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Preventing miscarriages of justice: A review of forensic firearm identification

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ABSTRACT

The role of a firearm examiner is wide ranging, involving tasks that require scientific understanding in aspects of chemistry, physics and biology. This article aims to provide a critical review of the key scientific principles and practices specifically involved with forensic firearm identification and to discuss how misidentifications have resulted in cases of injustice. Implementation of quality assured examination practice, demonstration of individual examiner competence and more objective methods of reporting are being adopted by firearm examiners and laboratories to address some of the criticisms relating to subjectivity and standardisation inherent within the discipline. The impact of these changes is outlined and further recommendations are made for both examiners and legal professionals to minimise the potential for future injustices involving firearms evidence. Latest research in the field is cited, continuing to support the theory and use of firearm identification as admissible evidence in court.

1. Introduction

Between 2008 and 2009, a number of reports were published [1–3] regarding the position of forensic science, current issues and the recommendations that need to be made in specific forensic disciplines going forward. Of these, the National Academy of Science (NAS) report [2] has been the most widely cited reference, especially referred to by legal professionals and the media, to criticise and undermine work undertaken by forensic practitioners when applying their scientific interpretations and discipline knowledge to casework in the pursuit of justice. In particular, this report identified concerns regarding the scientific underpinning of pattern recognition based disciplines such as fingerprints, firearms and questioned documents. These fields were highlighted due to the perception that there were limited published research and documentation to support the validity and reliability of the science and the interpretations made following forensic analysis.

In response to the NAS [2] report, the American Society of Crime Laboratory Directors (ASCLD [4]) identified the two fundamental issues highlighted by NAS; 1) the lack of standardisation of procedure across laboratories within disciplines and 2) the need for more resources, education and training for practitioners to carry out casework. Both of these issues are typically caused due to the lack of stable and sufficient funding in the United States (US). However, these issues apply in other countries worldwide and are significant causes of miscarriages of justice (Section 2), negatively impacting confidence in forensic evidence presented in court. The ASCLD [4] response therefore highlights the need for experts in the forensic community to be fully prepared to answer questions in the courtroom and provide evidence to document, justify and support the scientific underpinning and validity of the analytical methods utilised within their disciplines.

Other organisations, such as California Association of Criminalists (CAC [5]) also responded to the NAS report, with only non-expert reports such as the National Association of Criminal Defense Lawyers (NACDL [6]) predominantly agreeing with the NAS [2] report outcomes. The ASCLD response [4] highlights that to change these perceptions the discipline experts need to engage and collaborate with non-experts, such as legal professionals, to communicate the science underpinning our fields. Although, to achieve a successful outcome this engagement needs to be a two way process. Professionals using information provided by subject experts need to ask the right questions to ensure their understanding of the capabilities and limitations of the science and interpretation supporting casework is presented in an unbiased way to those in the courtroom, especially jurors.

One of the most basic and fundamental issues experienced by this field is the common misuse of the term 'forensic ballistics' to holistically cover the three core disciplines; forensic firearm examination, firearm identification and ballistics. These three areas are quite separate scientific concepts for which different articles could be written. Forensic firearm examination covers the examination of firearms to evaluate their forensic value and establish their functionality. Forensic firearm identification involves the comparison of fired ammunition components to test fired exemplars from a suspected firearm. Ballistics relates to the motion of the projectile from the time the ammunition is fired until

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the moment it comes to rest. Ballistics is further sub-divided into three key areas; internal (everything that happens to the projectile before it leaves the weapon), external (the motion of the projectile as it is travelling through the atmosphere) and terminal ballistics (the motion of the projectile once it comes into contact with matter of any kind). Intermediate ballistics is sometimes considered as an additional component of ballistics that covers the motion of the projectile just as it exits the muzzle of the barrel until it escapes the flow of gases and enters free flight. The identification of gunshot residue (GSR) as coming from firearm ammunition using analytical chemistry techniques such as scanning electron microscopy and energy dispersive x-ray (SEM EDX) is an additional area of expertise sometimes considered within 'forensic ballistics'. Firearm examiners are typically not qualified to identify primer particles as being GSR, however, they may be asked to interpret GSR evidence from unburnt and partially burnt gunpowder to estimate shooting distances.

The field of firearms and ballistics is extensive and truly multidisciplinary, requiring the firearm examiner to be knowledgeable and demonstrate depth of understanding across all three core sciences (chemistry, physics and biology) and apply mathematics to compare, analyse, interpret and link shooting related incidents. Typical tasks that a firearm examiner may be asked to carry out and be called upon as an expert witness are summarised in Table 1. However, it is important to appreciate that a single firearm examiner may not have the training and experience to carry out all of these roles due to the broad nature of the discipline. Tasks associated with firearm examination and function testing, legal classification and firearm identification may be considered the more common skills. Shooting incident reconstruction and serial number restoration may be considered as specialised areas of the field.

