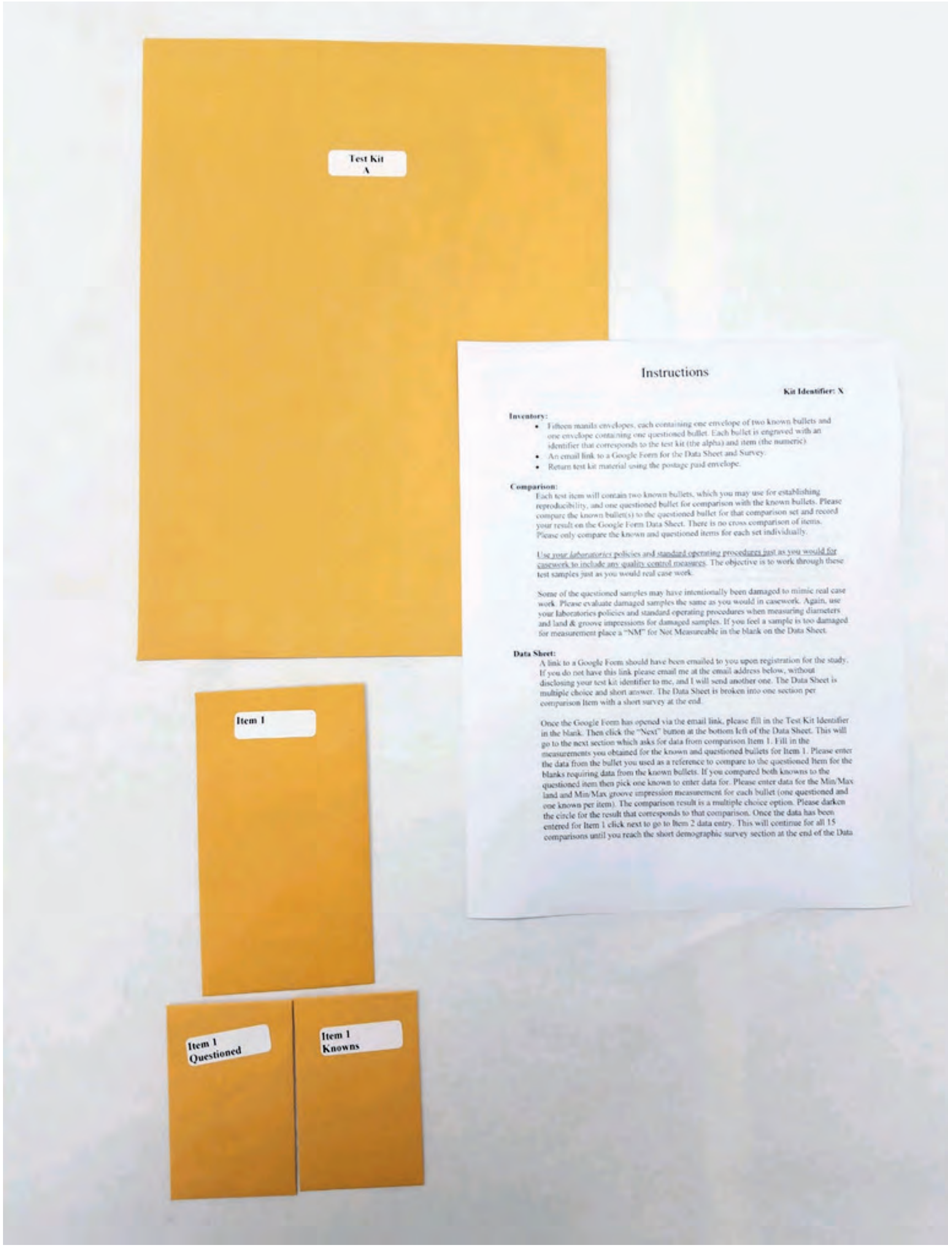

Figure 9: Test kit consisting of 15 comparison sets, each with two known and one questioned bullet

Three kits, kits A-C, were sent to three firearm examiners with a combined thirty-five years of experience as a beta test. These examiners verified that the test kits were identifiable and that the kits replicated casework. Ten percent of the comparisons, or 70 comparisons, from the remaining forty-seven test kits were examined as a quality control measure.

Participants were asked to compare the known samples to the questioned samples for each set. There were no cross comparisons of test sets. The point of this open-set design is to prevent participants from working through the samples in a process of elimination fashion. Each of the comparison sets were created using randomly generated variables, such as what barrels comparisons would be made from, what result would be expected, and what questioned bullets would be damaged, using a random number generator and assigning each variable a number. This created fifty test kits with no two kits being the same. Each test kit was made as its own unique case.

The intent was to make test samples that represented real casework. To achieve this, five questioned bullets out of the fifteen comparison sets per test kit were intentionally damaged **(Figure 10)**. One bullet each was fired into wood, metal, drywall, glass, and a bullet proof vest. Most of these materials are commonly encountered as intermediate or terminal targets that cause damage to bullets found at crime scenes. To further replicate real casework, participants were asked to follow their laboratory's policies and procedures to include any quality control systems and verification.

