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Interpol review of forensic firearm examination 2019–2022

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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 2019 until and including 2021. A literature search was conducted covering articles on this topic published in the main forensic journals:

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

1.2. Current topics

The forensic firearm examination literature of 2019, 2020 and 2021 covers a broad number of topics. These include topics such as firearm examination itself, but also technical examination, shooting incident reconstruction, and wound ballistics. Within these topics, specific effort has been spent on some areas of research. Recent work within the topic of firearm examination has focused on gaining more insight in the validity and reliability of firearm examiners' source judgments and how these can be affected by bias. Furthermore, considerable efforts have been spent on the development of computer-based methods for the comparison of striation and impression patterns. These combined efforts are in line with the recommendations of the President's Council of Advisors on Science and Technology (PCAST) report "Forensic Science in Criminal Courts: Ensuring Scientific Validity of Feature-Comparison Methods" [1] and the National Academy of Sciences (NAS) report "Strengthening Forensic Science in the USA: A Path Forward" [2].

Similarly, efforts within the topic of shooting scene reconstruction have focused on the validity and reliability of estimated bullet trajectories, as well as on the implementation of newer techniques to facilitate firearm examiners with these reconstructions. In addition to what can be examined at the crime scene itself, researchers have also focused on the application of forensic radiology to assess intra-corporeal bullet trajectories and on the use of soft tissue or skull and bone simulants in studies on bullet behavior.

The published articles related to these topics are addressed in the subsections "Validation studies and statistical foundations", "Proficiency testing", and "Development of computer-based methods" of the "Firearm examination" section; subsection "Bias, reporting and quality assurance" of the "Firearms and ammunition miscellaneous reports" section; subsections "Research" and "Methods" of the "Shooting incident reconstruction" section; and the "Research" subsection of the "Wound ballistics" section.

In addition to the current research topics which can be derived from recent literature, the ENFSI Firearms/GSR Working Group has published a white paper concerning their future perspectives [3]. They discuss the development of computer-based methods for the comparison of striation and impression patterns and highlight the need for the development of sizeable reference databases to be able to calculate the evidential value of a comparison, according to the Bayesian approach. The use of the. x3p file format as a standard for surface topography data will enable global exchange and interoperability of data. Furthermore, they address the potential of 3D crime scene reconstruction techniques for capturing and documenting crime scenes and later on presenting evaluations. These efforts can be combined with the application of forensic radiology (computerized tomography) to visualize intra-corporeal bullet trajectories. Additionally, they mention the need to manage contextual information to minimize the occurrence of bias in casework, the need to keep up to date with novel manufacturing techniques, and the emerging trend of 3D printed firearms.

2. Firearm examination

In accordance with the 2009 NAS [2] and 2016 PCAST [1] reports' recommendations several studies have been performed with the aim to strengthen both the foundational validity of firearm examination as well as to provide insight into the validity as applied.

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2.1. Validation studies and statistical foundations

Firearm examiners provide judgments about the source of fired bullets and cartridge cases. To do so, they examine the features – striations and impressions – in these ammunition parts that result from imperfections of the components of the firearm that was used to fire them with. Firearm examiners compare these features between for example several cartridge cases recovered at a crime scene or between those and test shots fired with a specific firearm. The observed degree of similarity in features as well as their characteristic values are used to provide a judgment about the source of the cartridge cases. Generally speaking, shots fired with one firearm are expected to show similar features (a high reproducibility and therefore low intra-variability), while shots fired with different firearms are expected to show different features (high inter-variability and characteristics value). As a result, an observed high degree of similarity will typically result in a high degree-of-support judgment for the same-source proposition. The evaluative process is facilitated if the imperfections of the firearm components are durable, ensuring a low intra-variability of features over a large number of shots.

To assess if features can be expected to differ if shots are fired with different firearms, several studies have been performed with consecutively manufactured firearm components to test if examiners can discriminate between them. These consecutively manufactured components provide the highest likelihood for similarity in features between firearms as a result of carry-over of imperfections during manufacturing.

An update from on ongoing study [4] utilizing bullets fired with ten consecutively manufactured 9 mm Luger Ruger P-85 rifled pistol barrels shows a low error rate with a posterior mean of 0.053% (95% probability interval [1.1×10^{-5}, 0.16]) [5]. This is based on all data acquired in over twenty years, where 697 participant have examined over 240 test sets.

Another study utilized thirty consecutively manufactured Beretta 9 mm Luger broach-cut barrels [6]. Following an "open set" design – where participants should have no expectation that all questioned samples should correspond with one of the reference sets – a total of 74 qualified examiners participated in this study consisting of 15 knowns and 20 unknowns, including known non-match comparisons. The resulting false-positive rate was 0.55 (95%-CI [0.2, 1,1]) and 0.08% (95%-CI [0.01, 0.4] for the corrected data (after correction of typographical errors).

Bullets fired with 18 Glock pistols with "Glock Marksman Barrels" – having small rifled profiles on either side of the polygonal fields – were compared [7]. These barrels are typically seen in Glock G42, G43 and Gen 5 pistols. Based on the comparisons, the authors conclude that the striations observed in the bullets fired with these barrels can be used to provide high degree-of-support judgments. While a durability test, firing 500 shots with one barrel, showed a decrease in the observed degree of similarity, the authors could still assign the 500th bullet to the first.

The reproducibility and persistence of the barrels of five Chinese Norinco QSZ-92 9 mm Luger pistols was studied over 3000 shots [8]. The striations in the bullets were compared with the Evofinder system which also contained 3000 bullets from 1000 other QSZ-92 9 mm Luger firearms. The results show that similarity decreases slightly over time, but not so much that bullets were not correctly ranked on top when combining LEA, GEA and slippage marks.

A study on ejection port marks from thirty cartridge cases fired with ten consecutively manufactured Glock 17 pistols showed that these can be acquired using IBIS BULLETTRAX [9]. The authors suggest that the addition of these features will enhance the correlation ranking of the system for cartridge cases. Furthermore, the marks do not seem to reproduce well, as variation in shape and location was observed.

2.2. Parameters that affect the identification process

The effect of a methanol-based dye stain – used to chemically develop latent prints – on cartridge case examination and firearm functionality was studied for twelve firearms [10]. All of the firearms functioned properly with no obvious metal reaction. All cartridge cases could be identified to their originating firearms.

Also, the effectiveness of extracting touch DNA from cartridge cases (i.e., "dunking") was studied, in particular the potential detrimental effects that this process may induce prior to microscopic examination [11]. This study involved many variables such as caliber, metallic composition of cartridge case and primer, type of extraction buffer used, time for which the cartridge cases are incubated, post dunking cleaning, and packaging. Severe effects were observed on samples which were submerged in an organic lysis buffer, a procedure most commonly used. As a result the comparison quality of items submitted for firearm examination degraded.

Another study to recover trace DNA from fired cartridge cases focused on "soaking" [12]. The results show that firing decreases the quantity of DNA recoverable from cartridge cases and that higher quantities of DNA are recoverable from nickel ammunition compared to brass. In an earlier study Prasad examined the effects of soaking for DNA recovery on striation patterns of fired cartridge cases. It was shown that the used ATL buffer has no detrimental effects on striation details [13].

The choice of the ammunition most suitable for preparing test bullets is discussed [14]. A choice solely based on the same brand and model as used on the crime scene is considered unsuitable in this study. The examined commercial .22LR ammunition shows very wide interbrand, interlot and intralot variability. The authors state that SEM-EDS is a useful tool for selecting suitable ammunition to prepare test bullets to be compared with the evidence.

Addinall et al. discuss the differences in the overall topography of firing pin impressions in different primer cup materials, and the effect it has on the successful correlation of ballistic toolmarks evidence [15]. Material composition of the primer cup has an effect on the areal topography of the firing pin impression, and therefore on the correlation results (Alias ballistic imaging systemTM). The authors state that care should be taken when correlating areal impressions with a dissimilar substrate material and that not all findings can solely be attributed to material composition.

The variability of firing pin impressions, which might increase the likelihood of a false negative or false positive judgments, was studied by evaluating the dimensions (diameter and depth) of firing pin impressions on primer cups of 7,62 × 39 mm caliber ammunition [16]. The results show that in single shot mode, the dimensions were quit stable for each of the four different ammunition types used and fired with three different rifles. In burst mode the depth and diameter of the impressions increase after each shot. The increase of the size of the impression could be correlated with the shooting sequence using linear equations.

The claims of David Tubb's Final FinishTM product, to polish or smooth the bore of a gun, including improved accuracy and higher muzzle velocity were tested [17]. The product consist of a series of jacketed bullets coated with boron nitride. The bullets were fired with a World War I vintage '03 Springfield rifle. The striation patterns in all land engraved areas were changed by using this product. It did not polish or smooth the surfaces of lands, rather they became somewhat rougher. No effect was observed on the metal constituting the grooves. Muzzle velocity did not increase as a result of using this product. Accuracy test were not carried out due to the open sights of the rifle.

Haag examined five consecutively button-rifled barrels from Hi-Point C9 pistols with a 3 left rifling. Due to the minimal engagement between common 9 mm bullets and the three lands in these pistols, associating fired bullets with the responsible pistol is often difficult and may be impossible in some cases. Examination of the five barrels revealed no evidence of any sub-class features. Test-fired bullets could be matched to the source barrel after the settling-in process of approximately 5 rounds. Only a small area of the driving edge of each land engraved the bullets. Determining the brand of ammunition associated with a shooting incident is important for a successful comparison with test fired bullets [18].