There are numerous recommended textbooks [7–11] designed for reading by both laypeople and experienced examiners, which discuss each of these scientific areas in significantly greater depth. The purpose of this article is therefore not to summarise those already written, but to provide a critical reflection on the causes of miscarriages in justice (Section 2) in the area of forensic firearm identification (Section 3) and discuss how professionals are trying to minimise the occurrence of these occurring in the future (Section 4).

2. Miscarriages of justice

Miscarriages of justice are undoubtedly damaging to the lives of those wrongfully convicted, the victim of the crime as well as the families, friends and associates of these parties. In comparison to the number of those correctly and successfully convicted for the crimes they have committed, known injustices are typically infrequent. The criminal justice system and criminal proceedings involve a number of key parties who all have a role to play in ensuring that the outcome is appropriate to the gathered evidence and intelligence presented in the courtroom. Expert witness evidence is only one element of this wide network of individuals. The judge, lawyers (both prosecution and defence) and importantly the members of the jury (if applicable) are all pivotal and responsible for reducing the probability of a miscarriage of justice occurring, however, this chance will never be eliminated. The judge should act as gatekeeper to ensure only appropriate expert witnesses present admissible evidence and legal counsel need to ensure they do not make assumptions about the work undertaken by the expert. When undertaking cross-examinations counsel should fully question the procedures and outcomes presented and should examine the expert's training, experience and competence prior to and during proceedings.

Over recent years there has been more emphasis and importance realised in the legal community about the requirement for them to become educated and understand the science underpinning forensic evidence. The jury however, do not have this luxury and therefore it is critical that those involved with cross-examination and presentation of expert testimony in court provide opportunities for experts to communicate the necessary science effectively to laypersons. Such communication needs to be to an extent whereby each juror sufficiently understands the evidence, how it has been interpreted and the significance of the interpretation in the context of the case. Jurors get limited opportunities to clarify their understanding of scientific evidence and therefore it is vital that legal counsel ask expert witnesses the right questions to ensure that jurors correctly interpret and weight the information presented to them by both the prosecution and defence.

Due to the limitations of firearms evidence (Section 3), a specific person under suspicion for a crime cannot be attributed by analysis of firearms evidence alone. This means that information provided by firearms evidence is typically corroborative rather than conclusive; there must be other forms of physical or intelligence-based evidence to increase the probability that one particular individual was more likely to have committed the crime than another. Each case of miscarriage of justice may therefore involve a number of contributing factors that resulted in an incorrect verdict, not just related to the interpretation of firearms evidence. For example, in a case where a suspect weapon is recovered and can be test-fired for comparison against recovered crime

Table 1
Tasks potentially requested to be undertaken by a firearm examiner.

Task	Purpose(s) of task
Firearms classification	Identify the legal classification of a firearm (or component) within the local region's firearms legislation to determine whether any charges should be brought by law enforcement for the possession of a firearm
Function testing	Determine whether the firearm is functioning as per manufacturer's design, whether it has been modified or converted, deactivated or reactivated and/or the capability of accidental discharge
Firearm restoration	Restore a firearm to its functional order so that the weapon can be test-fired
Serial number restoration	Recover obliterated serial number(s) on the firearm components, which can determine the date of manufacture, and trace the current and previous owner of the firearm
Test-firing	Create fired ammunition components (e.g. bullets and/or cartridge cases) from a known firearm for reference and forensic comparison purposes
Forensic firearms identification	1. Identify whether fired ammunition components recovered from a crime scene have been fired from a specific suspect weapon by comparing to known reference samples test-fired from the weapon 2. Determine the number of firearms used in a shooting incident 3. Link crime scenes together by comparing fired ammunition components (evidence samples) from multiple scenes
Firing angle determination	1. Identify the angle of the projectile impact (e.g. using bullet hole or ricochet mark) 2. Identify the direction of the projectile impact 3. Determine the possible firing location
Muzzle-to-target distance determination	Determine how far away (range) the muzzle of the gun was positioned from the target/victim by comparing known results from simulated crime scenes
Trajectory analysis	1. Estimate the range of fire and thus determine where the projectile (e.g. bullet) may be located 2. Determine the firing location 3. Establish whether the firing location is consistent with the terminal location of the projectile 4. Confirm or refute eyewitness testimony

scene evidence, forensic firearm identification and shooting incident reconstruction can only identify the tool (i.e. specific firearm) and manner in which the shooting incident occurred respectively. The interpretation of this evidence cannot solely be used to determine when the incident occurred and/or identify the individual who did the shooting—this would require additional expertise in DNA (deoxyribonucleic acid) or fingerprint evidence together with other corroborative evidence and intelligence from other sources e.g. CCTV (closed circuit television), eyewitness testimony etc.

