Interpol review of forensic firearm examination 2016-2019

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ABSTRACT

This review paper covers the relevant literature on forensic firearm examination from 2016 to 2019 as a part of the 19th Interpol International Forensic Science Managers Symposium. The review papers are also available at the Interpol website at: https://www.interpol.int/content/download/14458/file/Interpol%20Review%20Papers%202019.pdf.
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1. Introduction

1.1. Scope

This review paper covers the advances in scientific methods and general discussions concerning firearm examination, published from 2016 until and including 2018. A literature search was conducted covering articles on this subject published in the main forensic journals:

- AFTE Journal
- American Journal of Forensic Medicine and Pathology
- Australian Journal of Forensic Sciences
- Forensic Science International
- Forensic Sciences Research
- International Journal of Legal Medicine
- Journal of Forensic Identification
- Journal of Forensic Sciences
- Science and Justice

1.2. Current topics

Former USA president Barack Obama requested the President's Council of Advisors on Science and Technology (PCAST) to identify additional measures that could be taken to improve the state of forensic sciences in the USA. The investigation and resulting report

"Forensic Science in Criminal Courts: Ensuring Scientific Validity of Feature-Comparison Methods" [1] built on the 2009 National Research Council's (NRC) report "Strengthening Forensic Science in the USA: A path forward" [2]. The committee defined two critical parameters for the assessment of both objective and subjective feature-comparison methods: foundational validity and validity as applied. Foundational validity refers to the scientific standard for whether evidence is based on "reliable principles and methods" and validity as applied refers to the scientific standard for whether one "has reliably applied the principles and methods". Firearm examination was one of the forensic disciplines that were investigated. For firearm examination the committee concludes that insufficient studies exist with the required quality and quantity to provided sufficient foundational validity or to estimate the reliability of the method as applied. The PCAST reports that the current situation could be much improved by 1) ongoing developments in computer-based methods and with 2) additional validation studies of examiner judgments which are vulnerable to human error, inconsistency across examiners, and cognitive bias.

When considering the recommendations written in the NRC and PCAST reports in combination with the recent literature in firearm examination the following topics have received specific attention in the last three years:

1. Development of computer-based methods
2. Validation studies and proficiency testing
3. Influence of the human factor on forensic judgments

The published articles which are related to these three topics will be addressed on sections *2.7 Development of computer-based*

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methods, 2.1 *Validation studies and statistical foundations* and 2.6 *Proficiency testing*, and 3.5 *Bias, reporting and quality assurance*, respectively.

2. Firearm examination

Following the recommendations made in the 2009 NRC [2] and 2016 PCAST [1] reports to strengthen the scientific foundations of firearm examination, several articles have been published.

2.1. Validation studies and statistical foundations

When providing judgments about the source of fired ammunition parts forensic firearm examiners consider the observed degree of similarity of features: striations and impressions. To be able to provide a judgment about the source of these features in fired cartridge cases or bullets they should be reproducible from shot to shot. When the features are highly reproducible, the intra-variability will be low. At the same time the inter-variability (between different firearms) is expected to be (a lot) higher. As a result of these differences in intra- and inter-variability, a higher degree of similarity will usually result in a higher degree of support for a same-source judgment. Preferably, the intra-variability will also be low over a prolonged period time or after firing a large number of shots. In other words, that the features are reproducible and that the responsible imperfections in the firearm are durable.

A study, using twenty-four new 9 mm Luger Ruger SR9 firearms, focused on the reproducibility of features over time. Two hundred shots were fired with each of the firearms and compared with IBIS Heritage. Both the firing pin and breechface impressions were considered in the analyses. No decreasing trend in performance of the IBIS Heritage system was observed between earlier and later test shots, indicating that change in features over time is small [3].

Another study, using five 9 mm Luger Norinco QSZ-92 firearms, and firing 3070 shots per firearm showed that the firing pin and breechface impressions were more similar when shots were fired closer in sequence. But at the same time the intra-variability of features did not exceed the inter-variability, resulting in nearly 100% correct correlations by the used Evofinder system [4,5].

Based on the expected difference between intra- and inter-variability a study was set up to investigate the hypothesis that no cartridge cases fired from two different 9 mm Luger Glock pistols would incorrectly be concluded to come from the same firearm. A sample of 1632 cartridges cases, fired from 1632 Glock pistols, was used. All of these were manually compared, where none of the cartridge cases were perceived to 'match'. A subset of 617 cartridge cases was compared by the IBIS system and none of them were found to match. Based on these results a random match probability of 0.0001% was calculated [6].

Two types of prototype barrels for Glock pistols were studied. Ten 12 right and ten 18 right consecutively manufactured barrels were test fired. Ten examiners received twenty-five questioned bullets with twenty sets of reference shots. From the 250 comparison, 8 were judged 'inconclusive' while the others were correctly assigned to the reference shots [7].

2.2. Parameters that affect the identification process

Test shots have to be made to compare fired ammunition parts with a submitted firearm. The features in these test shots can then be compared to those in the seized ammunition parts. For the purpose of creating test shots, the performance of three bullet recovery systems was compared: a water tank, a cotton tube, and layered synthetic non-flammable fleece. The authors conclude that the water tank is the most efficient system, also in terms of quality of features in the fired bullets. However, the water tank does not work well with some types of ammunition, such as hollow-point bullets. The other two systems work well for these, with the fleece-based system being more universal, but the fibers will have to be removed from the bullet before comparison [8].

A complicating factor when comparing seized ammunition parts to test shots occurs when the firearm was found in a burned car. The features in test shots from three 9 mm Luger CZ 85B firearms were compared to the features in test shots from the same firearms after exposing those to a car burnout. The formation of oxide layers was observed as the primary influence on the surfaces of the firearms. It was still possibly to relate the pre- and post-burn cartridge cases, but this was not possible for the bullets. The difference in the formation of the features used for comparison (impressions and striations, respectively) is given as a possible reason for this different outcome in cartridge case and bullet comparison [9].

The used ammunition can also result in complications when comparing the features in fired ammunition parts. As an example, the American Eagle, Syntech 'lipstick round', a total synthetic jacketed bullet, is discussed. Deformation and poor rifling engagement of the synthetic material complicated the comparison of the features resulting from the barrel. This became increasingly evident when comparing two Syntech bullets two each other [10]. The earlier plastic-coated Nyclad bullets by Smith and Wesson showed similar problems while comparing the features resulting from the barrel [11]. Haag (2018) mentions that the presence of individual characteristics is unlikely in Syntech's caliber .45 Auto bullets and that only the general rifling characteristics will be available for the examiner. He mentions that this is in contrast with the Nyclad and Herter's Total Nylon Jacket bullet in which striation patterns can be seen and compared [12].

The effect of applying Hi-Tek-Lube Supercoat, a polymer heat-set coating for lead bullets, on the comparison of the features is discussed. Most of the examinations of the features resulting from the barrel in the coated bullets resulted in 'inconclusive' judgments (80%–90%). Identifications were only called when (a part of) the coating was sheared off by the barrel [13].

The Winchester Varmint LF caliber .22 Long Rifle ammunition is examined. These cartridges have lightweight pure tin bullets. Due to their low mass, the muzzle velocity is quite high but due to the decrease in ballistic coefficient they also show a rapid loss of velocity over time and distance when compared to equivalent lead bullets [14].

Ahmad, Adnan & Sagheer (2016) discuss that firearm examiners should use caution when considering differences in the position of the firing pin impressions as evidence that cartridge cases are fired from different firearms. The spring loaded firing pin of a 7 mm bolt action rifle can potentially move in the bolt housing, resulting in varying impact locations on the primer. The features in the impressions are reproducible and can still be used for comparison purposes [15].