Five hundred solid copper bullets fired through three different 9 mm pistols are examined as well as their effect on the individual rifling characteristics of the barrel [19]. In general, marks on bullets disappeared and appeared over the course of the study. The authors state that the striations in bullets fired by one of the firearms, a Beretta, allowed identification up to the 245th bullet. After this point the marks were deemed insufficient for identification purposes. For the other two firearms (Glock and Taurus), the authors state that identification was no longer possible after a few dozen shots. It is noted that copper bullets are harder than lead cored bullets and quite abrasive to the bore's land surfaces.

2.3. Examination based on unusual markings

A Smith & Wesson pistol with an altered firing pin and breechface was examined after it was used in crime [20]. The author states that recently altered parts of a firearm can be recognized by the lack of soot and/or sealant and bright surfaces. Altered parts could be a reason for pitfalls (false negative judgments). Identification in the particular case was reached using the aperture shear marks and chamber marks.

The examination of an altered breechface of a Springfield Armory XD-45 is reported [21]. The firing pin aperture was much larger than normal. The author expresses his concerns that individuals become more educated with the techniques and areas that examiners are using during microscopic comparisons.

Chamber lip marks produced by Glock pistols are described [22]. As the cartridge moves across the intersection of the feed ramp and the chamber, toolmarks are produced either through manual or automatic cycling. Four Glock 19 pistols from different generations were used in the test. The chamber lip marks turned out to be reproducible, with a very low potential for subclass characteristics. The author found these marks to be identifiable to a specific Glock pistol.

The use of homemade or modified firearms leaves typical markings on bullets and cartridge cases and these marks can be used to classify the associated firearm as homemade. This is shown for typical marks created by homemade barrels on steel jacketed 9 × 18mm bullets [23]. These homemade pistol barrels are used in modified gas pistols and revolvers. The typical marks on cartridge cases when homemade or modified firearms are used are also discussed in the literature [24].

A case with a very typical mark from an unknown Spanish-made magazine is reported [25]. Marks produced by magazines are expected to be from the magazine lip area. In this case, a small protrusion on the follower – of which the purpose is unknown to the author of the paper – interacted with the cartridge during the cycling and firing process, leaving not only class characteristics, but also identifiable marks.

An examination of bolt rotation marks on cartridges cycled and fired in .223 caliber AR-15 type rifles was performed [26]. Seven firearms and three different brands of ammunition were used in this study. Bolt rotation marks were unable to be associated with only the fired cartridge case. These marks appear as a result of firing but also as a result of cycling.

Grabowski observed toolmarks on fired bullets which were distinctly different from traditional rifling marks on evidence bullets [27]. Examining the origin of these marks showed that they originated from the chamber of the cylinder.

Toolmarks from a drill bit were found in three explosively formed projectiles (EFSs), that were used in improvised explosive devices (IEDs) (S [28]. These uncommon toolmarks could be linked to each other and were identified as having originated from the same source tool. Later, an additional reference was added to the previous paper [29].

Bullets from the event were found long after the execution of the family of the Russian Emperor Nicholas II [30]. The bullets remained in the ground for over 70 years and despite such a considerable period of time, examiners managed to make comparisons that resulted in identifications.

An online poll on the AFTE Forum indicates that the number of requests for bullet to cartridge case comparisons is growing [31]. Therefore, Everett III studied the individual nature of toolmarks inside the mouth of a cartridge case of ten consecutive trimmed Remington brand cartridge cases. The author states that this study revealed the presence of individual characteristics on the inner circumference of the case mouth and that no subclass characteristics were present or carrying over on the seated bullets. The source of the individual characteristics on the test bullets was not irrefutably determined. As a limitation of this study it is mentioned that the consecutive cases under examination had not been loaded with bullets by the manufacturer.

2.4. Class characteristics

Pavlovich demonstrates the recognition of improvised firearms and workshop-manufactured firearms by exploring the ability to extract and group visually similar images from multiple sources [32].

2.5. Subclass characteristics

Two articles showing subclass have been published. One of these provides manufacturing information of the Walther PPQ [33]. All marks produced by such a firearm are discussed. The potential of subclass carryover is mainly caused by the limited presence of individual characteristics. The article emphasizes the importance of drag marks on the rim of the cartridge case, chamber marks, and marks from the firing pin aperture. A second article shows subclass to be present on the firing pin of Smith & Wesson M&P 15–22 rifles [34]. Even after the firing of 3500 cartridge cases the firing pins did not change significantly. The author also emphasizes the use of other markings like marks from the chamber, extractor and/or ejector to support any identifications.

2.6. Proficiency testing

As in most feature-comparison disciplines, source judgments in firearm examination are typically provided by human examiners. It is necessary to study the performance of these examiners to get more insight into the validity of their judgments.

The validity and reliability of firearm examiners' source judgments was studied and the outcomes were compared to those of a computer-based method [35]. A total of 200 9 mm Luger Glock pistols were fired twice to create both a same-source and between-source database. A total of sixty comparisons was selected (over-representing difficult comparisons) that were shown to 77 examiners. They were asked to provide a source judgment as well as a degree-of-support judgment based on comparison images of the aperture shear marks. The true positive rate of the examiners was 0.932 and the true negative rate 0.810. The validity of the source judgments increased when "inconclusive" judgments were not considered in the calculations (TPR = .970 and TNR = 0.892) and when examiners provided higher degree-of-support judgments. The examiners outperformed the computer-based method when correctly identifying different-source comparisons, while the computer-based method was slightly better at correctly identifying same-source comparisons (TPR = .947, TNR = 0.545). While the judgments of examiners varied, their mean between-reliability (Spearman correlation) for degree-of-support judgments was 0.631 for same-source comparisons and .457 for different-source comparisons. The degree-of-support judgments of the examiners did not seem well-calibrated, but this might be improved by performance feedback.

Another study looked into the validity of examiners' source and degree-of-support judgments using cast replicas of cartridge cases fired with firearms of several manufacturers [36]. Examiners were asked to provide judgment on both the breechface and firing pin impressions separately and their judgments were compared with the outcomes of a computer-based method. A total of 73 firearm examiners compared 48 test sets. The examiners' true positive rate was at least 95.3%, which was higher than the 94.4% of the computer-based method. The computer-based method however outperformed the examiners for different-source comparisons with a true negative rate of at least 91.7% compared to at least 86.2% for the examiners. This study showed that the validity of judgment increased when examiners provided higher degree-of-support judgments and when the information from different marks was combined. The degree-of-support judgments of the examiners were not well-calibrated and showed signs of overconfidence.

Using cast replicas of cartridge cases fired with firearms of several manufacturers, the reliability of examiners' source judgments was examined with 21 test sets [37]. While the casts ensured that every examiner had access to the same features, significant differences in performance were observed between examiners, with up to 23.5% of conclusions being non-consensus for a specific test set. This variability almost exclusive existed within the realm of three "inconclusive" categories, which can shortly be explained as "inconclusive", and a tendency towards an "identification" or towards an "elimination". Additionally, the result from the applied computer-based method are promising and the authors state that such a method could be used as quality control measure for the benefit of examiners.

A total of 107 examiners participated in a virtual comparison microscopy (VCM) study in which 40 test sets of cartridge cases were fired with firearm of several manufacturers [38]. The VCM software allows examiners to annotate areas of (dis)similarity to substantiate their source judgments. This information could provide insight in the examiner's decision-making process. The 76 qualified examiners from the United Stated and Canada had a false positive rate of 0.43% (95%-CI [0.09, 1.26]) and a false negative rate of 0.0% (95%-CI [0.0, 0.75]), providing support that VCM can be a valuable comparison tool.

2.7. Development of computer-based methods

The development and implementation of more objective computer-based methods will facilitate firearm examiners. The outcomes of these methods can be used in conjunction with examiners' source judgments which are based on their training and experience. To do so, the surface topographies of bullets and cartridge cases are acquired in 2D or 3D. These measurements can then be compared using algorithms. The resulting comparison score can be compared to reference databases of same-source and different-source comparison to calculate the evidential value of the comparison.

One such a computer-based method, utilizing a bi-dimensional statistical model, was developed for the comparison of 3D measurements of breechface and firing pin impressions [39]. The authors show that seven test shots fired by the same firearm results in comparable misleading evidence rates when compared to sixty test shots per fired. Furthermore, the brand of ammunition used affects the same-source and different-source distributions and thus the calculated evidential value of a comparison. A mismatch in ammunition between the case samples and the reference databases can therefore result in an over- or underestimation of the evidential value. The computer-based method's outcomes of seven comparison cases were in line with the degree-of-support judgments of eight examiners. The authors state that such a computer-based method can assist and enhance the examiners' decision-making process.

Several papers discuss the Congruent Matching Cells (CMC) method that was developed by the National Institute of Standards and Technology in the US. The method was developed for the correlation of impressed toolmarks, such as breechface and firing pin impressions [40]. The method divides a surface in smaller cells which can be used for pairwise comparisons instead of correlating the entire surface at once. This enables the differentiation between valid and invalid correlation regions of which the latter could negatively affect the correlation score and accuracy of registration when the complete surface is compared at once [41]. The method can be applied to both 2D and 3D measurements and was tested on breechface impressions in two sets of 9 mm Luger cartridge cases with different imaging methods, sample sizes, and ammunition [42]. For the 3D image pairs all same-source comparisons resulted in evidential value assignments of over 10^6 in support of the same-source proposition while all different-source comparisons resulted in likelihood ratios over 10^2 in support of the different-source proposition. For the evaluation of such likelihood ratios, the frequency distributions of the observed CMC results in the same-source and different-source reference databases need to be modeled appropriately. One binomial and three binomial-related probability distributions to do so are discussed in combination with the use of nonlinear regression models to estimate the model parameters [43]. The CMC method is further developed for use with firing pin impressions based on a convergence feature for the development of practical convergence-improved algorithms [44]. The authors show that this increased the reliability and accuracy of the number of CMC pairs.