With respect to criminal cases involving firearms evidence there have been a number of successful appeals resulting in quashed convictions. There have also been instances where convictions have been quashed due to the recovery of new firearms evidence or request for further testing of evidence not originally requested by the investigation. These cases have typically been associated with four aspects of firearms evidence; legal classification of a weapon as a firearm, forensic firearm identification, identification of gunshot residue and bullet lead analysis. The scope of this article only considers firearm identification.

Understanding the root cause of miscarriages of justice involving multiple types of evidence are not well discussed in literature and can be complex to determine, even after reading transcript summaries. In the media, injustice is frequently reported as unreliable or flawed ballistics evidence yet they typically provide no explanation for why the evidence was deemed unreliable. Such claims may also be misreported as the major cause when there may have been other major factors involved when reaching an incorrect verdict. Cates [12] summarises the 1989 case of Troy Davies vs State of Georgia highlighting 'unreliable ballistics evidence' as the cause of the injustice and also mentioning errors in eyewitness testimony. However, it is possible that during the decision making process the original verdict was reached by more heavily weighting eyewitness testimony rather than firearms evidence.

Instances where miscarriages of justice have primarily resulted from incorrect forensic firearm identification are illustrated by casework undertaken in a number of US police crime laboratories including Detroit [13,14], Boston [15] and Houston [16]. Initial review of the Boston crime laboratory identified that 10% of 200 sampled cases resulted in a misidentification of a specific weapon to the recovered scene evidence. Although, due to the corroborative nature of firearms evidence one should not assume that those cases of misidentification actually resulted in any miscarriages of justice; there is of course the potential for there to have been some. Without having direct access to the evidence and trial transcripts in each of these cases, the author cannot go into further detail about specifically how these misidentifications impacted in each case outcome. Investigations within each of the three crime laboratories typically found issues predominantly arising from insufficient training and experience of the individuals conducting forensic firearm identification. Without appropriate depth of understanding regarding the scientific theory that underpin firearm identification and the impact of a wide range of variables influencing the ability to identify firearms, there is a much higher probability of an individual making an incorrect conclusion regarding firearms evidence. Training and experience of forensic firearm examiners is therefore of critical importance to accurately interpret and compare firearms evidence and these aspects will be further discussed in Section 3.

Over recent years there have been criticisms made regarding the variability in methods used in casework and potentially overemphasised strength of the conclusions made by examiners 'to the exclusion of all others', potentially resulting in miscarriages of justice. However, improvements in standardisation of analysis procedures, reporting and training in expert witness testimony have started to address these concerns and improvements are continuing to be implemented (Section 4.4). It is important that examiners follow the laboratory's standard operating processes in routine casework. However, there are times when general protocols are insufficient or inappropriate and additional testing or variations in protocol are required. In such cases it is imperative that the method employed is fully documented and justified so that the records can be subject to peer-review during criminal proceedings. Lack of disclosure of evidential findings and/or incomplete recording of examination methods and interpretations can understandably raise questions over reliability and accuracy of evidence presented leading to appeals and writs of habeas corpus, as demonstrated by Bernal vs Dretke [17,18].

Any instance of miscarriage of justice will taint the reputation of the use of relevant scientific evidence and put into question the reliability of the opinions presented by the majority of very experienced and fully trained individuals in that field. Humans are and should be at the heart of all final conclusions regarding forensic analysis and interpretation of evidence. Even when technology and consistent procedures are used to support their conclusions, human input will have been necessary to setup equipment, carry out the procedure and make judgements based on prior experience and knowledge, therefore the outcome has some potential to be impacted by error and/or bias, no matter how small or tolerable. Jayaprakash [19] highlights that miscarriages of justice are typically a major consequence of human and system errors and therefore professionals should focus on addressing and minimising these issues rather than undermining the concept of individuality and uniqueness (Section 3.1), which is inherent in forensic firearm identification. However, experts should continue to deepen current understanding, demonstrate the scientific foundations of firearm identification, improve the method by which conclusions are drawn and fully acknowledge the limitations and significance of their interpretations when applied to casework (Section 4). The evolving nature of science, also means that as our understanding and knowledge continues to expand it may be inevitable that interpretations made in the past, may upon reflection, be seen as too significant/conclusive or unfortunately proved incorrect. This limitation should not cause growing or emerging disciplines, including forensic firearm identification to be deemed inadmissible in court, just that when conclusions are communicated to laypersons the capabilities and limitations of the evidence should be appropriate to ensure the correct weighting and significance is assigned in the decision making process.

3. The firearm identification process and the firearm examiner

Modern forensic firearm identification is principally concerned with comparing the surface contours of two components of ammunition created during the firing process to establish if they could have been fired from the same firearm. In a firearm, a component part (of harder material) operates as a tool that transfers gross (class characteristics) and fine (individual characteristics) features (toolmarks) to the comparably softer ammunition surface. Toolmarks can be created by either impression (perpendicular compression between two surfaces) and/or striation (impression plus lateral movement between two surfaces; also known as engraved) and the differential importance of class and individual characteristics in the process of identification are further explained in Section 3.1.