Felix (2016) describes a comparison case involving a 9 mm Luger Glock pistol. Although the correspondence of features in the firing pin aperture shear mark and the breechface impression led to an identification, the features in the firing pin impression were completely different between the test shots and the seized cartridge cases. Careful examination of the debris channel of the firing pin led to the conclusion that the firing pin was replaced by an aftermarket part, modeled after the original firing pin design. The author concludes that these results mean that the firing pin was switched between the shooting incident and submitting the firearm for comparison [16].

Although most firearm examiners use a comparison microscope to compare the features in fired ammunition parts, this instrument is not available to everyone. A simple method, using a binocular, a

digital camera, and Microsoft Word is explained to still be able to compare the firearm features in the absence of a comparison microscope [17].

Haag (2017) studied the relation between peak pressures in cartridge cases, and the appearance of fired primers and the clarity and completeness of breechface marks. Although several factors such as headspace variations, method of operation, hardness of primers, and bullet and primer seating affect the appearance of the primer after firing, there seems to be a relation between appearance and peak pressure. In cartridges with normally seated primers (without retaining crimp) there is an increased likelihood that evidence of excessive pressures will occur. Signs of high peak pressure are primer flattening, cratering (back flow) around the firing pin impression into the firing pin aperture and pierced primers [18].

2.3. Identification based on unusual markings

The marks resulting from e.g., the breechface, firing pin, ejector, extractor and chamber of the barrel are quite apparent and seen in the fired cartridge cases of most firearms. Features in marks resulting from other origins are encountered or used less often. Eckert (2018) discusses the origin of the slide scuff mark. These 12 o'clock striations are formed as the breechface strips a cartridge from the magazine and loads it into the chamber. They are not a result of the actual firing process [19].

The Beretta 'swoosh' mark on the wall of the cartridge case is seen after firing a cartridge with certain 9 mm Luger and .40 S&W Beretta pistols. This mark, which in shape resembles the Nike Sportswear logo, is formed by the ejection port of the slide. Due to rather uncontrolled engagement between the ejected cartridge case and the ejection port this mark shows quite some intra-variability [20].

The marks resulting from the barrel extension lugs of the M-16 assault rifle are formed on the neck of the cartridge case during the extraction and ejection cycle. The ejector forces the cartridge case towards two lugs as the extractor draws the cartridge case out of the chamber. The authors mention that the appearance and quality of this mark can be used to indicate whether the firearm was fired semi- or full-automatically [21].

Features in bunter marks can be used to relate seized cartridge cases to live cartridges. The author discusses that the resulting evidential strength is influenced by the comparison results, but also by the age of the ammunition, by how common the ammunition is and by the explanation offered by the suspect about the acquisition of the ammunition. Imaging and comparison techniques such as applied by devices such as Evofinder can facilitate the comparison of the features in these bunter marks [22].

2.4. Class characteristics

Class characteristics can be used to provide insight in the used make or model of firearm. Warren and Pitts (2017) provide an elaborate overview of the comparable class characteristics seen in firearm models manufactured by Glock, Smith & Wesson (Sigma) and Springfield (XD) and how to distinguish between them [23]. They conclude with a useful decision flowchart to facilitate the examiner to benefit from the differences in class characteristics between manufacturers and model generations. They also provide a reference that Glock has stated that the new teardrop-shaped firing pin aperture will be the standard design for future models.

Another study uses Naïve Bayes and Random Forest classification methods to distinguish between ejector marks from Glock and Smith & Wesson Sigma pistols. The differences in the shapes of the ejector marks provide information to differentiate between the two manufacturers. The inter-variability of the ejector mark shape

between manufacturers is larger than the within-variability. Although the ejector mark location of the Glock Gen4 has changed, the marks still have a similar shape [24].

The features in test shots of ten pistols from various manufacturers were acquired with BALISTIKA 2010. They authors show that differences in comparison scores can be used to group cartridge cases based on manufacturer and model. The firing pin impressions seem to provide the best differentiation [25].

The differences in appearance of the extractor marks between M-16 and IWI Tavor assault rifles is discussed. The edges of the 'banana shaped' marks resulting from the M-16 are curved while those from the Tavor are almost straight. This difference can be used to distinguish between the two manufacturers [26].

The General Rifling Characteristic (GRC) can also be used to indicate which make(s) or model(s) of firearm(s) can have been used to fire the seized bullet. A study was set up to determine which variance would be most appropriate to take into account when searching a GRC database for possible used firearms. The authors conclude that a good balance between the length of the possible firearms list and the potential misses is found when a variance of ± 0.003" (approximately 0.1 mm) or 0.015" (approximately 0.4 mm) is used for pristine and damaged bullets, respectively [27].

2.5. Subclass characteristics

The AFTE Glossary defines subclass characteristics as discernible surface features of an object which are more restrictive than class characteristics in that they are: (1) produced incidental to manufacture, (2) are significant in that they relate to a smaller group source (a subset of the class to which they belong), and (3) can arise from a source which changes over time [28]. Nichols (2018) provides a well-structured article about subclass characteristics. The first part of the article defines subclass characteristics, the second part adds information about manufacturing/machining fundamentals, in which the main machining fundamentals are explained and their potential for subclass characteristics. In the third part the evaluation of working surfaces and marks is discussed to help recognize subclass characteristics [29].

A study focusing on nineteen .22 Long Rifle Smith & Wesson M&P 15—22 rifles showed the presence of subclass characteristics in the firing pins. The authors conclude that firearm examiners should be cautious when features appear to be continuous and parallel, showing virtually no variation along their length [30].

Another study showed the presence of subclass characteristics resulting from the molded insert in the breech of .32 Auto Tactical Hulk PT-12/PT-12 Pro [31].

Casts and test fired bullets from thirty-five Glock Marking Barrels (replacing the Glock EBIS barrel) were evaluated. The presence of subclass characteristics was determined in the "rails" of the barrels. These rails run along the "shoulders" of the lands. Although it is mentioned that the rails did not create striation patterns in any of the test shots of this study, the authors advice caution when examining the corresponding area in the bullets. The striations in the land engraved areas are said to result from the normal cross-hatched striations from honing of the barrel [32].

Five consecutively manufactured rifled barrels from 9 mm Luger Hi-Point pistols were examined for the presence of subclass characteristics. No significant subclass characteristics resulting from the button rifling process were observed. The author discusses that this is the result from the creation of individual characteristics on the barrel's surface due to cold drawing and manual deburring [33].

2.6. Proficiency testing

In the traditional forensic disciplines, where a human is usually the main instrument for analysis and interpretation, a well-established scientific foundation should be established [34]. This should ensure that sound research, instead of experience, training and longstanding use will become the central method by which judgments are justified. To add to this research culture, Stoel, Kerkhoff, Mattijssen & Berger (2016) announce their blind testing program and the intention to publish the results, regardless of how these will turn out. The authors propose that others should also do this to ensure unbiased publication of the results of proficiency tests and thus removing the potential bias towards 'good results' [35]. In 2018, the results of the announced study were published. A total of 53 conclusions were drawn based on the comparison of cartridge cases mainly fired by 9 mm Luger Glock pistols. For 31 of these conclusions, the ground truth was 'same source' and for the remaining 22 'different source'. The comparisons were performed under casework circumstances as the cartridge cases were submitted as 'real' cases in the normal case flow. No misleading evidence was reported, resulting in a 95% confidence interval for the error rate of 0−6.8% [36].

In a study, involving 126 firearm examiners who each performed twenty cartridge case comparisons, it was found that the overall error rate was 0%, with a sensitivity (# of correctly reported identification/# of true identifications possible) of 99.7% and a specificity (# of correctly reported exclusions/# of true exclusions possible) of 79.9% [37]. Additional analysis added the 95% confidence intervals and estimated a false identification probability between 0 and 0.003 and a false exclusion probability between 0 and 0.002 [38].

Another study, involving 31 firearm examiners, studied the validity of their source judgments. The results demonstrated an overall error rate of 0.303%, a sensitivity of 85.2% and a specificity of 86.8%. Some variability between examiners and between cartridge case and bullet comparisons was observed. The sensitivity and specificity of cartridge case comparisons were higher than for bullet comparisons [39].