While most researchers focus on the comparison of surface topographies, the possible use of micro-CT in cartridge cases comparison was also studied [45]. The method was shown to be able to repeatably and reliably measure 3D surface information (firing pin shape/sphere) as well as internal cartridge case features. For the internal features the depth of the primer cup impression and the height of the primer cups' anvil were considered. Test showed that these three values enable the differentiation between cartridge cases fired by one Steyr M9 and one Beretta 92FS pistol.

One of the first steps in the computer-based comparison of fired bullets is the ability to locate and separate land engraved areas (LEAs) from groove engraved areas (GEAs). A method, based on robust locally weighted regression (LOESS) was developed to automatically remove GEA utilizing shoulder locations [46]. The method consists of an iterative re-weighting process to decrease the effect of outlying data in the shoulders. The authors conclude that this method is an improvement upon the "rollapply" method [47].

Another study applies a Baysian Kalman filter to optimally and automatically reduce high frequency noise during bullet data pre-processing [48]. This filter is added to the earlier introduced Ensemble Empirical Mode Decomposition (EEMD) which is used for smoothing and feature extraction [49]. The Kalman filter is applied to a bullet's averaged profile resulting in a pre-processed measurement which helps the normalized cross-correlation of samples. Using this approach, the resulting comparison metric is robust to start- and endpoints (including shoulders) of bullet profiles.

Once pre-processing and comparison methods have been developed, it is important to validate them by evaluating their performance. The performance of a comparison algorithm [47] is assessed using three comparison scoring measures: 1) cross correlation, 2) random forest score, and 3) consecutive matching striations (CMS) [50]. The scoring measures are both assessed at the LEA-to-LEA level and at the bullet-to-bullet level, using Sequential Average Maxim scores. In the test, utilizing Ruger pistols, the cross correlation and random forest scores showed perfect discrimination between same-source and different-source comparisons. At LEA-to-LEA level, the area under the curve (AUC) was excellent (>0.90) for both the cross correlation and random forest scores.

In line with the Congruent Matching Cells (CMC) approach for the comparison of impression patterns the Congruent Matching Profile Segments (CMPS) method is proposed for striation patterns [51]. The method divides one of the patterns to be compared in segments. Each segment can then be compared to the other sample's striation pattern instead of correlating the entire profiles at once. This is done to address possible issues with lateral scales, varying height scales, and poorly marked or damaged sections of the striation pattern. The outcome measure is the number of profile segments that show both a sufficiently high correlations score and have a congruent registration position. Initial test showed a clear separation between the scores of the same-source and different-source comparisons.

While most studies are performed on non-deformed fired bullets with pristine striation patterns, bullets in casework can be heavily deformed and damaged. For these bullets an image reconstruction procedure followed by the congruent matching profile segments (CMPS) method is proposed [52]. A total of 57 bullets with varying degrees of deformation or fragmentation, fired with a 9 mm Luger pistol, were used. Comparisons were performed at the LEA-to-LEA level. LEAs of a deformed bullet were compared to those of a nearly-pristine reference bullet and to those of another deformed bullet, both before and after image reconstruction. The correlation results improved significantly after image reconstruction, especially for LEA with large deformation and good visibility of striations.

2.8. Ballistic imaging database

Several studies have looked into the performance of ballistic imaging databases to developed efficient standard operation procedures. Systems are evaluated by using test sets or by evaluating case results.

The Evofinder® system is evaluated using 1000 Norinco pistols, using 1000 test bullets and 1000 test cartridge cases [53]. The majority of the known same-source comparisons ranked 1st. The system was able to highlight the known same-source comparisons from the known different-source comparisons in a sample of 1000 pistols. The time required for correlation increased as the size of the database increased. The authors emphasize that the result of either identification or exclusion must be verified optically by firearm examiners as they believe that the results of the system alone are insufficient.

Sharing ballistic data becomes more urgent due to recent events such as terrorist attacks. Sautier et al. discuss sharing ballistic data via two methods [54]. The first one relies on a centralized common database using a unified protocol. The second one advocates for a distributed framework relying on existing national infrastructures using local protocols. The results demonstrate that the second option paves the way for a distributed network and answers the practical needs of member states.

Pope describes how the Evofinder® automated ballistic identification system is validates and implemented at the DC department of forensic sciences [55].

Unless all exhibits in a correlation review list are going to be reviewed it will be necessary to define a criteria for deciding the limits of the correlation review. For this goal an evaluation of 2548 leads by the NIBIN National Correlation and Training Centre (NNCTC) was performed [56]. The rank sort feature of IBIS® Technology has been observed to be very powerful. Using the rank score and the six different types of available scores, almost all leads were placed in the Top 30 what can be used within the standard operation procedures (SOP). A similar evaluation was performed, but with a dataset of 750 exhibits containing known matches [57]. After an upgrade to IBIS BrassTRAX version 3.1 the performance of the rank sort function was examined. The results were largely similar to Nichols' [56], all known same-source comparisons were found in the top 30 of the correlation list. Personnel aspects such as number of reviews per person per day have also been studied.

3. Firearms and ammunition miscellaneous reports

3.1. Firearms

3.1.1. Firearm related sounds

The analysis, comparison and identification of the different sounds firearms make due to their mechanical operation (e.g. cocking, trigger pulling, etc.) is discussed [58]. The authors found machine learning the most promising approach and point out that this way of analyzing acoustic sounds made by firearms can be used in forensic identification.

3.1.2. Codes

More than a decade ago, firearms manufacturers began using barcodes to identify firearms. Recently, manufacturers are using the 2D matrix barcode on the individual firearms. The process to retrieve such as 2D matrix barcode and the consecutive steps to take in order to gain the stored encoded information are discussed [59].

Similarly, the process of obtaining the serial number by using a 10-digit code, found on the frame beside the locking block, is described [60]. By searching in their records, Glock was able to help the author determine the serial number, based on the 10-digit code.

3.1.3. 3D-printed and polymer resin firearm (components)

3D-printed firearm and parts of firearms have been in the spotlight in recent years. 3D printing, also referred to as additive manufacturing, raises new forensic issues for forensic firearm investigators.

Two 3D-printed metal barrels for a Colt 1911 were tested [61]. With the barrels, made of INCONEL® alloy 718, a total of 100 rounds of ammunition were successfully test fired through each barrel. The striations on the bullets were found to be identifiable by the authors. Bullets fired from one 3D-printed gun barrel were easily excluded from those fired from the other 3D-printed gun barrel by visual examination.

Scott & Jones deal with the recognition of 3D-printed objects, in particular the Selective Laser Sintering [62]. They emphasize that understanding of the theory and limitations of the design and printing process are necessary for forensic examiners to be able to recognize and describe 3D objects.

McVeigh warns that polymer resin casted AR-15 platforms lower receivers, which are commercially available in the US, are a potential safety risk [63]. While these platforms function, catastrophic failures can occur.

The "Liberator", a 3D-printed firearm, is tested, and 3D-printed firearms identification is explored [64]. The only metal part of the Liberator, a nail used as firing pin, was found to have sufficient marks for an identification.

Honsberger et al. manufactured six Liberators and focused on the traces that could orientate forensic investigations when the use of a 3D-printed Liberator is suspected [65]. The Liberator was investigated to study its behavior during discharge and characterize traces produced by the discharged ammunition. Liberators, in caliber 9 mm Short, fired bullets with a speed of 140–170 m/s with a penetration in ballistic soap of 14 and 21 cm, respectively. Despite the damage sustained by the Liberator and a disrupted trajectory of the fired projectile, the wounding potential of these guns is undeniable. In a second paper, the authors focus on the physical traces which can be found and used from a forensic point of view after discharging 3D-printed Liberators [66]. The results showed that bullets and cartridge cases fired by Liberators carried polymer traces transferred during the firing process.

Thirty-six Liberators were manufactured using different printing processes (Material Extrusion (ME), Vat Photopolymrization (VP) and Powder Bed Fusion (PBF)) [67] as well as different printers, polymers and parameters. This paper provides a clear overview of printing techniques and related traces used for forensic examination. All barrels were destroyed during discharge. Polymer pieces or fragments from the guns allowed to differentiate between elements printed with different processes as also some of the printing parameters (layer height, filling pattern and infill density).

3.1.4. Time since discharge

In order to estimate the time since discharge, the heat decay of different firearms was examined [68]. After firing firearms (differing the magazine capacity), temperature measurements were documented by using a portable thermal imaging device. Mathematical models were created with these measurements for each firearm and magazine capacity. In order to calculate a steep gradient rate of heat decay, swift measurements had to be taken and the initial temperature had to be high enough. If those criteria are met, the time of fire could successfully be estimated.

3.2. Ammunition

3.2.1. Manufacturing marks

Striated toolmark patterns, similar to breechface marks were found in Federal American Eagle .40 S&W 180 grain FMJ ammunition [69]. These features were determined to be manufacturing marks, caused by cutting parts from the brass wire.

3.2.2. Replicas and casts

There are multiple ways to create a standardized cartridge case. Casts of the National Institute of Standards and Technology's (NIST) standard cartridge case (SRM 2461) were analyzed in order to map the variance between the double-cast cartridge cases [70]. Although the authors found significant differences between the mold and the cast sets on some occasions, they state that the double-casting method reliably reproduces even the fine details.

3.2.3. Trace analysis

A new version of the CCI .22 Long Rifle ammunition was examined [71]. Sold in 300-round cartons, they consist of red, white and blue polymer-coated 40-grain lead bullets. The polymer colors could be seen on the lead-in portions of certain ricochets, but no visible residues of the coatings could were observed in the bores of the used firearms. An essential outcome of this study for the forensic firearms examiner is the observed concealment or lack of striations due to the polymer coating.