Table 2 summarises the possible range of conclusions that may result from a comparison between similarly fired ammunition components as proposed by The Association of Firearms and Tool Mark Examiners (AFTE). Conclusions are achieved by observing these characteristic surface features using a standard examination method for firearm identification outlined by the Scientific Working Group for Firearms and Toolmarks (SWGGUN [20]), which comprises of four stages:

1. Evaluation—class characteristics are observed by eye between two specimens; if these agree then the comparison moves into stage 2, if they do not agree then the specimen is eliminated as having come from the same tool.
2. Comparison—comparative examination of the subclass (see AFTE Glossary [21] and/or individual characteristics between specimen through pattern matching using a comparison macroscope (or microscope).

Table 2
Definitions for range of conclusions related to the AFTE theory of identification [21].

Conclusion	Definition
Identification	Agreement of all discernible class characteristics and sufficient agreement of a combination of individual characteristics where the extent of agreement exceeds that which can occur in the comparison of toolmarks made by different tools and is consistent with the agreement demonstrated by toolmarks known to have been produced by the same tool.
Inconclusive	A. Agreement of all discernible class characteristics and some agreement of individual characteristics, but insufficient for an identification. B. Agreement of all discernible class characteristics without agreement or disagreement of individual characteristics due to an absence, insufficiency, or lack of reproducibility. C. Agreement of all discernible class characteristics and disagreement of individual characteristics, but insufficient for an elimination.
Elimination	Significant disagreement of discernible class characteristics and/or individual characteristics.
Unsuitable	Unsuitable for examination

3. Conclusion—determination if there is sufficient agreement between only the individual characteristics to render one of the ranges of conclusions.
4. Verification—peer-review process to evaluate the conclusions of the first examiner as outlined within a laboratory's quality assurance policy [22].

The AFTE theory of identification [21] is principally a spatial relationship comparison of the reproducible, three dimensional (width, height/depth, curvature) unique and individual surface contours within two toolmarks to determine whether they have been produced by a common source (tool). Moran [23] provides an overview to the changes and development of the theory of identification as it relates to toolmarks, a theory that has been reviewed and clarified repeatedly since the 1980s and should continue to be studied and researched. If there is sufficient agreement in class and individual characteristics this is commonly referred to as a match, however, do not misinterpret the term 'match' as the two toolmarks being 100% identical (Section 3.1). To contextualise how the range of firearm identification conclusions can provide corroborative evidence and intelligence to an investigation, Table 3 summarises the capabilities and limitations of firearm identification.

The science underpinning firearm identification is more complex than some other forensic disciplines due to the wide range of variables that require consideration in the production of toolmarks used in the comparison and identification process. The type and material composition of both firearm and ammunition used, the quality and consistency of the manufacturing processes, the history of the weapon and ammunition since production and even the environmental testing parameters may all influence the ability of firearm components (i.e. tools) to create reproducible toolmarks on the surfaces of fired ammunition. It is beyond the scope of this article to explain the scientific mechanisms related to each of these variables and research cannot be expected to be publishable for every ammunition–manufacturer combination that may ever exist when many thousands of firearm models and ammunition lines are in existence. Therefore, examiners may be required to investigate, test and evaluate the evidence on a case-by-case basis and this process is substantially more difficult when the firearm is not recovered. Unfortunately, a 'no gun case' is a common occurrence in shooting investigations worldwide as criminals have become more aware of the capabilities and limitations of forensic science to investigate crime. No gun cases are often only used for intelligence purposes so the implication of errors are less significant than cases involving evidential analysis and

Table 3
Comparison between the capabilities and limitations of forensic firearms identification for the AFTE range of conclusions.

Conclusion	Capabilities	Limitations
Identification	Unique identification of suspect weapon to discharging the fired ammunition components using individual characteristics	The identification of fired ammunition components from a crime scene can only be identified to a firearm when a weapon is recovered for test-fire comparison
	Comparison between multiple corresponding fired exhibits can determine the type and number of weapons that were discharged at the crime scene when no weapon is recovered for test-fire comparison (inferred weapons)	Identifications cannot routinely be made between the abraded surfaces of shot fired simultaneously through a smooth bore shotgun barrel as individual characteristics in abrasions are not reproducible
	Comparison between corresponding fired exhibits from multiple crime scenes can identify a crime series by linking to an inferred weapon	Cannot determine who fired the weapon, when the weapon was fired or how long fired ammunition components or firearm has been in the location of a crime scene
	Identification and comparison of reproducible individual characteristics on the surface of plastic wadding fired through a smooth bore shotgun barrel may be specifically identified to that weapon	It is not always possible to determine the make and/or model(s) of the guns used to fire ammunition components recovered from a crime scene
Inconclusive	Some evidence to support the suspect weapon may have fired the ammunition components and insufficient evidence to eliminate	Insufficient individual characteristics to support identification to a specific weapon
Elimination	Elimination of suspect weapons from discharging the fired ammunition components using class characteristics	In cases where the weapon was recovered at some point after the crime occurred, eliminations based on comparison of individual characteristics to test-fired samples may be incorrect if there was opportunity for the component surface to naturally change and wear so that identification may no longer be possible (note, in most cases examiners are more likely to render an inconclusive conclusion than an elimination, especially if damage appears to be deliberate in nature)
	Elimination of suspect weapons from discharging the fired ammunition components using individual characteristics	
	Determination of a smaller range of firearms capable of firing the ammunition components recovered from crime scenes	
Unsuitable		Firearms evidence cannot be used to eliminate or identify the firearm that may have discharged it
		Firearms evidence lacks firearm produced toolmarks e.g. lead core, lead fragment or ogive portion of a bullet