2.7. Development of computer-based methods

Forensic firearm examination is traditionally based on examiners' judgments. Although these examiners are highly trained and experienced, there is a call for more objective methods. Different approaches to perform the comparison of features in cartridge cases and bullets following a more objective method have been proposed in recent years. To do this, surface topographies are acquired in 2D or 3D and these measurements are compared using computer-based comparison algorithms. The resulting comparison scores are then used to provide a strength of the evidence such as a likelihood ratio, a categorical conclusion or an estimated error rate when applying the method.

When implementing 3D surface topography in practical firearm examination several requirements will have to be met. Stocker, Thompson, Soons, Renegar and Zheng (2018) discuss these requirements with a focus on e.g., the necessary instrument specifications, instrument performance and evaluation, traceability requirements, the use of reference standards and necessary assurance procedures. They mention that the specific requirements will depend on the intended use of the instruments and data, which could focus on e.g., database searches, virtual comparison microscopy and computer-based comparison/verification [40].

For the comparison of impressions, such as breechface and firing pin impressions, the National Institute of Standards and Technology (NIST) has developed the Congruent Matching Cells (CMC) method in 2012 [41]. The total surface area is split up into cells which can then be compared to the cells of another surface. The reason for dividing the surface into multiple cells instead of comparing the complete surfaces at once is to differentiate between valid and invalid correlation regions. The valid correlation regions are thought of to consist of features which can effectively be used for comparison purposes, while the invalid correlation regions result from minimal interaction with firearm components and therefore do not contain useful features. When complete surfaces are compared the invalid correlation regions potentially reduce the similarity and accuracy of registration [42]. Several cells are considered to be congruently matching cells when they show 1) a high surface topography similarity (quantified by the area cross correlation function maximum ($ACCF_{max}$), 2) similar registration angles for all correlated cells, and 3) a 'congruent' x-y spatial distribution pattern for the correlated cells [43,44]. Chen, Song, Chu, Soons and Zhao (2017) propose an accuracy improvement of the CMC method by considering a feature named 'convergence'. This convergence is explained by the tendency of the x-y registration positions of the correlated cell pairs to converge at the correct registration angle when comparing same-source samples at different relative orientations. This additional criterion in the CMC method is shown to improve results by reducing the number of false positive and false negative CMCs when applying the method to four datasets of test shots. This is the result of a better separation between same-source and different-source comparisons, which is most evident for the two test sets with striated impression [44].

The CMC method was also applied to two Collaborative Testing Services (CTS) tests for both breechface and firing pin impressions. The resulting similarity maps from a comparison are shown to help relate the features used by examiners to those used by the algorithm. The results are perceived to be good, and can be improved by combining the information from both breechface and firing impressions [45].

Because of the limited surface area and curvature of firing pin impressions, the Congruent Matching cross-section (CMX) method is proposed besides the existing CMC method. This methods uses cross sections of the firing pin impression which are converted to 2D linear profiles. After this, the congruency of pairwise profile patterns is determined. The proposed method is tested with a dataset of 40 cartridge cases fired by 10 firearms. The cartridge cases were of three different brands and the firearms were produced by three different manufacturers. The results show a clear separation between same-source and different-source comparisons and it is suggested that the performance can be improved by combining this method with the CMC method which should then by applied to the bottom of the firing pin impressions [46].

Murdock et al. (2017) discuss the requests for additional information about the validity of firearm examination [e.g., 1, 2] and focus on the random match probability for firearm examination. In their article they provide a literature review regarding random match probability models and statistical applications that have been performed in firearm and toolmark examination [47].

Song et al. (2018) applied the CMC method to two datasets of cartridge cases to provide an error rate. They observed good separation between same-source and different-source comparisons, resulting in low cumulative false positive and false negative error rates. Because of variability in manufacturing of firearms and the firing process they expect that the error rate in actual casework will not be as low as for DNA comparison [48].

The selection of marks from which the features will be considered by the algorithms is usually done by an examiner. This introduces a subjective aspect in an otherwise fairly objective method. To try to minimize this human involvement, an automated selection of marks is proposed. The authors demonstrate an

improvement in accuracy when applying the method to 2D optical images. They also propose an empirical calculation of the random match probability based on data resulting from known sources [49].

Apart from the methods which take into account similarity scores of compared impressions, two publications focus on a feature-based method. One of these methods is a scale invariant feature transform (SIFT) and RANDom SAmple Consensus (RANSAC) integration algorithm. The SIFT algorithm extracts the local extrema which serve as local key points of impressions representing their invariant features, and to build the feature descriptor for each point based on its neighboring local gradients. RANSAC is applied to improve the matching performance. A validation test is performed which shows good separation with respect to the number of matching features between same-source and different-source comparisons [50]. Another method focuses on the extraction of arbitrary shapes from firing pin impressions. The results of the comparison algorithm, using these extracted features, do not depend on image orientation and could for instance be applied as a preliminary, but fast search in a larger database. This step could be followed by additional correlation methods. The methods shows a lower accuracy for extracted circular shapes [51].

Several studies have focused on the parameters which could influence the outcomes of more objective computer-based methods. One of these considered subclass characteristics from a probabilistic perspective. The authors show that the influence of subclass characteristics on calculated likelihood ratios is limited. To see a significant change in calculated likelihood ratios, the proportion of firearms sharing subclass characteristics in the relevant population should be larger than 40% [52].

Law, Morris, and Jelsema have published two studies investigating the number of test shots which will be needed to represent the variability of features between shots. The first study focused on 9 mm Luger firearms and shows that 15 test fired cartridge cases should be sufficient to represent the score distribution, but that 30 test fired cartridges would be a more conservative number [53]. In a follow-up study they applied the same methodology with .40 S&W, .45 ACP, .38 Special, and .357 Magnum cartridge cases. Overall, they again conclude that 15 test fired cartridge cases are sufficient for above an 80% probability of representing the full score distribution, but that 25, instead of 30 will be sufficient to reach full equivalence [54].

Although the cited publications above focus on the computer-based comparison of impressions in cartridge cases, similar methods can also be applied to striations in bullets. One such a study focused on the comparison of striation patterns in pellets fired by an air pistol. The author reports that in most comparisons limited to reasonable success was achieved. Although the identification of land engraved areas was still performed by a human, the comparison was performed objectively [55].

Bigdeli, Danandeh, and Moghaddam (2017) propose an alternative approach for bullet striation pre-processing and comparison. They do not use linear time invariant filters, such as Gaussian bandpass filters, but Ensemble Empirical Mode Decomposition (EEMD) to smooth the profile and to select a particular range of modes with fast and strong oscillations that correspond to striation information. This method is likely to be faster than others and can be used as a pre-processing step before of any system that uses cross correlation as a comparison metric [56].

2.8. Ballistic imaging database

Ballistic imaging databases are often used to find 'hits' in the open case file between seized evidence and between test shots and seized evidence. Several studies have looked into the performance of such systems.

Wang, Beggs-Cassin & Wein (2017) have some suggestions to optimize the ballistic imagine operation for laboratories that are dealing with large numbers of cartridge cases, but have limited resources. The number of hits seems to increase by prioritizing evidence over test shots, and by grouping cartridge cases by their caliber and allocating most of the capacity to the higher ranking calibers [57,58].

The overall performance of the IBIS system was evaluated using the standard cartridge cases from the Standard Reference Material (SRM) 2460/2461 set created by the National Institute of Standards and Technology. The authors conclude that the system provides excellent discrimination between same-source and different-source comparison scores for the breechface impression and small overlap for the firing pin impressions [59].

The factors that influence the effectiveness of ballistic imaging databases were studied using Evofinder. Overall the effectiveness for bullets seems to be higher than for cartridge cases. When only looking at the cartridge cases, the effectiveness based on the breechface impressions was lower than that for the firing pin impressions. Furthermore the effectiveness decreased when different types of ammunition were compared, when the size of the database was increased and when students without firearm examination experience performed the required actions [60].