A study utilized the use of wavelength dispersive X-ray fluorescence (WDXRF) to analyze rifle bullets and identify the spectral similarities between samples [72]. Fifty-four lead core fragments from 5 different manufacturers were obtained in caliber 7.62 × 51 mm NATO. Besides being quick and relatively simple, the results indicate that the WDXRF technique can be useful to differentiate between bullets' manufacturers in case studies.

3.2.4. Recovery of traces from firearms and ammunition

Several papers deal with human traces on casings such as DNA and fingerprints. The papers about DNA extraction discuss not only the effectiveness of the methods but also the effects on the marks in casings. In the published studies on fingerprints on casings, it is remarkable that test results are many times better than the achievable reported efficiency in case work.

3.2.5. DNA

DNA and protein from touched, unfired cartridge cases were extracted to produce both genomic and proteomic information [73]. Two sample methods, dry tape and wet swabs, were tested. DNA and protein collection was similar for both methods. Proteins can be collected from fingerprints at levels necessary to provide identifying information obtained from challenging evidence.

A study of DNA recovery rates for 17 firearm parts and cartridges, bullets and cases (CBCs) was performed [74]. The least DNA was recovered from the hammer, safety and CBC's, while a single swab of multiple firearm parts resulted in the highest DNA recovery. The results suggest areas to prioritize for DNA recovery from firearms.

DNA recovered from fired hollow point ammunition was examined [75]. A series of 40 Winchester .22 LR hollow point bullets were loaded with cell suspensions from a donor. These were shot in a 500 sheet reams of A3 paper for capture. Repeatable partial profiles with five reportable loci pairs were obtained. To the knowledge of the paper's authors, this is the first reported evidence of DNA surviving the cycle of fire.

Malanio et al. aimed to quantify the number of epithelial cells or cell-free DNA that are present on cartridge cases throughout the handling process [76]. This included directly out-of-the-box ammunition, ammunition loaded in magazines but not fired, and cartridge cases collected post-firing. DNA was found on 93% of the out of the box rounds (three different manufacturers). Results indicate that cartridge cases are likely to have ample cellular material to produce interpretable DNA profiles.

3.2.6. Fingermarks

The effectiveness of processing fired cartridge cases for fingerprints was tested [77]. Latent prints were deliberately placed on a sample of unfired rounds (9mm/.38). Another sample of unfired rounds was handled naturally prior of being fired. Of the 150 rounds with deliberately deposited prints, 68 developed ridge detail of value for identification. Of the 511 naturally handled cartridge cases, no positive results developed at any stage of processing. The results indicate that latent fingerprint processing of discharged casings is possible, though unreliable.

During a period of a year 1431 cartridge cases collected in casework were evaluated [78]. Ridge details were observed in 50 cartridge cases, but only in 5, the marks were considered to provide sufficient information for identification. In one case it was possible to obtain the suspect's identification. Referring to earlier work, the authors mention that the abrasive friction when an expanded cartridge case is extracted from the chamber as one of the main causes of deterioration of the fingermarks due to the firing process.

A test using gun blue to enhance fingermark ridge detail on ballistic brass was performed [79]. To evaluate the effectiveness of gun blue as an enhancement method, fingermarks were deposited on brass metal discs and left to age. The feasibility of enhancing fingermarks on fired brass cartridges was also assessed. The most favorable results for fired casings was 1 out of 20 with identifiable quality. For the majority of the metal discs fingermarks were successfully enhanced to an identifiable grade.

A case report discusses an untreated latent fingerprint, left on a 10 mm Auto spent casing that was swapped for DNA on the scene [80]. The latent print was discovered on a photograph. The image was improved and subsequently identified to the suspect in the case.

Swank and Davis focused on recovery rates of latent prints on firearms, magazines and cartridge evidence [81]. The result of a case with a substantial amount of evidence was compared with studies about friction ridge examinations. As a result they calculated approximate recovery rates of useable latent prints on similar firearms-type evidence: firearms 10%, magazines 8.5% and cartridges 0.21%.

Another test to visualize latent fingermarks was performed [82]. For the test five types of ammunition, caliber 9 mm to .45, were left for different periods of aging prior to firing. After firing, 200 cartridges were processed with the vacuum metal deposition method (VMD). As a result 12% of the print were good and 28% had a moderate quality.

Another test was performed with fingermark on brass tiles and on fired cartridge cases using the VMD method [83]. The study shows that the method is effective on ballistic brass surfaces. The findings suggest that the quality of the original print will determine the level of enhancement achieved, rather than an aspect of the VMD mechanism.

3.2.7. Statistics

The statistics of gunshot homicides in Denmark over 25 years (1992–2016) were evaluated [84]. The authors analyzed the number of gunshot homicides, victims and offenders, weapons, locations and gunshot wounds. In this evaluation, tools like the Abbreviated Injury Scale (AIS) and the New Injury Severity Score (NISS) were used. Many statistics were found to correspond with previously published data.

3.3. Bias, reporting and quality assurance

3.3.1. Influence of human factor on forensic judgments

The effects of blind peer review and non-blind peer review on forensic firearm examiners was studied [85]. The results show that examiners are more likely to disagree in the blind peer review procedure than when they see the other's interpretation and proposed conclusion (non-blind peer review). This finding supports that bias occurs during non-blind peer review. Furthermore, an examiner's professional status affects the outcome of a discussion, where reporting examiners have a larger effect on the outcome of a discussion than non-reporting examiners.

3.3.2. Reporting

The reputation of the word “subjective” is discussed [86]. The authors discuss that both subjectivity and objectivity are misvalued. They claim that there is no getting around the subjective nature of many comparisons. Critics decry the subjective aspects of comparison processes and suggest that on that basis they should be disallowed in court. The authors state that subjectivity is a tool used on a daily basis and that an examination involves both objectivity and subjectivity. They state that subjective results are real and can be shared with others.

In another paper the authors expresses their concerns about the permitted wording used in courts. A judge ruled that the firearm examiner could testify only that the evidence firearm “cannot be excluded as the source of the casing”. Other courts are picking up on this. The others claim that the truth is at stake because of these developments [87].

The new definitions of machine guns that now includes Bump-Stock Type devices are discussed [88]. The poor definition of machine guns would lead to discussions in the coming years if no reference is included regarding the application of forward force by the shooter resulting in an accelerated semi-automatic firing cycle.

3.3.3. Quality documents

It is argued that there should be a harmonization of the measurement method for the barrel length and overall length of a firearm [89]. In the UK, this determines the categorization of firearms. Multiple measurement methods are in use that are described in this paper.

4. Technical examination

4.1. Modified and homemade firearms

A firearm capable of discharging a .22 LR caliber cartridge was constructed by converting a plastic toy gun [90]. This shows that it is possible to create a working firearm with metal and polymer parts which are easily obtainable from a hardware store.

In a similar unusual finding, a homemade assault rifle was found, created from both M16 and Kalashnikov mechanical parts [91]. This hybrid firearm is capable of firing 5,56 × 45mm cartridges.

Related, Martini discovered that incorrect assembly of the firing pin and striker in the “KG” and “TEC” pistol series of Interdynamic and Intratec could result in a fully automatic firing mode [92]. No machining or other modifications were necessary to achieve this effect.

Another study regarding the firing mode of pistols involved Glock pistols [93]. By simply removing a small amount of material, a select-fire auto sear originally produced for Glock-type airsoft pistols was made to function on a real Glock pistol.

In another study involving modified firearms (converted), blank-firing pistols (mainly the Ekol and/or Ekol-Voltran) were analyzed for functionality in order to provide awareness of potential safety issues [94]. The authors identified the conversion as a growing issue and believe in the need for stricter legislation.

4.2. Accidental discharge

There are cases when firearms discharge in other ways than intended. This was seen in a semi-automatic American Tactical model Omni Hybrid MAXX Limited, caliber 5.56 mm NATO rifle which was found to fire upon trigger release [95]. The author states improper manufactured parts as a potential reason for this phenomenon.

Similarly, inertial discharging of a Colt model 1911 semi-automatic pistol showed that if a pistol was dropped on concrete and plywood in different settings (e.g., orthogonal, non-orthogonal, slide assembly alone) it could be made to fire the cartridge [96]. This was tested at increasing heights, until the firearm discharged consistently.

In another example of unintentional discharge it was determined that the Fabrique Nationale model FNS pistols had a factory flaw that could allow the firearm to discharge unintentionally [97]. By moving the slide one eight of an inch backward, pulling and releasing the trigger would not release the striker. However, the striker would not reset. Tapping on the side of the firearm, without touching the trigger, would cause the striker to release and initiate the primer.

4.3. Reconstruction of events

It was studied if a gun-holding hand unintentionally applies enough force to discharge the firearm if the non-gun-holding hand applies a force [98]. Sixty-nine volunteers (32 male, 37 female) used hand grip tests to measure the force applied. Participants were told to hold dynamometers in both hands and told to clench as hard as they could with one hand while the other hand was supposed to remain passive. The authors found it unlikely that applying a force with the non-gun-holding hand could involuntarily evoke a force great enough to discharge a handgun in the other hand.

4.4. Methods

Challenges have always occurred when examining a firearm suspected of accidental discharge. Reconstructions, similar to the conditions under which the stated malfunctions appeared may have to be performed. When those reconstructions do not provide sufficient information, the examiner may need to disassemble the firearm. Disassembling the firearm is a delicate task. If, for example, the alignment of the internal parts changes, the conditions may not be the same anymore. To overcome such issues, the use of Computed Tomography (CT) scanning to analyze the internal workings of a firearm, without the risk of altering the alignment of internal parts is demonstrated [99].