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interpretation that may reach court. The interpretive approach utilised in casework (e.g. Bayesian; see Section 4.3) may then be chosen depending on the nature (intelligence or evidential basis) of the information attained.

Most firearm–ammunition combinations demonstrate reproducible toolmarks for comparison when consecutive test-fires are produced. The number of test-fires may be two or three, or another arbitrary number determined only through examination and testing. Variability in reproducibility of toolmarks may be due to the condition of the firearm and/or ammunition surface being utilised when the toolmark is created. To produce a repeatable pattern for comparison it is important that all the possible variables are consistent as possible. Reference test-fires from suspect weapons for comparison to evidence samples therefore should fire where at all possible, the same type and specification of ammunition. If the manufacturing consistency and tolerance of the ammunition (including cartridge dimensions, weight of bullet, composition and quantity of combustible propellant etc.) is poor this may adversely affect the quality and reproducibility of the toolmark created on each cartridge of ammunition fired and hence more than three test-fires may need to be created to undertake the comparison.

Heard [7] theorises a scenario where only 20 individual characteristics (striations) match in a firearm identification comparison and calculates that the chance of another tool creating a toolmark with these same matching striations is 1 in 193,730,707,456. Such probabilities are considered by AFTE as a practical impossibility [21], although this statistical model has not yet been applied to a real case for evaluation and review. Typically, as long as the firearm component such as a barrel has not been damaged by corrosion or some other external influence, for example cleaning with a steel rod or heavy use of steel wool then a fired bullet is likely to have sufficient agreement to match the 100th fired component to the 1st. Research has demonstrated with firearm components that are particularly resistant to wear that the 5000th [24] and even 10,000th [25] test-fired component can be matched to the 1st. Research using traditional comparison methods have also been supported by quantitative comparisons for 500 consecutively fired cartridge cases [26]. However, in other types of firearms or when firing different ammunition the variation in individual characteristics may be sufficient to make identification questionable after only 50 fired cartridges [27]. There is also no guarantee that a firearm will produce usefully reproducible marks from one shot to the next, meaning that not all fired ammunition components may be able to be identified to the original firearm source. Such variation in the degree of degradation in toolmark quality and reproducibility will in part depend on the materials and manner in which the weapons are used and the resulting wear of the firearm components. Table 4 illustrates how a number of factors may affect the rate of component wear. Firearm examiners should therefore consider undertaking such investigative comparisons as part of their training and/or continuous professional development to assess the extent of variability in individual characteristics, especially when casework questions the use of a firearm since the crime occurred.

Laypersons cannot be expected to know the influence all these variables that may need to be considered and referred to when making their interpretations; hence why an expert is required. A body of published research [28–30] has been compiled identifying some key research in the field using not only the traditional 'more subjective' approach, but also employing a variety of empirical, more 'objective' approaches (Section 3.2). All the studies to date have ultimately supported the theory of identification, however, for those working outside the discipline it is not correct to assume that firearm examiners believe this body of published work is sufficient. As part of the examiner's role, research is frequently conducted to test scientific theory and hypothesis related to particular casework scenarios using appropriate scientific methods. Such research is especially important when encountering casework where examiners observe new or unexpected phenomenon or features that require more background investigation before conclusions can be drawn. Due to case load and prioritisation of undertaking casework, unfortunately much of the practice-led research does not necessarily get disseminated through formal written publication. Key information does get disseminated through other mechanisms, such as verbal communication in annual training seminars, conferences and practitioner forums, although this dissemination method will not be as extensive.

Regrettably, rigorous scientific method and quality assurance processes have not always been employed by all firearm examiners over the discipline's history and this has been demonstrated by emerging miscarriages of justice. Unfortunately it is likely that these cases will still continue to emerge from the past. However, due to improvements in procedure, accreditation and training (Sections 3.3 to 3.5) since 2010, recent case outcomes are hopefully less likely to be questionable. To reduce erroneous evidence being admitted into the courtroom, the author advises laypersons not to make assumptions on the work undertaken by an expert and to promote dialogue between legal counsel and expert witnesses at the earliest opportunity.