Performance tests of IBIS Heritage and IBIS Trax-HD3D with cartridge cases from twelve pistols from various manufacturers show that the performance was better for firing pin impressions than for breechface impressions. For most firearms the performance on breechface impressions was better for the IBIS Trax-HD3D system especially when using side-light. For firing pin impressions the performance of the IBIS Heritage seemed to be better [61].

Another study using IBIS BrassTRAX v3.0 again shows that the performance was better for firing pin impressions than for breechface impressions. Side-light resulted in better performance than ring light and the combined 'rank score' resulted in the best performance. The authors also discuss possible casework strategies [62].

The added value of open case file hits between cases is studied by King et al. (2017). They interviewed detectives of 65 gun-related violent crime investigations in nine police agencies in the US. Based on these interviews they discuss that a hit report rarely contributed to suspects being identified, arrested, charged or sentenced. This minimal added value is coupled to the delay between the incident and the reported hit, which was on average 181.4 days. Additionally the hit reports rarely contained detailed information that was immediately useful to the detectives. The added value of open case file hits might be increased by quick processing and detailed reporting [63].

3. Firearms and ammunition miscellaneous reports

3.1. Firearms and ammunition

3.1.1. History

Haag (2016) describes the exterior and terminal ballistics of the model 1780 Girardoni air rifle such as used by Meriwether Lewis during the "Voyage of Discovery" from 1803-1806. The article shows penetration result in several media and the sound discharge. Both of these are discussed in the context of approximately 200 years ago [64].

Fifty-year old ammunition was recovered in Agarta, Tripura, India. The soiled and oxidized ammunition was examined and the authors conclude that the chemical composition of the ammunition remained unchanged, but that the ammunition became ineffective due to absorption of moisture by the primer [65].

3.1.2. Serial number restoration

Because of an increase in the use of titanium in modern fire-arms, several reagents were tested for their potential to restore serial numbers. One of these reagents, concentrated hydrochloric acid, seemed promising, especially while applied on heated titanium [66].

3.1.3. Firearm related sounds

Nineteen categories of investigations and research related to sounds occurring during operation, discharge and post-discharge of firearms are described with exemplary data. These categories, which included e.g., 1) the detection and recognition of gunshot sounds amid ambient noise, 2) the determination of the sequence of shots, and 3) discrimination between semi- and full-automatic shooting, are recognized as potential evidence for shooting incident investigations [67,68].

3.2. Ammunition

3.2.1. Manufacturing marks

The striation patterns visible in the extractor groove of Winchester .40 S&W and .45 Auto cartridges are discussed. These striations are the result from the hold-down plate used to extract the cartridge case from the die during manufacturing. Due to their similarity in appearance and position they could be mistaken for extractor marks [69].

Manufacturing marks were also found in the primer and cartridge head of Fiocchi 7.62 mm Nagant ammunition [70].

Marks which can be used to recognize reloading are discussed by McCombs & Hammen (2016). They show examples such as misaligned die marks from bullet seating, resizing die marks, crescent shaped impressions in the primer, and the availability of multiple extractor, ejector and ejection port marks [71].

3.2.2. Manufacturer identification

Warren (2018) provides information about the manufacturers of polymer-coated bullets such as the earlier discussed Nyclad and Syntech 'Lipstick' bullet and suggests the use of FT-IR spectrometry to help differentiate between manufacturers [72].

3.3. Replicas and casts

BALISTIKA 2010 was used to compared the features in the original cartridge cases with those in replicas of the same cartridge cases. Based on the ranking by BALISTIKA 2010, the features in replicas are very similar to those in the originals. Because of these similarities, the casts can be used for comparisons with the open case file [73].

3.4. Statistics

Information about the demographic and epidemiologic differences between fatal firearm injuries in Shelby and Davidson County between in 2009 and 2012 were compared (total N = 1081). Information about the age-adjusted gunshot mortality rates, homicide rates and suicide rates are given depending on race. Overall, homicide was found to be the most common manner of death for gunshot related deaths, and handguns were most often used [74].

A study focused on the relation between past trauma, gun access and storage, and suicide rates. Based on qualitative interviews the authors discuss that the prevention of community violence and addressing its ramifications may help reduce suicide rates [75].

The characteristics of 228 gunshot wound suicide autopsies in Southeastern Minnesota are discussed. Some of the results are that 97% of these suicides were men, the majority involved shots to the head (70.9%), and that most (66.7%) took place at home [76].

The relation between unintentional non-hunting firearm deaths and changes in firearm regulation in Sweden is discussed. The 43 fatalities from 1983-2012 represent 46% of all unintentional firearm deaths. Human error was determined to be the main cause of these incidents. Most involved legally owned firearms. A significant decrease in death rate was observed during the last decades. The authors discuss that this can at least party be explained by changes in the Swedish firearm legislation, introducing the mandatory hunter's examination to ensure safer firearm handling, and limiting access to firearms by strict regulation of storage [77].

Khosnood (2017) discusses the firearm-related violence in Sweden in recent years. He mentions that this type of violence is increasing, especially in the most southern region Skane, where Malmo is located. He calls for more police personnel, additional training and education on gang criminality and more serious punishments [78].

Tsiatis (2016) provides detailed information about firearm crimes in Greece from 1995 to 2014, where ballistic evidence was submitted, and where firearms were used against human life. Main results are that in 66.6% of these crimes a person was actually hit. Seventy percent involved handguns, with the caliber 9 mm Luger being the most prevalent [79].

The online trafficking of weapons was studied by an assessment of the listed weapons on nine dark web cryptomarkets. Two of these cryptomarkets are responsible for most of this trafficking, but the proportion of weapon trafficking seems small when compared to illicit drug trafficking. From the total of 386 weapon listings approximately 25% were firearms. The authors discuss that firearm trading through social medias on the internet seems to be more important than trafficking on cryptomarkets [80].

3.5. Bias, reporting and quality assurance

According to the NRC [2] and PCAST reports [1] the forensic firearm examination discipline should focus on additional validation studies of examiner judgments which are vulnerable to human error, show inconsistency across examiners, and can be influenced by cognitive bias. The AFTE Board of Directors have written a response to the PCAST report discussing that determining the validity as applied by 'black box' studies only is a too unilateral approach. At the same time they welcome additional research to build upon the foundations of the discipline [81]. The Scientific Working Group for Firearms and Toolmarks (SWGGUN) provides a review of the development of the firearm examination discipline, concluding that they think that the discipline is founded on a sound scientific method that is applied in a logical way, concluding that the discipline is scientific and reliable. Although they state that sufficient validation studies have been conducted to affirm the theory of firearm identification they recognize the need for continuous testing, scrutiny of employed methods and procedures and the continual awareness of emerging technologies that could further improve the discipline [82].

A couple of studies focusing on the validity as applied have already been discussed in Sections 2.1 Validation studies and statistical foundations and 2.6 Proficiency testing. Other mentioned suggestions for research and improvement with a focus on the human factor are the implementation of context information management to minimize the risks of cognitive bias influencing forensic judgments [1,2,34,83—88] and the shift in focus from trying to prove the claim of uniqueness of features to establishing their evidential strength and to report judgments in probabilistic terms [1]. With a specific focus on firearm examination, Bolton-King (2017) provides an interesting review of the scientific principles and practices. She focuses on the human influence on the

validity of judgments and the importance of proper training and procedures to minimize the likelihood of injustice involving firearm evidence [89]. Through a letter to the editor an incorrect connection between comparison results and a crime laboratory is fixed [90].

3.5.1. Influence of the human factor on forensic judgments

A context information management procedure has been implemented in firearm examination. This procedure was designed to minimize contextual bias during forensic firearm examination as a result of case information [91]. The design and implementation of the procedure are described, guided by a taxonomy of different sources of context information [92]. After showing that removing all context information, except for the information that is necessary for the examiner to do their work, seems to work best, the authors conclude with a flow-chart of their implemented procedure. The implementation of such a procedure seems feasible in practice and provides the examiner with a response, which is founded on a procedure, to questions about potential bias during the examination.