Acknowledging that their research scope was small, Greenslade and Bolton-King state that their study demonstrates that there is no universal approach to predict muzzle velocity and energy based on air rifle modifications. Their aim was to quantify the effect of storage conditions (mainspring compression and oil travel/dieseling) and two modifications (reduction of barrel length and preloading through addition of washers). By using a small number of break barrel, spring powered air rifles for their study, they found a significant variation in muzzle velocities as a result of the two earlier mentioned modifications. They also found that the orientation of storing (vertically) and/or cocking statistically effected the consistency of recorded muzzle velocities, reinforcing the requirement to undertake the weapon examination in short order [100].

The Harrison County Institute of Forensic Sciences Firearms Identification Laboratory replaced their mechanical spring gauges with an Imada DS2-44 digital force gauge to perform more reproducible and precise trigger pull measurements. The author discuss how they validated the gauge and estimated the measurement error for the main firearm types/actions [101].

4.5. Firearms and their background

A technical report about the Armatix iP1 discusses that the key feature of this pistol is the electronic authorization system [102]. The pistol and the Armatix iW1 RFID watch are synced with the watch PIN and firearm serial number. The pistol’s smart system needs to be combined with the watch in order to operate. The author explores some vulnerabilities of this system, such as operating range, jamming and effects of magnets and indicates that the serial number of the pistol is registered on the memory chip, located in the receiver.

Molans and Warren provide an extensively description of the history and evolution of firearms, ammunition, bullets and ignition systems.

Starting from the earliest recorded making of gunpower and bronze gun barrels to the modern age firearms and ammunition. They compiled their gathered information into an article tailored towards the forensic practitioner [103].

The Levinson's prototype of a submachine gun is discussed [104]. This submachine gun is supposed to be an improvement on the Sten submachine gun, featuring a quite unusual design/construction based on an open bolt mechanism. By using a flywheel-type bolt, Levinson tried to minimize the drawbacks of the Sten, mainly size and protruding magazine.

Another unusual described design was an American made, single shot pen pistol, appearing in its carrying form as an oversized ink pen [105]. Although the production numbers were limited, it is also produced as a knife/gun combination. The author points out, that because of the need to reconfigure before firing, these pistols are not classified as NFA Title II weapons.

5. Shooting incident reconstruction

5.1. Research

5.1.1. Bullet behavior and bullet trajectory reconstruction

Several studies have been conducted on methods to establish the incidence (impact) angle at which a bullet hit an object from the shape and size of the bullet's defect.

In one of these studies, the angle of incidence at which a bullet impacted a 1.35 mm sheet steel plate was determined by placing a rod on the so-called lead-in part of the bullet defect [106]. The study describes the formation of this lead-in part, describes and proposes a method, lists the method's limitations and provides the results of its application. In this (blind) study, the results of 15 participants applying the proposed method, are compared to the known incidence angles. The defects were produced with ten different firearm/ammunition combinations (two rifles, eight pistol). Discrepancy between the known and measured angle varies with firearm/ammunition combination.

Another method to establish the angle of incidence at which a bullet impacts 1.35 mm sheet steel was determined by superimposing an ellipse on a digital photograph of the bullet defect, and calculating the angle from the length and width of the ellipse [107]. The study describes the formation of the defect and the applied method and gives the results of its application. The results of 12 participants applying the described method are compared to the known incidence angles. The defects were produced with six different 9 mm Luger bullets, fired from a Glock pistol, at seven different incidence angles. The results show an error pattern with a significant quadratic relationship for the patterns of three of these bullet types.

In a third study, the angle of incidence of bullets on drywall was established by applying the ELlipser app on digital photographs of elliptical bullet defects [108]. The study describes the method and provides the results of 31 participants compared to the known incidence angles. The defects were produced with bullets from four calibers, fired at eleven different incidence angles. In general, both accuracy and precision of the method are better at lower incidence angles (below 64°). Performance was best for the largest caliber (.45 ACP).

The influence of muzzle-to-target distance on bullet deflection was explored with a common construction material [109]. Muzzle-to-target distance is known to be of influence on bullet yaw (decreasing over distance after a bullet leaves the muzzle). This study indicated that this has an effect on bullet deflection with two of the three examined firearm/ammunition combinations. More yaw at 1 m appears to have caused more erratic after target deflection, compared to the 15 m situation.

Four studies have been conducted on various terminal ballistic aspects with 7.62 × 39mm bullets. In the first study, the interaction between 7.62 × 39mm lead core bullets from a test barrel (generating slightly higher velocities than with a typical assault rifle) and 1 mm thick steel was explored [110]. Bullets ricocheted completely at 3° and 5° impact angles. The substrate ruptured and the bullet deformed strongly at 5°. Between impact angles of 8° and 20°, bullets fragmented and partially perforated/ricocheted. A typical 'double-headed' bullet defect was observed in the defects resulting from these shots. Ruptured jackets were observed to have a characteristic, triangular shape and typically ricocheted. Parts of the lead core either perforated the plates or ricocheted. All bullets perforated completely above an incidence angle of 21°. Another important observation was made in this study: ricochet angles were found to be lower than the respective incidence or impact angles, despite the clear, yielding nature of the thin sheet metal. A positive relationship was found between incidence angles and the lead-in length, the length to the first head of the double headed mark and the length of the whole defect.

A second study explored the interaction between 7.62 × 39mm mild steel core (MSC) bullets from an assault rifle and 1 mm thick zinc-coated automotive steel plates at different incidence angles [111]. Several interesting observations were made. For the orthogonal shots the mean bullet defect diameter was about equal to the nominal bullet caliber, with individual shots measuring both below and above that diameter. Separation of the mild steel core and jacket (and possibly the lead sleeves as well) occurred between incidence angles of 15° and 30°. The cores perforated the plates, while the jackets ricocheted of the plates. As earlier studies showed that the ellipse method was less suitable for sheet metal, incidence angle was calculated using only the length of the bullet's defect. This worked well at all incidence angles, including those where core/jacket separation took place. At incidence angles below 40°, bullet deflection with the perorating intact bullets and bullet fragments increased from around 1° with the higher angles to a maximum of 7°. This will negatively affect trajectory measurements by stringing or probing. Bullet impacts below 40° can be recognized from their length (15 mm+) and/or by their distinct 'double-headed' appearance.

The interaction between similar (MSC) bullets with two different concrete surfaces and one type of cement surface was also explored [112]. Critical angles were found to be 10.8°, 11.1° and 13.2° for the different substrates respectively. Above the angles, bullets started to fragment, resulting in core/jacket separation. The hard and brittle substrates behaved as semi-yielding surfaces, as craters were being formed by the bullets. There was a strong linear correlation between the angle of incidence and crater depth.

A last ballistic study on the interaction between these MSC bullets from an assault rifle explored the interaction of those bullets with four different types of wood [113]. The wood types had a different Janka hardness. Density of the wood was not measured. Critical angle for ricochet of pine, mahogany and teak were calculated to be between 12.7° and 13.3°. Critical angle for Jack wood was a little lower, at 9.9°. Critical angle was not notably higher for the harder wood types, as was found in other studies with handgun bullets [114]. The width of the ricochet marks could be measured and was on average 0.26 mm wider than the nominal caliber of the bullet. Ricochet mark length was found to be inversely proportional to the incidence angle. Ricochet angle was found to be directly proportional to the incidence angle.

Two studies were performed on bullet deflection and stability through soft tissue simulants. Although dealing with soft tissue interaction, these particular two studies are not discussed in the section "Wound Ballistics" because of their explicitly stated purpose to facilitate trajectory reconstructions. One of the studies focused on deflection of four different types of 9 mm Luger bullets, fired through 25 cm thick blocks of ballistic gelatin (10% by weight, cooled to 4 °C) [115]. Bullet deflection from their original trajectories was measured behind the blocks. With non-deforming full metal jacket flat nosed bullets, deflection was found to be low but consistent (mean = 0.4°, SD = 0.1, n = 20). Deflection with full metal jacket round-nosed bullets was found to be higher but consistent (mean = 6.0°, SD = 0.3, n = 20). Behavior of the two deforming bullet types was more erratic (means 3.2° and 3.8°, SD 1.4 and 1.9, and n = 20 for both). An influence of yaw, caused by shorter muzzle-to-target distances, was not found with the aforementioned full metal jacket round nosed bullets.

Another study focused on stability with truncated cone and flat nosed bullets [116]. As in the previous study [115], very little deflection was measured for bullets of this particular types. Additionally, the bullets did not yaw in the soft tissue simulants but kept traveling nose forward.

Liscio, Le and Guryn compared trajectories in a scanned, 3D space [117]. Twenty-one reference trajectories were modeled as straight lines between the muzzle of a (fixed) Glock 22 to a primary bullet defect in drywall. These lines were compared to the extended lines drawn through the centers of two 80 mm spheres on a bullet probe, inserted through the primary and secondary defect in drywall. The comparison was performed by twelve participants. Horizontal (azimuth) angles and two vertical angles we assessed. Vertical angles were both measured to a virtual plane based on three points defined by the participants in the model and also to the build-in inclinometer of the scanner. The measurements resulted in a total of 756 comparisons, nine of which were removed from the data because of clear misalignments by the participants of the virtual plane. Absolute error between known and measured angle was on average 0.47° lower when the data from the build-in inclinometer was used. 75% of the absolute errors were below 0.91° and 0.98° for the horizontal and vertical angles respectively. Maximum recorded error of the 747 comparisons that were included in the dataset was 4° (horizontal, azimuth).

An extensive overview of various aspects of bullet and target interactions that have been studied in a forensic context has been written [118]. The authors list the known parameters that might play a role in shooting scene reconstructions and make a plea for more and better (internationally) coordinated research and better implementation of the results of this research in actual casework through 'translational research'.