The NAS [2] study had a significant impact and has encouraged practitioners and academics to actively increase the number of research publications specific to the field of firearms and toolmark identification. Fully qualified and experienced examiners are being motivated to pursue self-funded research-based Masters and PhD programmes in forensic firearm identification in their own time for example, to increase publication and research outputs in the field. The author believes published research outputs will continue to increase over time, especially due to the relatively recent growth in number of collaborative projects and committees involving key stakeholders of both practitioners and academics within the field.

3.1. Class and individual characteristics

Firearms are designed to discharge specific types of ammunition and typically each model of firearm produced will exhibit the same gross features known as class characteristics in every firearm produced with this design. In barrels for example, gross features include the calibre or gauge, number of lands and grooves, direction and angle of rifling twist, groove profile and groove depth, which will all be similar. All of these features i.e. class characteristics are transferred through an engraving action to the surface of the projectile (e.g. bullet) as it travels down the barrel towards the muzzle (barrel exit). For any component part that comes into contact with ammunition there are designated class characteristics (Fig. 1) to describe and compare the dimensions,

Table 4
Some factors potentially affecting the speed of change of original manufacturing toolmarks on firearm components.

Factor affecting wear	Example of how the factor could affect wear	Potential influence on speed of toolmark change on component surface
Firearm component material properties	Increased hardness and density of material e.g. gun steel	Reduces rate of toolmark change by increasing resistance to wear
Manufacturing processes	Hammer forging or swaging compresses the material increasing density and hardness	Reduces rate of toolmark change by increasing resistance to wear
Use of the weapon	Fast consecutive firing causes accumulation and increase in temperature inside weapon	Increases wear and rate of toolmark change
Cleaning method of weapon	Use of abrasive cleaning materials	Increases the degree of toolmark change
Deliberate damage	Corrosion due to water; damage due to extreme temperature (fire); damage from tools	Increases the degree of toolmark change

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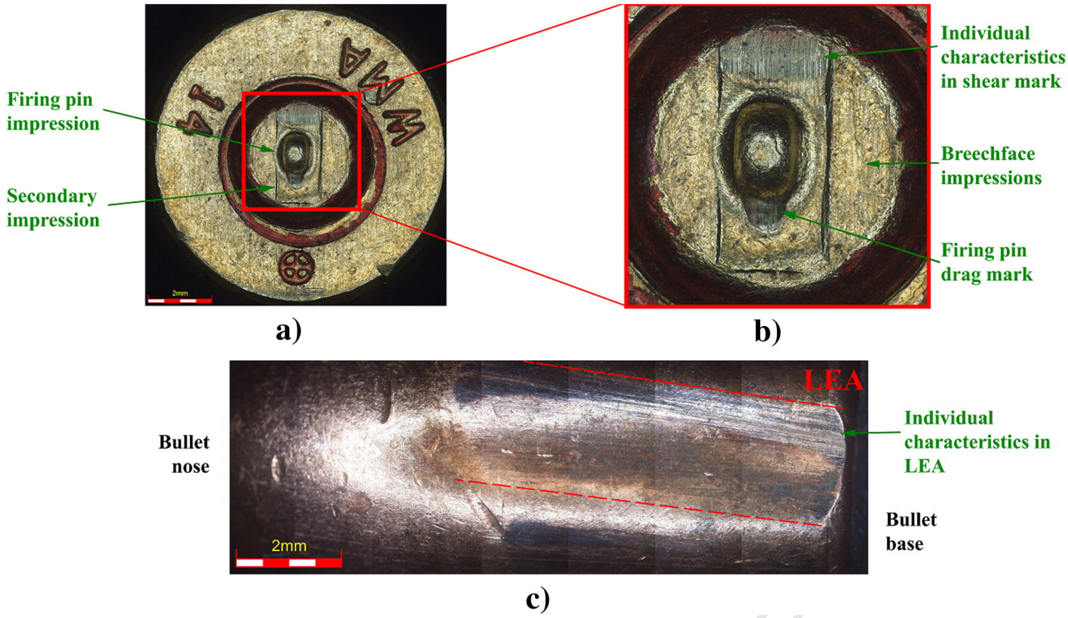

Fig. 1. Annotated images illustrating examples of a) class characteristics and b) individual characteristics on a cartridge case headstamp and c) bullet fired through a 9 × 19 mm Glock 26 semi-automatic pistol.

geometries and relative spatial relationships between these to allow gross differentiation between different firearm models.

The individual characteristics are toolmarks (striations) on the surface of the firearm component that are randomly generated by the natural wear of the manufacturing tool surfaces. The number, width and depth of striations within any toolmark area on a firearm component surface are therefore specific and unique to each component part produced. The toolmarks present on the firearm component surface are then transferred by impression and/or engraving actions to the ammunition surface(s) during the firing process. Over the lifetime of the component the manufacturing toolmarks will be randomly modified to some extent by wear depending on the use of the firearm. As these striations are random, the special pattern and dimensions are unique and thus allow for differentiation between separate firearm components manufactured by the same tool.