3.5.2. Reporting

In accordance with the PCAST's suggestion to report judgments in probabilistic terms [1] two publications provide examples of how this could be/is done in practice. Dutton (2017) discusses that reporting in a probabilistic and logically correct format provides the possibility to provide additional information for current 'inconclusive' judgments [93]. At the same time he discusses some difficulties with reporting the evidential strength of a comparison as a likelihood ratio, such as the unintuitive conclusions, the lack of concrete data to underpin judged likelihood ratios and the interpersonal differences in the perception of used verbal conclusion scales. Kerkhoff et al. (2017) discuss these practical issues and the pros and cons of reporting results using a probabilistic approach. They provide a balanced discussion about the comparison of this probabilistic approach with categorical source judgments, concluding that the introduction of the likelihood ratio approach is a serious asset for the firearm examination discipline, shaping the evaluation process and acknowledging limits of knowledge that exist within the discipline [94].

3.5.3. Quality documents

Suggestions about which uncertainties should be and do not have to be assessed or reported during firearm examination casework are given by Knapp et al. (2018). Reporting the uncertainty in measurements of e.g., bullet mass, diameter and GRC are not deemed necessary, while this would be appropriate for trigger pull measurements and shooting distance determinations. They provide examples of how these uncertainties can be reported [95]. The AFTE Board of Directors shows their appreciation of the authors' effort to share the information but state that is not an official AFTE document [96].

MacPherson and Haag (2018) describe a project to test and analyze chronograph performance. They focus on the issues related to and a practical approach for the calibration of chronograph units [97].

SWGGUN has published two guidelines to provide a framework of standards:

- SWGGUN Guidelines: Criteria for Identification [98].
- SWGGUN Guidelines: Barrel and Overall Length Measurements of Firearms [99].

4. Technical examination

4.1. Modified or homemade firearms

Examination of a submitted firearm showed that after some adjustments it was possible to create a functioning pistol by combining the frame from a KWA/Tanfoglio Witness 1991 CO2 BB pistol with a .22 Long Rifle conversion kit from German Sport Guns/American Tactical marketed for standard 1911-type frames [100].

A Chinese manufactured 7.62 × 39mm model 56−1, a Kalashnikov type assault rifle, was examined. The firearm was converted to caliber 5.56 × 45mm using parts from an Israeli Galil along with some minor machining of the internal dimensions [101].

An examined Jennings model J-22 pistols was found to operate with a penny and electrical tape substituting the missing grip plate [102].

A modified British Enfield, Pattern 1914 rifle was submitted to test for operability. The chamber was drilled, creating a drill purpose rifle used for training exercises and ceremonies. The firearm received dummy and primed empty cartridges as well as unaltered cartridges. Firing these live cartridge cases resulted in small discs, from the cartridge wall, being separated and pushed out of the drilled holes of the chamber. The bullets of each of the test fired cartridges were lodged in the barrel [103].

Several examples of examined homemade firearms have been published. In Turkey an increase in numbers of homemade long-barreled rifles is seen. After examination of a few of such rifles they were deemed unfit for efficient use and might result in harm to the shooter when fired [104]. Another publication discusses the examination of four rudimentary homemade firearms seized from an individual convicted of a felony [105]. Dutton (2017) discusses the use of a homemade firearm with unconventional ammunition in a suicide case [106]. That some homemade firearms can be of fairly high quality is shown by Sofer, Bar-Adon & Giverts (2016). They discuss the construction and forensics aspects of a homemade pump-action shotgun resembling a Remington 870 [107].

4.2. Firearms and their background

The applied processes when manufacturing barrels will affect the marks found in the barrel's interior surface and consequently the features on fired bullets. Bolton-King (2017) provides a comprehensive overview of the applied manufacturing processes and contact details for a wide range of 9 mm Luger pistol manufacturers and some aftermarket barrels [108].

Phetteplace (2018) examined two .22 caliber lever action Henry Repeating Arms rifles, produced in 2002 and 2006. Although outwardly the rifles appeared identical (except for the serial number) the rifling was different (6 right and 12 right). Contact with the technical services at Henry Repeating Arms suggested that this difference might be the result of some unrecorded running changes or that the 12-groove barrels have been experiments or trial-runs as the rifles are supposed to be fitted with 6 right barrels [109].

A .32 Auto Tactical-Hulk PT12-Pro was received for examination. The authors provide the specifications of the firearm. Although no references about a possible manufacturer were found they describe similarities in appearance and operation to the Turkish Zoraki M-906 or M-2906 starter pistol [110].

The features of an examined 9 mm Luger Walther model CCP pistol, such as the disassembly, polygonal rifling, the gas recoil/piston, and the locations and printing of the serial number(s), are described [111].

The design and capabilities of pre-charged pneumatic (PCP) air guns and the corresponding projectiles, such as lead pellets, lead

spheres and lead bullets are discussed including their velocities and terminal ballistics [112].

The use of cross-sectional imaging, such as computed tomography is discusses as a possible way to get a clear visualization of the different components of a firearm. These visualizations could provide insight in the mechanisms of action without taking apart the firearm [113].

Pellet seating in the barrel is shown to affect the external ballistics of fired air gun pellets. Seating pellets slightly deeper in the breech of spring-piston air guns (2 mm) resulted in a mean increase of kinetic energy of 31% (range 9−96%). For reliable and reproducible measurements of pellet velocity and kinetic energy this variable should be considered [114].

5. Shooting incident reconstruction

5.1. Research

5.1.1. Bullet behavior and bullet trajectory reconstruction

Several methods can be applied when reconstructing bullet trajectories based on bullet defects found at a shooting incident. Mattijssen & Kerkhoff (2016) provide a review of these methods and provide information about the accuracy and precision of estimated bullet trajectories by six firearm examiners. They studied the probing, ellipse and lead-in (or rocker point) method when applied to bullet defects resulting from 9 mm Luger FMJ bullets on drywall, MDF and sheet metal at various angles of incidence. They conclude that overall the best results are seen when applying the probing method and that only for the lower angles of incidence the application of the ellipse or lead-in method will provide more accurate results [115]. The accuracy and precision of the bullet trajectory estimates vary for each combination of applied method, target material and angle of incidence, resulting in different systematic errors and 95%-confidence intervals.

A study utilizing 3D laser scanning technologies studied the accuracy and precision of this technique for bullet trajectory documentation. Low error ranges (up to approximately 2.0° were observed. The precision, calculated by the inter- and intra-observer errors for probe placement and trajectory marking, showed that the range of variation was between 0.1° and 1.0° in drywall and between 0.05° and 0.5° in plywood. The authors discuss that the use of these 3D technologies seems to aid in the reduction of errors associated with the documentation of fitted trajectory probes [116].

One of the factors influencing the accuracy and precision of bullet trajectory reconstructions is the bullet's behavior upon impact. The bullet's behavior is influenced by its own properties upon impact, the properties of the target material and by the true angle of incidence. Several publications discussed the behavior of bullets on target materials such as glass, wood and laminated particle boards.

Based on numerical simulations and test shots with .38 Special LRN bullets it is demonstrated that angles of incidence (angle between the bullet's path and the substrate) of <30° resulted in ricochets and angles of incidence >45° resulted in perforation of car windshields [117].

A study focusing on bullet behavior on 5 mm plain float glass showed that the estimated critical angles of ricochet were 21.0° for .32 Auto FMJ bullets, 15.8° for 9 mm Luger FMJ bullets, 17.6° for .45 Auto FMJ bullets and 21.3° for 9 mm Luger Action NP bullets. The critical angle of ricochet is defined as the angle of incidence at which 50% of the fired bullets of a given ammunition type ricochet from a given object type. The mean ricochet angles per angle of incidence and bullet type were always lower than the corresponding angle of incidence, but were higher for bullets with damaged jackets than with undamaged jackets [118].