5.1.2. Shot and ejection patterns

In a study on range estimation, the authors fired 12 gauge shotgun cartridges, loaded with shot no 4 from five different single barrel shotguns [119]. Shot patterns were recorded at various muzzle-to-target distances in triplets with the original barrel lengths. Approximately 10 cm of the barrel was sawn off, after which the shot patterns were recorded again. This was repeated another four times, resulting in shot patterns with six different barrel lengths. The results confirmed that removal of the first part of the barrel, with the three shotguns that had a choke, has a significant effect on shot dispersion. This effect was greater than the effect of shortening the rest of the barrel. Pattern size increased with increasing muzzle-to-target distance in a (near) linear correlation (Pearson correlation coefficient >0.99) within the short range (10 m) of the study.

In another study on range estimation with 12 gauge shotguns, the distribution patterns of cartridges, loaded with bulgur wheat, wheat and vetch seed, was examined [120]. These cartridges are used to scare of large animals without causing harm. Eight different brands and types of these grain-loaded cartridges were fired from a single shotgun at 50, 10, 200, 300 and 500 cm. The grain-loaded cartridges showed a much wider distribution on targets at these shooting distances than conventional lead pellets.

5.1.3. Shooting distance determination

In a study shots were fired with three different revolvers, using .357 Magnum cartridges from the same brand and batch [121]. Per revolver, 10 shots were fired upwards, horizontally and downwards. Muzzle velocity, chamber pressure and firing pin impression depth of the fired cartridge cases were measured. Going from upwards via horizontally to downwards, muzzle velocity, pressure and firing pin depth decreased. The difference in firing pin impression depth has the potential to identify the orientation of the revolver at the moment of the shot. The authors attribute this effect to a different orientation of the powder charge in the cartridge and/or the orientation of the cartridge in the chamber due to gravity. The study opens the question whether this effect would also be measurable with other cartridges, for example those with a smaller powder volume.

To study the magnitude of error when estimating a shooter's position from the location of retrieved cartridge cases, a large cartridge case ejection pattern database was created by firing Glock 22 pistols [122]. Four shooters of different length fired three magazines each from a kneeling position and three magazines from a standing position. Both the initial impact location and final resting position of the cartridge cases was captured with two camera's and a laser scanner. Smaller, 'blind' datasets, with 1–6 cartridge case positions were used to estimate the shooters position using the larger reference database. Error decreased with an increasing number of cartridge case locations in the blind datasets.

The effect of two types of crossbow arrows fired from a 175 lb (nominal draw weight) crossbow against the tempered glass of six Ford Fiesta front doors was explored [123]. With all six shots, the windows shattered and the arrows perforated the windows. Measured velocity loss of the arrows went up to 25 m/s. Damage to the arrows varied from tip holder decoupling, shaft damage, to removal of the fletches.

5.2. Methods

The potential of the open-source software product CloudCompare and its application in bullet trajectory and shooting incident reconstructions is described [124]. The software is a versatile 3D point cloud and triangular mesh processing product that can load FARO (.fls and. fws), Leica (.ptx and psz) and Agisoft Metashape (.xyz and. dxf) files. The point clouds can be coupled with texture and/or color information (.ply) to produce a more realistic presentation of the crime scene. The authors provide various examples of how this software can be used to visualize a crime scene and bullet trajectories.

In a comparative study on velocity measurement devices [125], the author fired .22 Long Rifle bullets and measured the muzzle velocity with two different Doppler radar systems, a conventional (CED) chronograph and with a MagnetoSpeed velocity meter. The latter device is attached to the muzzle of the firearm. The muzzle velocities recorded with the three different methods and four different devices were very similar. Additionally, calculation of the G1 ballistic coefficient with the Doppler radar measurements is explained. This parameter is of importance with long-range trajectory reconstructions. One of the Doppler-radar systems that was tested, was described and evaluated in more detail in Ref. [126]. The affordable system was found to be an easy-to-use device, capable of calculating reliable muzzle velocities that are derived from a series of downrange measurements. The system was tested with a range of calibers and bullet types. Depending on bullet type, velocity measurements up to 50–150 yards (approximately 46–134 m) are possible. Function is independent on lighting conditions, but measurement of the velocity drop when a bullet perforates an intermediate target is not possible.

5.3. Case reports

A fatal hunting accident with a .30-06 TUG bullet was reconstructed mathematically [127]. The authors state that the results demonstrate that the wound of the victim (keyhole entry wound, bullet found in the abdomen) was consistent with a ricochet, not a direct shot.

In a case with a fatal shot from a 12 gauge shotgun, two opposing scenarios were evaluated [128]. One possible scenario was that a shot was fired at close range in a struggle over the firearm (suspect statement). In the opposing scenario, the shot was fired from a greater distance and through an intermediate target. The fact that the non-attached fiber wad that pushes out the Winchester Super X slug was found in the body of the victim was used by the defense as support for the close-range scenario. The authors demonstrated that the wad accompanies the slug over a distance of up to 6.7 m even after perforating the intermediate target in question (vehicle headrest).

Mushroom-shaped ends in synthetic fibers around bullet defects in clothing were observed [129]. The samples stemmed from executed victims that were exhumed decades after the time of death. The authors discuss that the mushroom phenomena was observed before and is an indicator of bullet-induced damage to garments. Caliber, ammunition type and muzzle-to-target distances were unknown.

In a fatal shooting incident involving a shotgun, tissue was found up to 29 m from the location were the victim was hit [130]. The circumstances of the case indicate that the tissue was expelled from the victim's head by a shot with a 12 gauge Winchester Super X 00 Buck cartridge. The tissue was found behind the victim, in the direction of the shot. The author argues that the approximate 12% downward slope of the terrain might have aided in this extraordinarily long distance.

6. Wound ballistics

6.1. Research

6.1.1. Tissue simulants

The performance of synthetic gels such as Clear Ballistics and Perma-Gel as soft-tissue simulants in ballistic studies was evaluated [131]. The author shows that these products are not equivalent to standard 10% gelatine (by weight) cooled to 4 °C, with respect to projectile penetration depth and velocity loss per unit path length. These noted differences limit the usefulness in ballistic studies and shooting incident reconstructions.

In another study on soft-tissue simulants, energy transfer to 12 cm cubes of 10% (by weight) gelatine cooled to 4 °C was studied [132]. Temporary cavity formation was both filmed and assessed from the cracks in 1 cm thick slices that were cut from the blocks after shooting. Differences were noted between the deceleration of hollow-point bullets (proportional to energy transfer) measured from the high-speed films, and their deceleration measured from the cracks in the slices. Total energy transfer to the blocks correlated with all measured parameters from the slices, for all shots, but energy transfer per centimeter did not for the hollow-point bullets.

Fenton, Horsdall and Carr list the known physical and mechanical properties of human skin and provide a contemporary (up to 2018) overview of the various natural and synthetic skin simulants used in ballistic studies [133]. They discuss the studies behind the simulants and their pros and cons.

Isolated porcine ribs were used in a study on the behavior of bone when impacted by a projectile [134]. Steel balls and chisel nosed projectiles with a diameter of 5.5 mm were used. Bone proved strain-rate sensitive, in that it behaved differently with different projectile velocities. Below 323 m/s the ribs behaved as an elastic, plastic and brittle material. Above a velocity of 551 m/s, the ribs behaved as a brittle material, with instant failure and formation of secondary fragments. Perforation occurred with energy densities a low as 0.14 J/mm^2.

In a comparative study on the use of polyurethane as a simulant for bone in ballistic studies, porcine (sus scrofa) ribs were compared to 5, 6 and 12 mm polyurethane plates [135]. Both where imbedded in 10% ballistic gelatine and shot with 5.56 mm open tip bullets. The number of fragments, energy deposition, onset of yaw, angle of deviation and temporary and permanent cavity formation building in the gelatine were compared. There was no significant difference between the results with the porcine ribs and the three thicknesses of polyurethane plates, except for a difference in depth and maximum gelatin disruption between the 6 and 12 mm plates and the ribs. This lead to the conclusion that the 5 mm plates were a suitable simulant for porcine ribs in ballistic tests with 5.56 mm ammunition.

Two well documented shooting incidents, both with multi-victim fatal head shots, are reconstructed with ballistic head models [144,141]. The models combine skin, bone and brain tissue simulants. In one of these studies, two male individuals and one female individual died as a result of a single headshot wound each [136]. These were inflicted with full metal jacket bullets from the same .32 Auto caliber pistol. The shots could be reproduced by using ballistic soap as a simulant for skin and subcutaneous tissue, polyurethane plates for (cranial) bone and 10% ballistic gelatine for brain tissue. Overall bullet penetration was similar to the documented wounds of the deceased, but bullet deformation of the bullets that were fired at the model was slightly less. In the other study, two young males died as a result of a single headshot wound each, inflicted with full metal jacket bullets from the same .25 Auto caliber pistol [137]. The shots were reproduced with a 'closed' (spherical) and an 'open' model. The open model consisted of leather (skin simulant), 10% gelatine (subcutaneous tissue), a flat plate of polyurethane (bone simulant) and 10% gelatine brain simulant. The closed models consisted of the same materials but the polyurethane plates were replaced by a sphere, filled with gelatine and clad on the outside with the skin and subcutaneous tissue simulants. The closed model was more anatomically correct but the open model allowed better controlling of the shooting parameters and allowed the bullet's passage through the brain simulant to be filmed with a high-speed camera. As in the earlier study [136], the overall characteristics of the shots were reproduced but bullet deformation in the models was less than with the fatal incidents. This lead the authors to conclude that the bone simulant might under-represent either the strength or the density of human bone.

Deceleration and associated energy dissipation in 10% gelatine 12 × 12 × 12 cm 'reference cubes' were studied with a high-speed camera [138]. The frame-by-frame analyses of the high-speed footage allowed for measuring the deceleration of the bullets in the gelatine. The tested expanding bullets decelerated abruptly in the first 2 cm. After this, deceleration was more or less constant. Deceleration of the tested FMJ bullets was more or less constant over the entire length of the wound path, but less than with the expanding bullets after expansion.