This means that two weapons of the same manufacture and model cannot be differentiated by comparing the class characteristics alone. Individualisation and identification can only arise through the comparison of corresponding individual characteristics. The greatest similarity between individual characteristics may be visible when comparing the toolmark surfaces of consecutively manufactured components. However, there is still sufficient uniqueness between the striated toolmarks to differentiate consecutively manufactured surfaces [31]. This may be due to the manner of interaction between the ammunition and firearm component surface and/or the processes involved in modern manufacturing methods. For example, finishing processes may be applied to the surface after cutting or forming the component parts [32], which generates further individualising toolmarks on the surface and thus similarity of striated or impressed toolmarks on consecutively manufactured components is further reduced.

In forensic firearm identification, the transfer process of the manufacturing toolmarks (individual characteristics) on the parent component surface to the fired ammunition surface(s) is an important consideration. The chemical and physical composition of the ammunition surface will affect the degree of transfer of the individualising toolmarks. The individual characteristics observed on the ammunition surface are typically not duplicated exactly from the parent tool surface and are considered as another unique pattern, whilst retaining some of the parent tool's uniqueness. As a result, it is very important to compare like-for-like surfaces where possible when undertaking firearm identification. As mentioned previously, no-one has yet observed the individual characteristics of any two fired ammunition surfaces to be sufficiently similar when fired from different weapons. There have been occurrences where very similar non-class marks have been produced by different guns, but then this is attributed to 'subclass' effects. The potential issue arising here is that there is no clear division of when a striation is categorised as an individual or subclass characteristic. In these instances an examiner should undertake research to determine the potential for subclass to occur using the firearm in question and comment on the evidential strength of the conclusion reached.

A comparison between two different toolmarks knowingly created by the same tool will never result in surface contours that are identical in their surface topography. Vanderkolk [33] explains this variation is natural and expected due to the variability in environmental factors involved with surface interactions and "noisy randomness" in patterns; patterns that are not permanent and will change, albeit slowly or quickly. Thus comparison and 'matching' requires a level of sufficient agreement to allow for some degree of natural variation, which can be achieved by both subjective and objective mechanisms (Section 3.2). The term 'match' in comparison science is therefore not identical and should not be expected to be as such unless one compares exactly the same toolmark with itself. The experience and training of a practitioner and use of a scientific method is therefore important to determine the toolmark surface contours that are reproducible and the contours that result due to natural variation in the interaction between a specific tool and surface pairing. Such evaluation is achieved in practice by comparing multiple test toolmarks after examination of the question evidence toolmark surface. Exposure to very similar, but knowingly different toolmarks allows the practitioner to develop what is sometimes referred to as a 'best known non-match' that allows a practitioner to evaluate the quantity and quality of individual characteristics in questioned toolmarks encountered during casework. However, examiners should remain "conservative when reporting the significance of these observations" [34] when they themselves did not see the specific tool creating the toolmark being observed.

AFTE have categorised the reporting of firearm identification range of conclusions (Table 2) as an identification, elimination or inconclusive with a fourth category stating that the evidence is unsuitable for forensic comparison (for example, the exhibit is damaged and does not exhibit any class or individual characteristics to allow for a comparison).

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Prior to 2012, practitioners in identification based disciplines, including firearm identification, defined the term individualisation to mean the identification of a common source to the exclusion of all others [35], thus reporting an identification in firearms-related casework to the exclusion of all other guns, for example. However, this definition was understandably challenged and forensic identification-based disciplines have since accepted that it is not realistically possible for an examiner or discipline to examine and compare the individual characteristics exhibited by each source (e.g. firearms or tools) in existence within the world. In the case of firearms, it is estimated that there are now well over 875 million firearms in the world [36], therefore sampling within the discipline observed through casework is insufficient to represent truth about individualisation within the entire population. However, due to the naturally random patterns and comparative research undertaken between toolmarks created by consecutively manufactured components, there is support that toolmarks can be differentiated between even within these manufactured components. As a result, there is a high level of probability that toolmarks created by different sources can be differentiated between if the quality and quantity of individual characteristics present in the toolmarks compared is high enough. SWGGUN [30] therefore states that “any individual association or identification conclusion … is based not on absolute certainty but rather on the practical certainty of the underlying (validated) scientific theory”.