Haag (2016) studied the possibility to determine the direction of travel of perforating or non-perforating bullets based on the concentric cracks of bullet defects in windshields following shallow angles of incidence. When the center of these cracks is located on one side of the elongated bullet defect this seems to correspond with the entrance side of the defect [119].

The influence on wood grain on the ricochet and deflection angles of .32 Auto bullets is studied. The results of that study show that the mean ricochet angle per angle of incidence and type of wood usually exceeds the corresponding angle of incidence and increases when the angle of incidence increases. The angle between the wood grain and the plane of impact at which the highest deflection angle is observed varies between 30° and 75°, depending on the type of wood [120]. The results of this study are summarized and combined with those of an earlier study focusing on the critical angle of ricochet on wood [122]. The critical angle of ricochet increases with increasing hardness and density of the wood. The highest deflection angles were observed for shots near those critical angles of ricochet [121].

Bullet behavior of eight bullet types (.22 LR, LRN; .32 Auto, FMJ-RN; .380 Auto, FMJ,RN; 9 mm Luger, FMJ-RN; .38 Special, LRN; .38 Special, SJHP; .38 Special, FMJ-FP and .45 Auto, FMJ-RN) on laminated particle board was studies. The critical angle of ricochet was estimated between approximately 14° and 26° for all eight cartridge types, but between approximately 14° and 18° for the subset of jacketed bullets. The result show that vertical and horizontal deflection of perforating bullets can almost be neglected above an angle of incidence of 30° or 40° [123].

A study focusing on pistol bullet deflection when perforating soft tissue simulants shows that the degree of deflection is related to the length of the 'wound channel'. Virtually no deflection was observed for wound channels of 5 or 10 cm. For longer wound channels the mean absolute deflection and variability increased with wound channel length. Furthermore, bullet behavior varied between calibers and the results suggest that the angle of incidence also affects bullet deflection [124].

A similar study demonstrates that the magnitude of bullet deflection of rifle bullets (5.56 NATO and 7.62 × 39mm) also increases with 'wound channel' length in soft tissue simulants. This can be explained by bullet instability and to an even larger extent by bullet fragmentation during bullet travel through the simulant (5.56 NATO bullets) [125].

5.1.2. Shot and ejection patterns

Risk assessment can be in important aspect of the legal procedures following a shooting incident. A study focusing on the accuracy and precision of experienced and inexperienced shooters shows that there was a significant decrease in precision of the shot patterns while shooting in motion when compared to shooting stationary. Overall the precision of experienced shooters was found to be better than that of the inexperienced shooters. No significant change in accuracy was seen between shooting while in motion or stationary [126].

Tests with a shotgun show that shooting through an intermediate target (a foam-filled guitar bag with a double textile layer) results in larger shot patterns. This is important to take into account when using the shot pattern to estimate the shooting distance [127].

The cartridge case ejection patterns of six models of Glock pistols were compared. This was done for three firing conditions: firing with a loaded magazine, firing with an empty magazine, and firing without a magazine. Significant differences in distances covered by ejected cartridge cases were observed for the different models and firing conditions. The authors discuss that in casework it is important that test shots are fired with the same pistol (type)

and under the correct firing condition when examining ejection patterns [128].

5.1.3. Shooting distance and projectile behavior

The maximum range of 12 gauge shotgun slugs fired with smooth bore and rifled barrels was tested. With an angle of elevation of approximately 28° a shooting distance of 1,000 yards (915 m) was observed. Using cartridges with reduced loads it was examined that the slugs still penetrated quite deep in ballistic gelatin/soap at that distance. The sound of these slugs passing overhead was described by the author as the buzzing sound of a large bee or dragonfly [129].

Test shots were fired with caliber 9 mm Luger, .40 S&W, .45 Auto and 7.62 × 39mm firearms at departure angles of 30°, 40°, 50°, 60°, 70° and 80°. Visual representations resulting from Doppler radar data of the bullets' behavior are shown. The empirically determined maximum ranges for all calibers fell short of the calculated ranges using Sierra Bullets' Infinity-5 [130].

Copper "crowns" might be observed after shooting 5.56 × 45mm or 7.62 × 39mm bullets through sheet metal. These crowns appear to be formed when the bullet's jacket strips off as a result of the shearing forces when perforating sheet metal. The crowns seem to be formed up to shooting distances of approximately 250 m and 150 m for caliber 5.56 × 45mm and 7.62 × 39mm bullets, respectively. The authors discuss that the height of the "crown leaves" is larger for higher velocity (shorter distance) than lower velocity (larger distance) shots. Based on these results the presence of such crowns and the height of the leaves can provide information about the shooting distance [131].

A study focusing on backspattered biological material found on or inside firearms demonstrated that the recovery of analyzable DNA and RNA resulting from blood or brain tissues was possible with shooting distances of up to 15 and 30 cm, respectively. This was tested with 9 mm Luger, .38 Special and .32 Auto handguns. For shooting distances between 0 and 15/30 cm no robust correlation was found between the DNA/RNA yield and shooting distance [132].

For the estimation of the range of fire of a specific bullet, exterior ballistic calculations are often used. For these calculations the ballistic coefficient has to be known. Various versions of Sierra Bullets' exterior ballistics programs contain this information for common commercial bullets which are available in the US. This information is not readily available for numerous variants of the Russian M43 bullet (7.62 × 39mm). To provide this information, the effective G1 and G7 ballistic coefficients have been determined using Doppler radar and Sierra Bullets' Infinity-7 exterior ballistics program [133].

5.2. Methods

Hertzian fractures, or cone fractures resulting from bullet perforation through glass are often encountered but are difficult to document by photography. Surface reflectance photography is suggested to be able to document the fractures, including the information about which side of the glass is the bevel-bearing surface. This method makes use of the reflective characteristics of glass by illuminating the glass at an oblique angle [134].

A technique using a piece of paper (up to 150 feet/approximately 46 m) or white, high-intensity reflective tape (up to 270 feet/ approximately 82 m) is explained to document laser trajectory beams during daylight. Combining long shutter times (enabling the CSI to walk the reflector card down the length of the trajectory beam) with a diaphragm setting of f/22 resulted in photographs of the trajectory beam without obvious ghosting of the reflective card or CSI [135].

5.3. Trace analysis

Due to difficulties when comparing features resulting from the barrel in coated bullets, the possible evidential strength of trace evidence resulting from these coatings is studied. Worden (2018) looked at the presence of trace material from fired bullets which were coated with Hi-Tek-Lube Supercoat. Some of the coating could still be found in the barrel of the firearm, but none was found on perforated target materials (wood, metal, and drywall) [136]. Berk & Horn (2017) shows that trace material from Nyclad bullets can also be found in the barrels that were used to fire them [137].

5.4. Case reports

A case report of an officer-involved-shooting discusses the use of bullet trajectory reconstruction based on gunshot wound trajectory analysis. This case relates the evidentiary findings to the statements from the involved officer and eye-witnesses [138].

Haag (2015) provided a step-by-step review and analysis of the assassination of President John F. Kennedy who was hit by two bullets. He discusses the exterior and terminal ballistics of the unaccounted for third bullet, a 6.5 mm WCC Carcano bullet. The author concluded that the missing shot was the first shot fired and must have hit the asphalt of Elm Street at a relatively steep angle of incidence and subsequently self-destructed [139]. Additionally, the so-called "Magic" bullet in the JFK assassination that passed through two individuals and remained intact is discussed. Taking into account the exterior, terminal and wound ballistics of the novel 6.5 mm WCC Carcano bullet, the author explains that there is nothing "magical" about the bullet [140]. These publications have triggered several letters to the editor [141–143] and subsequent responses from the author [144–146] during the last years.