6.1.2. Imaging

Several studies explore and describe various ways and techniques in which different radiology techniques can be used in a medico-legal and ballistic context. In one of these, the authors describe the present (2019) state of affairs around various imaging modalities in medico-legal context [139]. They conclude that these ever improving techniques are valuable complementary tools but no substitute for an autopsy in most instances. Another paper explains how computed tomography (CT) can be used to evaluate and conserve temporary cavities in soap blocks [140]. Important features such as cavity length and volume can be measured. This method is compared to measuring the same aspects from silicone castings. The authors conclude that the scanning method is faster, more precise and more sensitive that the silicone casting method.

In an extensive and systematic literature study the efficiency and limits of radiology techniques, in comparison to forensic autopsies, is discussed [141]. The authors gathered 86 papers within this scope, published before December 2017 and weight the evidence by the OCEBM grading system. They conclude that radiology represents the present and the future of wound ballistics. However, traditional, micro and molecular imaging techniques require further validation through blind cross-sectional studies with appropriate reference standards. The general level of evidence was found limited. Despite this fact, some recommendations and statements can be derived from the (graded) evidence as to the identification of bullets, detection of gunshot wounds, determination of entrance and exit wounds, trajectories and firing distance.

A forensic radiologist and a forensic pathologist assessed 100 bullet trajectories through the bodies of 21 deceased victims [142]. PMCT footage and an autopsy report were available for all 21 victims. PMCT was found to provide superior information on the presence of metal fragments, internal injuries and the course of trajectories. PMCT provides limited information on the discrimination between entrance and exit wounds but was found to provide added relevant information in over 60% of the studied cases.

CT, flash X-ray, physical dissection and ultrasound were used to study 7.62 × 39 mm bullet trajectories through cadaveric fallow deer hind legs [143]. CT with contrast proved the most effective in adequately mapping the gunshot wounds, though the other techniques might have suffered from the fact that the studied material was cadaveric.

A study explored how well bullets could be characterized with CT [144]. A metal reference phantom was made with various metals. Eleven bullets were imbedded in gelatine blocks and scanned. The bullets' external geometric features could be characterized but not the internal structures (e.g., jackets and cores). Material characterization suffered from severe beam hardening and photon starvation artifacts and was not feasible.

PMCT footage of 80 deceased victims of shooting incidents where evaluated retrospectively by an experienced radiologist, without having knowledge of case circumstances or autopsy findings [145]. Abnormalities were scored per region (head/neck, thorax/abdomen and extremities). Discrepancies between the radiologist's findings and premortem clinical/postmortem autopsy findings were assigned to one of seven classes. The study demonstrated that the radiologist identified mayor firearm injuries and excluded injuries related to the cause of death in other regions when a single body region was injured.

The benefits of using MRI over the more commonly used CT in Postmortem Computed Tomography are discussed and illustrated by a case in which a victim had received two gunshot wounds to the neck [146]. One bullet had exited, while the other (lead .22 Long Rifle) bullet had lodged itself in the cervical spine. The perforating wound was well visible on the CT footage, along with a ring of radiopaque material in the skin around the entrance wound (also visible with other wound), indicating contact shots. Radiological assessment of the second shot with CT was severely impeded by the metal artifacts. MRI allowed clear visualization of the soft tissue injuries of this wound, including the ruptured medulla oblongata, explaining the rapid incapacitation of the victim.

6.1.3. *Impact behavior and effect*

Three papers were published within the subfield of Molecular Ballistics. The term was coined by the authors and encompasses the study of biological trace evidence generated by gunshots. One study starts with a description and history of the field [147]. It continuous with a field guide that focusses on backspatter that can be generated by bullets and ends with a look at future applications and prospects of molecular ballistics. Another study is a feasibility study [148]. Shots were fired at an anatomically correct but standardized skull replica covered with a thin layer of rubber and filled with an internally attached reservoir (with blood, acrylic paint and contrast agent) and gelatine as a brain simulant. The model was tested for usability in backspatter testing. The authors found the results promising. In the third study, contact shots were fired with various blank-firing guns at gelatine blocks [149]. The blocks were doped with human blood and radiological contrast agent and covered with three different skin simulants. The model generated backspatter with all shots. Wound cavities in the gelatine ranged from 1 to 4.5 cm.

In three studies, several combined head models were shot at with 7.62 × 39mm mild steel core bullets under different circumstances. Since the primary focus of these studies was to assess the wounding potential and mechanism of the bullets and not the validity of the simulants themselves, these studies were not listed under the 'Tissue simulants" subsection of the "Wound ballistics" section. The damage of the models was assessed by experienced professionals, to explore the model's feasibility and usefulness in ballistic research. The bullet-induced fracture patterns in gelatine filled polyurethane generic spheres were compared to patterns generally observed by two forensic pathologists in the human cranium over their careers [150]. Overall, comminution was stronger in the polyurethane spheres than observed in military head injuries. The pathologists also made the remark that the fact that the side walls of the spheres had a constant (6 mm) thickness and the fact that thickness of human cranial bones various influences fracture patterns. In another study the fracture patterns of gelatine filled anatomically correct polyurethane skulls, covered with a soft, polymer skin and soft tissue simulant, were compared to patterns observed in two casualties (frontal and left temporal impact) from a military conflict [151]. The models were covered with helmets similar to those worn by the deceased and shot at with bullets at velocities associated with the circumstances of the fatal incidents. Three models were prepared and shot to represent each of the two fatal shots. Comparison of the wounds, fracture patterns and CT-scans revealed positive and negative features of the models. The anatomically correct overall shape, allowing a helmet to be placed was a positive feature. The cut line of the skull simulant (made in two pieces) interfered with fracture propagation. In the third paper, wwo documented fatal headshots, one with a victim wearing an aviation helmet and one shot through a laminated vehicle windscreen, were reproduced with synthetic head models [152]. The anatomically correct synthetic skull models were covered with synthetic skin/soft tissue faces and filled with synthetic PermagelTM as a brain simulant. A military radiologist and a forensic pathologist found the damage to the models to be clinically realistic.

Twenty different configurations of simulated full-copper hollow-point bullets were fired in simulated gelatin blocks in a finite element analysis [153]. The results showed that the penetration and expansion process can be subdivided in four different stages and that the expansion mechanism is extremely sensitive to velocity.

Captive-bolt guns are used to stun cattle before slaughter and are sometimes used in suicides. It was explored whether the 'plug' of skin and bone that is pushed out by the bolt in a cranial shot can penetrate beyond the depth is pushed in by the bolt and acts like a secondary projectile in that sense [154]. The study indicates that it does not. High-speed footage showed that the plug did not move further than the bolt in the skin, bone and soft tissue simulant that was used.

An unusual suicide by an 82-year old male lead to a study on the wounding potential of 4.4 mm BB's and other projectiles in this caliber [155]. Especially the full perforation of the base of the skull after an intraoral shot and deep penetration into the brain raised questions. Based on the ballistic data from a series of test shots the potential penetration depth in human bone was calculated to be 36.4 mm. Test shots from 'hard' contact shots in gelatine generated average wound tracks of 120 mm.

The results of a study suggest that a human wearing HG2 body armor may suffer increased wounding when the armor is perforated by a .223 Remington 62 grain (Federal Premium Tactical Bonded) bullet [156]. No evidence for increased wounding after perforation of the same armor with a 9 mm Luger (124 grain full metal jacket) bullet was found.

The diameters produced by non-deforming projectiles are compared to the diameters produced by deforming projectiles in post-mortem human cranial bone samples [157]. Diameters caused by deforming projectiles were found to be significantly larger. This indicates that not only bullet caliber but also bullet type should be regarded when making statements on the causative bullet that produced a bullet hole in a cranium. In another experimental study on the relationship between bullet caliber and type and bullet defects, .22 Long Rifle (lead round nose), 9 mm Luger (full metal jacket) and .38 Special (lead round nose) bullets were fired through porcine (sus scrofa) humeri [158]. The results of the pairwise comparison of the defect diameters showed that the results for the .22 Long Rifle bullets were significantly different from the 9 mm Luger and .38 Special results. Cortical flaking at the entry side was observed with the 9 mm Luger bullets and found to be indicative for the bullet type (jacketed). Possible effect of bullet velocity was not discussed. Macroscopical lead bullet wipes were observed on the defects caused by the .22 Long Rifle and .38 Special lead round nose bullets.

The various problems that can be encountered when assessing wounds caused by .410 caliber firearms are discussed [159]. Cartridges in this caliber can be fired from both revolvers and shotguns and contain both shot and single projectiles (slugs). Shots were fired at porcine abdominal wall segments. Shot dispersion was greater with revolvers than with shotguns and deposition of sooth was different. Bullet hole diameters of the .410 slugs was similar to .40 S&W, 10 mm Auto and .45 ACP bullets. The wound margins might show signs of the 'vanes' on some .410 slugs and help in making the distinction.

Three studies were conducted on the effect of (UK) military clothing on wound profiles with 7.62 × 39mm and/or 5.45 × 39mm ammunition. In one of these studies, the damage to gelatine blocks with both calibers was studied without clothing, with a single layer of clothing and four layers of clothing [160]. Significant increase in damage was found after the quadruple layer, compared to the other two clothing states with both calibers. This study was repeated, but with using cadaveric fallow deer hind legs as tissue simulants instead of gelatine blocks [161]. The permanent cavities in the legs were visualized using contrast CT scanning. Again, significant increase in damage was found after the quadruple layer, compared to the other two conditions with both calibers. The previous experiment [161] was repeated using only 5.45 × 39mm ammunition, but introducing bullet yaw as an extra parameter [162]. Permanent cavity size was again measured in cadaveric fallow deer hind legs without clothing, with a single layer of clothing and with four layers layer of clothing. Yaw was introduced by firing the 5.45 × 39mm cartridges from a 7.62 × 39 mm barrel. In contrast to the other two studies [160,161], no significant differences were found between the cavities after the three clothing states.