Figure 10: Some questioned bullets, such as this one, were damaged to resemble real casework

Each test kit was coded with a unique identifier. This identifier was alphabetical, A through AZ. This coding was used to link participant's results with the answer sheet without disclosing the participant's identity to the test administrator. To randomize which participants received which test kit, a third party was used to assign and mail the test kits to participants. Upon completion of the comparisons, the participants mailed the test kit back in a pre-addressed return envelope. This return envelope did not contain participant information such as name or address. Participants were asked to submit results via a Google Forms data sheet. This electronic submission allowed for anonymous data collection.

This design is considered declared with double-blind elements **[10]**. The participants were aware they were participating in a study, but they were unaware that the comparisons were from consecutively manufactured barrels or the number of true identifications or eliminations. Also, the test administrator was unaware of what test kits went to which participants due to the coded design. It is not currently feasible to conduct a true double-blind study due to evidence submission practices. To be considered truly double-blind, the test kit would have to be submitted and assigned to the participant without them knowing they were participating in a study.

Participants were asked to follow the Association of Firearm and Tool Mark Examiners (AFTE) Range of Conclusions, with a small modification **[11]**. Participants were asked to report any inconclusive result as just inconclusive. This removed the three categories of inconclusive results (Inconclusive A, B, or C) as described by the AFTE Range of Conclusions. Many laboratories in the United States do not subdivide inconclusive results. The decision was made to not allow subcategorization of inconclusive results as responses due to the author's own laboratory policy and the fact that results obtained from individuals from similar policy laboratories may not provide accurate data due to lack of training in the use of Inconclusive A, B, or C determinations.

Results and Discussion

<u>Participant Demographics</u>

Sixty-six practicing firearm examiners enrolled as participants in this study. They represent a diverse sampling from three countries, including 21 states within the United States, and are employed by federal, state, and local agencies. Of the 66 to enroll, 44 participants submitted results for a total of 660 comparisons **(Table 1)**. The years of experience covered a range of 0.7 to 32 years with an average of 12 years. From this group, 98% (43/44) were AFTE members, 91% (40/44) were from accredited laboratories, and 98% (43/44) perform verification of results as part of their quality control system **(Table 2)**. When asked if the quality of the comparisons were similar to that seen in casework 43% (19/44) said yes, 48% (21/44) were neutral, and 9% (4/44) said no.

<u>Damaged Barrel Discussion</u>

Barrels #7 and #10 were damaged during manufacture and were not finished. Therefore, these two barrels could not be fired. A very small percentage of barrels at Smith & Wesson are damaged during the manufacturing process and are pulled from the production line. Most are damaged during the startup and initial adjustment of a machining process. Due to these ten barrels being specially made, they encountered several machine startups and as a result two were damaged. This demonstrates that not every barrel makes it through the manufacturing process, so gaps in consecutiveness can be expected among the firearms that make it to the marketplace.

<u>False Identification</u>

False identifications are false positives, or Type I Errors. There was one false identification reported. The false identification error rate was determined to be 0.455 ± 0.139% (1/220) at the 95% confidence interval **(Table 3)**. This is a range of 0.316 to 0.594% for false positives. This false identification was reported by a participant that had more than fifteen

Enrolled Participants	66
Responding Participants	44
True Identification Comparisons	440
True Elimination Comparisons	220
False Identifications	1
False Eliminations on Class Characteristics	0
False Elimination on Individual Characteristics	8
Identification Correct Responses*	252
Elimination on Class Characteristics Correct Responses	37
Elimination on Individual Characteristics Correct Responses	23
Total Elimination Correct Responses	60
Total Errors	9
Total Comparisons	660

*This is the number of correct responses for identification. This does not take into account inconclusive results. A result of inconclusive is not considered incorrect.

Table 1: Study information and results data

Verification Type	Results	Percentage
100% Verification	30/44	68%
Random Sample Verification	1/44	2%
Other*	12/44	27%
Total	43/44	98%

*Includes verification of conclusive results only, just verification of identifications, and any other type of verification system.

Table 2: Break down of verification by type

	Results	Error Rate	95% Confidence Interval
False Identification	1/220	0.455%	+/- 0.139%
False Elimination	8/440	1.82%	+/- 0.555%
Total	9/660	1.36%	+/- 0.414%

Table 3: Error rate results with 95% confidence intervals

years' experience and was from an accredited laboratory that performs verification as part of its quality control system; however, it is unknown if this comparison was verified by a second examiner. It is important to note that this false identification was isolated to one comparison of the 220 true elimination comparisons. The conclusive false identification rate (the rate with inconclusive results removed) was found to be 1.67% (1/60).