During the reconstruction of a shooting incident, the entrance and exit wound characteristics were initially judged to be inconsistent with a large distance shot with a hunting rifle. Experimental shots show that the resulting wound defects are more extensive and consistent with the observed injuries, when the bullet first perforated an obstacle (cell phone) and deformed in the process [147].

6. Wound ballistics

6.1. Research

6.1.1. Soft tissue simulants

Ballistic gelatin is often used to study the lethality of projectiles under specified circumstances. An overarching review discusses the use of ballistic gelatin in wound ballistic studies in the fields of ammunition design, protective equipment design and medical and forensic investigation. The authors summarize that projectile type, body impact site and intermediate layers can affect the resulting wound profiles [148].

Ballistic gelatin blocks are often used in either 10% or 20% gelatin concentrations. Damage to such a block by 9 mm Luger bullets was compared between those two concentrations and with shots on porcine thoraxes. When comparing the shots on the two gelatin blocks with different concentrations of gelatin similar damage formation is observed, albeit on a smaller scale in 20% gelatin blocks. The penetration depth of .223 Remington expanding bullets was found to differ between porcine thoraxes and 20% gelatin blocks (shorter in the blocks), but not with 10% gelatin blocks [149].

The difference that gelatin blocks are homogenous and human bodies are heterogeneous in nature triggered a study on the applicability of ballistic gelatin to simulate organs in the thorax and abdomen. Based on the comparison of the energy loss of projectiles

in porcine organs and gelatin blocks (10%, 20%, and Clear Gel) the authors conclude that these might not be accurate simulants. Additional studies focusing on different concentrations of gelatin might prove beneficial in finding simulants for the various organs resulting in similar loss of energy [150].

In another study the synthesis of ballistic gelatin-polymer composites for human organs is discussed. These composites are said to overcome important issues when compared to 'standard' ballistics gelatin: they do not require special storage and have an increased duration between time of preparation and use. Additional tests have to be performed to assess their ballistic properties [151].

In these additional tests the authors compared the mechanical behavior of the simulants during stabbing and shooting with bovine and porcine organs. They found good similarity for the stabbing behavior. To test the shooting behavior they looked at the perforation/penetration of 10 × 28T rubber balls. The authors conclude that the proposed hybrid gelatin results in more reliable and reproducible values when compared to 'standard' ballistic gelatin [152].

In an effort to increase the duration of use of ballistic gelatin, a preservative (Methyl 4-hydroxybenzoate) was added during preparation to prevent microbial growth. The addition of the preservative did not significantly alter the penetration depth of projectiles. A significant effect on penetration depth was already noted after 4 weeks of storage, possibly related to dehydration of the exterior of the gelatin blocks [153].

For rather small blocks of ballistic gelatin (12 cm) it is important to take into account the characteristics of the surface on which the block is placed. This is especially important for shots with a greater energy transfer. For those shots the cracks were longer when the gelatin blocks were placed on a thick synthetic sponge than when placed on a firm table [154].

The influence on the bullet's trajectory of the distance from the top or bottom of the ballistic gelatin block and to bullet tracks from previously fired shots, was studied. No significant difference in 9 mm Luger bullet deflection was observed between bullets fired at a distance of 3.5 cm and at least 7 cm from the aforementioned aspects. Based on these results the authors conclude that it is possible to fire several shots in rather close proximity to one of those aspects (>3.5 cm) as long as non-expanding pistol or revolver bullets are used, similar in form to those used in this study and with an impact energy below 500 J [155].

Computed tomography was used to measure the volumes of temporary wound cavities in ballistic soap. These volumes represent the amount of transferred kinetic energy and can be used to assess traumatic results. Based on five shots there seems to be a proportionality of 4.2 ± 0.5 J/cc between transferred energy and cavity volume [156].

A follow-up study using computed tomography focused on the use of ballistic gelatin, which the authors discuss to be a more realistic muscle simulant due to the elasticity, which is not seen in ballistic soap. For the remaining (permanent) wound cavity a positive relation between impact velocity and cavity volume was observed. The authors discuss that due to the use of computed tomography it is possible to accurately calculate the density of the target material, store the measurements for future purposes, and to accurately visualize the total path length, deflection and final position of the bullet [157].

To use of photo-elasticity, a technique to visualize stress distribution in certain transparent materials, has been applied to ballistic gelatin to visualize the temporary stress distribution caused by penetrating pellets [158].

A common witness material to quantify the back face deformation resulting from high rate impact of ballistic protective equipment is ballistic clay (e.g., Roma Plastilina No. 1 (RP1)). The characteristics of a new silicone composite backing material (SCBM) are compared to RP1. The results show a similar response of SCBM at room temperature when compared to RP1 at 38°. The authors think that with additional optimization SCBM could be an easy-to-use replacement for RP1. The use of SCBM is expected to reduce test variability, simplify logistics (no heating) and enhance test range productivity [159].

6.1.2. Skull and bone (simulants)

The backspatter patterns as produced when shooting blood-soaked sponges differ from those resulting from a cranial gunshot to a human cadaver that was reinfused with fresh defibrinated bovine blood with respect to the number, size, size range and dispersion of bloodstains [160].

The impact of bone mineral density (BMD) on the estimation of bullet caliber based on bullet defects in cranial bones has been studied. A strong Pearson correlation was found between BMD and the minimum diameter of the bullet defect and between the minimum diameter of the bullet defect and the bullet's caliber. No correlation was found between BMD and bone thickness. The regression model to estimate bullet caliber is strengthened by the inclusion of BMD [161].

Mahoney et al. (2017) studied whether the optimization of an anatomically correct skull-brain model using simple simulants would result in realistic ballistic fracture patterns (resulting from 7.62 × 39mm bullets). They conclude that the patterns were assessed by at least one clinician out of five to be close to real injuries in over half of the models. Overall, the exit wounds were considered to be more realistic than the entrance wounds. Clear limitations of the models are the lack of a realistic skin layer and the fact that the skulls are manufactured from two separate parts [162].

In another study the damage, resulting from 7.62 × 39mm bullets, to skull simulants with a surrogate skin/soft tissue layer was assessed. The entry and exit wound characteristics as well as the fracture patterns were assessed to be realistic. Individual elements, such as bullet defect size, and skin and bone beveling, were not judged to be realistic [163].

Two bone simulants (Synbone and Sawbone) were tested for their suitability as simulants for human bones during ballistic tests. When compared to post-mortem human subjects it was found that the mean velocity at which fractures were produced following direct shots with armor piercing 5.56 mm bullets were higher for both the Synbone and Sawbone simulants. For indirect fractures the average distance did not differ between the post-mortem human subject and Synbone simulant, but was smaller for Sawbone. Fracture patterns were comparable for the Synbone simulant (albeit with slightly different input variables), but not for the Sawbone simulant. The authors conclude that no ideal bone simulant for ballistic tests has been identified [164].

Another study examined the bullet defects in Synbone spheres with a thickness of 5 mm caused by a limited number of shots with handgun ammunition. A positive association was observed between the radius of the entrance hole and the caliber. The authors mention that macroscopically Synbone is a proxy to cranial bone when considering the appearance of entrance defects, radial and concentric fractures, hydrologic shock and endocranial beveling. On the other hand, the exit defects seem to be larger in dimensions. Microscopically the behavior seems different due to differences in microstructure and flexibility [165].

The behavior of 7.62 × 39mm FMJ MSC bullets in ballistic gelatin was studied after perforation of bone (simulants) and intermediate materials such as skin simulants and helmets. A decrease in neck length (first slim part of wound cavity when the bullet is still stable) in ballistic gelatin was observed when additional material layers

were perforated, suggesting an influence on bullet gyroscopic stability. Greater variability in temporary cavities was observer for increasing complexities of intermediate layers [166].

6.1.3. Impact behavior and effect

Contact shots with 9 mm Blank cartridges fired with two blank firing pistols and one revolver on pig skin and ballistic gelatin showed that the powder gases penetrated the skin and the soft tissue simulant for 2.2 to 6.1 cm. Particles of the pig skin were found in the radial cracks of the gelatin [167].