In study [163], the influence of muzzle gas on the temporary wound cavity was studied by firing a total of 72 shots at 12 cm gelatine cubes with .32 Auto, 9 mm Luger, .38 Special and .357 Magnum bullets from a 0, 1, 2, 3, 5 and 10 cm distance. There was a tendency of the cavity volume to increase and of the wound profile change from a tubular to a pear-shape with decreasing muzzle-to-target distance. Generally, the influence of muzzle gas became detectable below 3 cm.

In a retrospective study on the relationship between the muzzle imprint marks around entry wounds with and the shape of the respective firearms, autopsy findings of 30 fatal contact shots were reviewed [164]. In 3 out of the 30 cases, the retractable parts (e.g., slide) were not depicted or only to a minor degree on the skin. Experimental shots on simulated head models showed that maximum bulging of the skin occurs when the retractable parts of the pistol have already travelled backwards to some extent, leaving the stationary parts to block more of the movement of the bulging skin and producing the most pronounced part of the imprint.

6.1.4. *Miscellaneous*

In a study on long bones, the various traits that can be observed when a projectile strikes at or near human long bones is listed [165]. The authors discuss the literature and present several case examples.

In a study on cranial trauma the author gives an overview in a systematic manner of what is currently (2019) known about bullet trauma to the human cranium [166]. The influence of intrinsic (relating to the victim) and extrinsic (relating to the case circumstances) are explained. What can or cannot be said about e.g. the firearms, ammunition, direction of the shot, distance and sequence (in case of multiple shots) from observed cranial fractures is discussed.

Study [167] is a feasibility study, exploring a quick and easy way to test the performance of airguns to a legal threshold limit. The perforation/non-perforation value of a projectile hitting a 0.55 mm thick 1100-H12 type aluminum plate was used as a proxy for testing against the legal power limit of 20 J/cm2 in Taiwan. As expected, the threshold value was found to be significantly affected by the projectile material and structure. Steel ball bearings are recommended for testing 6 mm and 8 mm smooth-bore airguns and spherical lead projectiles are recommended for 4.5 mm and 5.5 mm rifled airguns.

In study [168] a database of 204 images was created, containing photographs of the entry wounds from 50 contact (0 cm), 49 close range (20 cm) and 45 distant (100 cm) shots with a .22 Long Rifle pistol on piglet carcasses. 60 negative controls were added to the database as negative controls. A trained multilayer perceptron based model (MLP_24_16_24) reached an accuracy of 98% in assigning the 204 images to the right class.

The hexagonal profile of a Glock 17 barrel produced hexagonal bullet wipes on various textile fabrics perforated by bullets [169]. The composition of the fabric, cleanliness of the barrel's interior presence of intervening layers of fabric and the type of bullet can all be factors determining whether and to what extent a discernible hexagonal bullet wipe will be produced.

A bullet wipe resembling that of a bullet fired from a firearm was observed around the entrance wound of a field-tipped crossbow arrows with a carbon shaft used in a suicide. This lead to study [170], in which shots with similar arrows were fired at gelatine blocks covered with pigskin. The bullet wipe did not consist of the usual elements found in a traditional bullet wipe but of the arrow shat material, that appears to be transferred by a mechanism of friction.

6.2. *Case reports*

That immediate and total incapacitation does not always occur after a bullet enters a human cranium is supported by a case report, in which a man died as a consequence of two bullets entering through the right temporal region of the head and stopping in the left occipital and left temporal lobe respectively [171]. The case circumstances convinced the authors that both shots were self-inflicted. This implies that the improvised, single shot pistol was loaded a second time with a 7.62 × 51mm short-range cartridge after the victim was already severely injured by the first shot. Due to the nature of the pistol, only a fraction of the cartridges potential muzzle energy was generated.

In case report seven suicides with black powder handguns were analyzed [172]. Wounds were found similar to those produced by other firearms, but with larger entrance wounds and more sooth/unburned powder around the entrance wound and in the wound channel.

A suicide with a semi-automatic pistol, with an atypical entrance location and shooting distance was reported [173]. A man shot himself to death through the bridge of his nose. Shooting distance was large enough to produce an area of 6 × 7 cm of sooth and powder stippling around the entrance wound. All case circumstances indicated that the wound was self-inflicted, but from an unusually large distance.

Another case report describes an as of yet under-reported danger of deploying electrical weapons (Tasers) by police forces [174]. The authors found 131 incidents where an electrical weapon was deployed. Fifty-three of these resulted in a shooting incidents after (attempts to) gaining control of an officers electrical weapon.

In a retrograde analysis a 38-year old man had apparently died from a thermal runaway of the lithium-ion battery of his modified e-cigarette [175]. The thermal runaway caused an explosion, propelling the mouthpiece and battery housing of his e-cigarette. The apparatus entered the face of the victim below the nose and was retrieved from the cranium at autopsy.

A case report describes defects to the skull of a deceased female that were probably caused by a metal probing rod by members of a search party [176]. They probed the soil where the (dismembered) body was hidden. The defects resembled small caliber bullet holes. There were no bullet tracks in the brain, no exit wounds and no bullets retrieved in the cranium. This indicated the probe as the source of the defects, instead of bullets.

In a double case report, the two mechanisms of two different anti-tank weapons, that caused accidental deaths, are explained [177]. The first weapon was a counter mass type (Panzerfaust PzF3), expelling a mass in the opposite direction as the warhead. A 22 year old male was hit in the torso by the counter mass. The abdominal organs were covered with a thick layer of the metallic gray counter mass material. The second fatality was caused by the jet expelled from a rocket (Swiss Army 83 mm rocket tube 80), and to a lesser extent from the ignition cartouche that was expelled from the back of the launcher. The hot gasses from the jet had caused third degree burns, as well as a wound channel that had sought the path of lowest (tissue) resistance through the body.

The injuries of a multiple victim terrorist attack are described [178]. The victims had been shot with 7.62 × 39mm assault rifles and were exposed to explosions. The secondary blast injuries from shrapnel as well as the bullet wounds are described.

In an extraordinary case a 4 g, steel tipped 5.56 × 45mm bullet had fragmented in the head of a young female without producing an exit wound after an (apparent) self-inflicted gunshot wound [179]. The authors had some difficulty reproducing the shot with simulants for human bone and brain tissue. The most likely explanation for the lack of an exit wound was a ricochet on a hard piece of bone at the base of the skull.

Spagnolia and Kemp describe a fatal shot of a man, aiming at a bear but accidently hitting his partner that was being mauled by the bear [180]. In another description of a hunting accident, a man was hit and killed by a bullet that had first perforated a pair of binoculars that he wore around his neck [181]. The authors tried to reproduce the shot with a bullet that had ricocheted, but failed. Destabilized and decelerated bullets after ricochets failed to perforate binoculars, leading the authors to conclude that the deceased died as he result of a direct shot.

Two papers both describe two fatalities with an unusual use of firearms [29,82]. Khau and Melinek presents two cases in which persons were killed with atypical, multiple projectiles [182]. In the first case a ‘piggyback’ screw was fired along with a bullet. Caliber, make and model of the used firearm was not recorded. In the second case, three .38 Special wadcutter cartridges had been inserted in a .45 ACP caliber pistol. When the bottom cartridge was ignited, three wadcutter bullets and two .38 Special cartridge cases were fired and retrieved from the decedent’s body. The other paper describes a case in which a rusted and obsolete Lefaucheux (pinfire) revolver was used in a suicide [183]. The bullet failed to perforate the skull. Cause of death of the decedent was hanging. The second case in paper describes a suicide of a person that shot himself fourteen times in the frontal, temporal and parietal region of his head. Only one of the bullets eventually entered the cranial vault and caused death. Because of the number of shots, and the fact that the revolver contained three fired cartridge cases, the eight-shot cylinder of the Arminius .22 Long Rifle revolver must have been reloaded at least two times.

The sequence of events of a high-profile cold-case are described [184]. The author describes how the retrieved ballistic evidence and case circumstances recorded after the murder of US president J.F. Kennedy fit in the scenario of three shots, fired from behind with a 6.5 mm Carcano rifle. Several aspects of the case that were not fully understood at the time and are often misrepresented today are caused by the atypical wound ballistic behavior of the 6.5 mm bullets.

7. Training material and books

SWGGUN provides an outline to guide the development of a training program for forensic firearm and toolmark examiners [185]. It provides the elements they consider essential or recommended, and includes the following main areas of consideration: New Examiner Training Guidelines, Forensic Science Technician/Laboratory Aid, NIBIN Technicians Training Guidelines, and Continuing Education for Trained Examiners.

The previously unpublished book *Firearm Identification* by Calvin Goddard is now published by Neal Edward Trickel and reviewed by Luke Haag who proclaims this required reading [186]. He mentions that the book describes the early development of the firearm examination discipline and goes on to provide advice on note-taking, report writing, trial preparation and trial testimony. He also provides information on how the book can be purchased.

Eric Warren reviews a book about criminologist Luke S. May, who was a practicing firearm examiner ten years before Calvin Goddard formed the New York’s Bureau of Forensic Ballistics [187]. The book *American Sherlock: Remembering a Pioneer in Scientific Crime Investigation* was written by Evan E. Filby and describes May’s early life and family, his desire to use science to solve crimes, his desire to educate people about forensic science, and his WOII military service [188].

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