<u>False Elimination</u>

False eliminations are false negatives, or Type II Errors. There were a total of eight false eliminations reported. All eight of the false eliminations were based on individual characteristics. The false elimination error rate was calculated to be 1.82% ± 0.555% (8/440) at the 95% confidence interval **(Table 3)**. This is a range of 1.27 to 2.38%. Of the eight false elimination errors one participant made three errors, a second participant made two errors, and the last three errors were made by three different participants. Five participants made all eight false eliminations in the 440 true identification comparisons. This indicates that false eliminations are also isolated and are not systemic. Two of the participants to report a false elimination had more than ten years' experience and three had less than five years' experience. All five were from accredited laboratories that perform verification as part of their quality control systems. Two of these five participants did not report an inconclusive result for any of the fifteen comparisons. The conclusive false elimination rate (the rate with inconclusive results removed) was determined to be 3.17% (8/252).

Inconclusive Rate

The spectrum of correct responses for comparisons is not binary, as in identification or elimination, but rather it is trinary; the third valid response is inconclusive. An inconclusive result, in many instances, is the most correct response. When the data does not support an identification or elimination, a result of inconclusive is warranted.

Several factors can lead to markings on bullets that may not support a conclusive result: low ammunition pressure, increased hardness of the bullet, quality or quantity of striations, poor engagement of the bullet with the rifling, damage to the bullet, and even the firearm not imparting consistent or comparable striations on the bullet. It is common for these to occur in real casework, making for difficult bullet comparisons. There were 339 inconclusive results reported **(Table 1)**. This is an inconclusive rate of 51.3% (339/660). This inconclusive rate was considerably higher than those found by Smith, Fadul, DeFrance, and Hamby, which were 17.3% (165/955), 8.61% (142/1,650), 4.76% (3/63), and 0.066% (5/7,605), respectively **[8, 12, 13, 14]**. The elevated inconclusive rate in this study may be skewed higher by the difficulty of the comparisons and the level of damage observed. Of the studies listed, only Smith used damaged bullets and the inconclusive rate found in this study is nearly three times that of Smith's. This is potentially due to the use of consecutively manufactured barrels here, whereas Smith's barrels were from different manufacturers and used different rifling methods that would be apparent on fired bullets.

Error Rate Totals

The combined error rate was calculated to be 1.36 ± 0.414% (9/660) at the 95% confidence interval **(Table 3)**. This is a range of 0.946 to 1.77%. There were nine total errors out of the 660 total comparisons. Six participants out of the 44 made all nine errors. This indicates the errors were isolated and are not systemic. The nine comparison sets with errors reported by examiners were evaluated using the Evofinder 3D system by Leeds Forensic Systems. The data from the Evofinder system supports the ground truth results for all nine of those comparisons. The sensitivity and specificity were calculated to be 57.3% (252/440) and 27.3% (60/220), respectively **(Table 4)**. Sensitivity is a measure of how often an Identification conclusion was reached when comparing same-source samples. Likewise, specificity is a measure of how often an Elimination conclusion was reached when comparing different-source samples. The specificity in this study was relatively low; however, several factors may have contributed to this, including the use of damaged bullets, the use of consecutively button-rifled barrels with the same class characteristics, and the use of only a single questioned sample, which did not allow for an evaluation of reproducibility such as a group of multiple unknowns might provide.

	Results	Percentage
Sensitivity	252/440	57.3%
Specificity	60/220	27.3%

Table 4: Sensitivity and specificity

Conclusion

A total of 660 comparisons were made by 44 participants. Of the 660 results, nine errors were reported. These errors include one false identification and eight false eliminations on individual characteristics. The nine errors were reported by six of the 44 participants. This indicates that errors are isolated and are not distributed evenly among participants. As such, the error rates observed should not be misconstrued as an expected error rate for all firearm examiners.

The false identification error rate was determined to be 0.455 ± 0.139% (1/220) with the false elimination error rate at 1.82% ± 0.555% (8/440). The false elimination error rate was four times larger than that of the false identification error rate. Eliminations on individual characteristics alone are considered exceptional situations in which the condition of the firearm and the number of items exhibiting reproducibility should be considered **[15]**.

The inconclusive rate was 51.3% (339/660) which is considerably higher than most other studies; however, this study attempted to replicate the most difficult comparison situations that an examiner may face and therefore the inconclusive rate was expected to be higher than typically observed **[8, 12, 13, 14]**. The focus of this study was to incorporate several factors that are found in difficult comparisons in an attempt to test the error rate under the most difficult of situations. Factors that may have elevated the inconclusive rate included the use of consecutively manufactured button-rifled barrels, that the bullets were damaged by being fired into common materials, and that the study had an open-set design, with only one questioned sample available for comparison in each set.

The total error rate of 1.36 ± 0.414% (9/660) supports the scientific validity of Firearms Identification, including the core concept that trained firearm examiners can correctly associate bullets to the barrels that fired them, even when presented with very difficult comparisons such as the ones presented in this study.

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