In Germany, an increasing number of revolvers that fire 10 mm rubber balls actuated by 6 mm Flobert blank cartridges have been confiscated. Tests with these firearms showed that the kinetic energy of these projectiles was between 5.8 and 12.5 J. The energy density was close to or higher than the threshold energy density for the perforation of human skin. Although these projectiles have to capability to penetrate skin, the main injury potential for contact shots is attributed to the high energy density of the muzzle gas jet [168].

In contrast to what is often portrayed in movies and television series a bullet fired from a handgun does not have the potential to cause any significant body movement of a victim in the direction of the bullet's flight path. Gross movements as a reaction to being shot are mentioned by the author, but are not considered a direct effect of the bullet's kinetic energy transfer [169].

Computer simulations were run for shots fired with several handgun calibers (.40 S&W, .380 Auto and 9 mm Luger) at modeled mandibles from a shooting distance of 5 or 15 cm. All entrance defects presented oval aspects. Morphological differences in bullet defects caused by different caliber bullets and shooting distances were observed. The largest bullet defects and stress values were observed for .40 S&W ammunition at a shooting distance of 5 cm [170].

Contact shots with .22 Long Rifle, .32 Auto, .38 Special and 9 mm Luger bullets were fired on silicon coated, plastic boxes that contained ballistic gelatin. The boxes were fitted with thin pads containing a mixture of blood, radiocontrast agent and acrylic paint. Visualization, using endoscopy, high speed video and computed tomography, showed that the powder pocket rises in about 1.5 to 2.0 ms and that the powder pocket's collapse takes 2.5 to 3.0 ms. Although powder pocket volume decreases with increasing barrel length, no significant difference in powder pocket size was observed between .32 Auto and 9 mm Luger contact shots fired from barrels with the same length. No correlation between the amount and pattern of interior barrel staining and powder pocket volume was observed [171].

Another study, applying the same model, showed the occurrence of distinct staining of the barrel's interior following contact shots with caliber .32 Auto, 9 mm Luger and .38 Special ammunition, but not with .22 Long Rifle ammunition. Staining decreased from the muzzle to the chamber end of the barrel. In over half of the test shots the staining reached the chamber of the barrel. The authors mention that the staining is comparable to what is seen in real suicide cases [172].

The effect of intermediate saline breast implants on soft tissue penetration by .40 S&W hollow-point bullets was studied. Penetration in ballistic gelatin following perforation of the saline implant decreased by 20.6% when compared to direct shots (31.9 cm vs 40.2 cm). Bullets already mushroomed in the saline implant instead of in the ballistic gelatin [173].

Several characteristics of bullet defects in bone, such as beveling and keyhole lesions, are well documented in literature. A study by Amadasi et al. (2017) focuses on another characteristics: chipping or flaking. These are described as the formation of multiple detachments in the most superficial layers of the bone, which are most often observed in cranial shots. In 77% of 22 near-contact shots with 9 mm Luger bullets on bovine ribs, chipping was observed. In 5 shots at a shooting distance of 3 cm and at 40 cm no chipping was observed. The authors discuss that chipping may be indicative of close-range shots and could be a combined effect of the impact of the bullet and the expansion of gases [174].

6.2. Case reports

Ballistic analysis allowed a better understanding of the wound characteristics caused by a 7 × 64mm bullet. The authors discuss that the uncharacteristic features of the entrance wound can be caused by an impact with an intermediate target, deforming the bullet. The deviation of the bullet's internal path caused by the cervical column could have caused the bullet to exit tangential to the skin [175].

The likelihood of a fatal injury as a result of a direct long distance shot was compared to the likelihood of a fatal injury following a ricochet from water. Using Doppler radar, the author determined the impact velocity of a 9 mm Luger bullet after ricochet, velocity loss during ricochet, post-ricochet stability, and the effective ballistic coefficient. He concluded that only the bullet's calculated velocity of a direct shot would explain the observed gunshot wound [176].

The benefit of post-mortem computed tomography (PMCT) is increasingly recognized as it provides a means to re-examine a body. Because PMCT is not routinely performed in all countries, the potential of post-autopsy computed tomography is discussed. When combined with the outcomes of the first autopsy, this could be helpful for more complete examinations and to obtain information on bone injuries and the presence of trapped foreign bodies in the soft tissue [177].

In a case involving a cranial gunshot the body was first examined using computed tomography. The bullet was documented to be located in the right frontal area. During subsequent autopsy, the bullet was recovered at the left side of the head where it originally entered the cranium. The authors discuss that this migration might have been caused by gravity and head movement during hospital admission [178].

A case is described where the victim was hit in the eye with a paintball pellet. The injuries to the eye are discussed and the outcome that the patient was rated with 22% visual system impairment [179].

A home-made firearm, consisting of a spare barrel fixed on a pipe chair, was used in a suicide. A gas burner was used to heat the barrel from the side, causing the cartridge to discharge. The lead slug and wadding were left in the skull after perforation of the eye [180].

A home-made trap gun was examined after a suicide. The injuries resulting from an intermediate range discharge from this trap gun were determined to be the cause of death. The powder charge in the trap gun was probably ignited by a manually operated battery-powered ignition device [181].

A case is described where a modified firearm was used to fire a lead bullet. Autopsy showed that the bullet had fragmented upon impact on the skull of the victim. One part entered the cranium and the smaller part pushed its way alongside the cranial bone and beneath the scalp toward the other side of the cranium. Test shots on simulants showed that this pattern could be reproduced when shooting at an angle of incidence of 55°–60° with a velocity of approximately 200 m/s [182].

The details of two other suicide cases are reported where the used weapon was first position and then fired by the victim. One details a shotgun positioned in the steering wheel of a car [183] and another the use of a spear gun in combination with an extension to operate the trigger [184].

A small ring-shaped skin lesion was observed during examination of a body resulting from a suicide shot to the temple. Additional test were performed to investigate the likelihood of this lesion when this was caused by either an ejected and ricocheting cartridge case or by a cartridge case which was jammed in the ejection port of the firearm and came into contact with the skin when the body collapsed. The energy density of ricocheting cartridge cases was deemed to be insufficient to inflict this lesion. This resulted in the conclusion that the lesion was probably caused by a cartridge case which became stuck in the ejection port [185].

7. Training material and books

The book *Firearm and Toolmark Identification − The Scientific Reliability of the Forensic Science Discipline* [186] by Ron Nichols has been reviewed by Gerard Dutton [187]. He provides a short summary of each of the chapters detailed in the book that seem to focus on the two questions: 1) Do different tools produce different toolmarks and by extension, does the same tool produce similar toolmarks?, and 2) If so, can a trained examiner discern those differences and similarities, to enable them to provide reliable opinions as to whether those marks do, or do not, share a common source? Gerard Dutton provides a positive review of the content of the book and has some suggestions for a second edition.

The book *Reference Manual on Scientific Evidence* [188] has been reviewed by Rocky Stone [189]. He provides a critical review when referring to Section VIII *Firearms Identification Evidence*. According to his interpretation, the book is too critical about the discipline and he provides some quotes to illustrate this.

Disclaimer

This is a republication in journal form of a conference proceeding that was produced for the 19th Interpol Forensic Science Managers Symposium in 2019 and was originally published online at the Interpol website: https://www.interpol.int/content/download/14458/file/Interpol%20Review%20Papers%202019.pdf. The publication process of this was coordinated for the Symposium by the Interpol Organizing Committee and the proceeding was not individually commissioned or externally reviewed by the journal. The article provides a summation of published literature from the previous 3 years (2016−2019) in the field of forensic firearm examination and does not contain any original, experimental data. Any opinions expressed are those solely of the author and do not necessarily represent those of their agency, institution, government, Interpol, or the journal.

Declaration of Competing Interests

The author has no competing interests to declare.

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