Philosophical arguments exist stating there is no such thing as individualisation [37,38], however, Kaye [39] counters some of these statements and highlights that some of the criticisms made of forensic science disciplines are common and inherent in science generally. Chalmers [40] has written a book on the philosophies of what constitutes ‘science’, but underlying this constant philosophical debate is the concept that ‘science’ starts out with an observation which takes significant time (sometimes hundreds of years!) and a body of published and critiqued research to support a fundamental ‘scientific’ principle at any particular moment in time. There is continual movement towards empirical studies to support the hypothesis of general rather than unique individualisation particularly using more objective three-dimensional (3D) imaging and comparison databases (Section 4.2). Saks [41] identifies that whilst the body of available empirical studies is expanded, forensic scientists must be honest about the limitations of the interpretations and information available when applied to casework and the author agrees.

In case of firearm identification, there may be some non-matching striae evident between a test-fired component and its evidence exhibit. Heard [7] states that it is “by experience and training alone that the examiner is able to determine which are relevant and which are non-relevant microstriae”. To evaluate the variability in striae created on fired ammunition components the examiner should visually compare consecutively fired cartridge component from the same firearm under the comparison macroscope, but preferably after examining the crime scene evidence. This could reduce some elements of subjectivity that will be further discussed in the next sub-section.

When comparing unique reproducible striations (striae) on fired bullets and cartridge cases that are known to have been fired from different weapons, some striae will coincidentally align and appear to match from chance alone. However, it has been shown through empirical research that the number of quantitative consecutively matching striations (CMS) observed in two-dimension (no depth considered) is unlikely to exceed a minimum of a single group of eight striations or two groups of five striations [42]. Within every comparison there are likely to be hundred if not thousands of striae that are considered. An examiner should use more than one location on the fired surface; they will compare all forensically significant features available on an exhibit surface to establish not only a level of agreement, but also evaluate any disagreements in the surface contours being compared. Such locations can include multiple consecutive land engraved areas (LEA; Fig. 1) on fired bullets or multiple features on cartridge cases including firing pin impressions, breechface impressions, extractor claw marks etc. Thus when an identification is made, it is usually not the comparison of only one part of the component, but multiple areas and probably arising from multiple firearm components. The probability of the toolmarks therefore being rated as ‘identifiable’ in all of those locations on a single exhibit under comparison, makes the conclusion of an identification more probable, although still not absolute.

3.2. Subjectivity, objectivity and bias

Interpretation and comparison of objects and information includes elements of both subjectivity and objectivity. During an examination and comparison between two objects, the examiner will assess objective measurements of the relative features being observed, however, does not necessarily report these as quantitative data. The examiner uses their training and experience to determine whether individual characteristics under comparison have sufficient agreement for them to be considered as coming from the same source (firearm in this case) or another source. The main criticism in firearm identification is related to the high level of conceived subjectivity associated with pattern matching, which is not supported by objective justification. If subjectivity was not part of this process then anyone could undertake the analysis and thus prior training and experience would not be required [33]. However, miscarriages of justice have demonstrated the effect of lack of sufficient training, inconsistency in comparison process and issues in reporting findings by some firearm examiners. Therefore, efforts are required to increase objectivity and improve consistency in practice and reporting.

Over the last 20 years, more objective methods have been developed and implemented in firearm identification advancing beyond line counting and CMS, quantifying and comparing measureable changes in 3D surface contours by more automated and repeatable mechanisms. Such technological approaches were developed for the scientific field of surface metrology and have been adapted for this specific application. Such high accuracy, high precision techniques are discussed further in Section 4.2 and have been able to provide evidence to objectively support the theory of identification through mathematical comparison algorithms. However, this equipment is very expensive, continuously evolving and researchers are yet to optimise the technology for this bespoke application (Section 4.4). Objective approaches alone are currently unable to meet the subjective interpretation accuracy of complex outcomes achieved by trained experts [43]. It is unlikely that the full capability and widespread incorporation of such objective comparison techniques will meet or exceed that of the expert, meaning these technologies will only aim to support the reliability of examiner's interpretations. Questions relating to potential bias and human error will therefore remain, but can be significantly reduced.

Dror [40,42] has undertaken research into the effect of various types of bias that can affect the subjective nature of forensic comparison for identification. He has identified that some examiners are more prone to bias than others as well as the fact that comparing incomplete or partial patterns has a greater potential to produce variability in the range of conclusions attributed to identification [44]. The work of Dror and others in the psychological sciences has been seen to negatively impact the confidence in forensic comparisons and judges have since excluded forensic evidence from the courtroom due to the potential for bias to lead to erroneous identification. In the majority of routine cases, issues with bias are significantly reduced if the comparison is not complex [45]; complex examples include comparison of fragmented and significantly damaged evidence. Bias-based research is important to improve the expert's understanding of how examination procedures may introduce bias, identify actions that can be taken to reduce the chances of bias occurring and appreciate how bias can potentially adversely affect identifications made during casework [46]. For example, implementing protocol to examine firearms exhibits before test-fired reference samples from suspect weapons. Principally, published research indicates that it is not the science within forensic identification disciplines that

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is necessarily 'flawed', but the psychological manner that humans conceive and compare information that has the potential to affect the outcome of comparative pattern recognition.

The protocol within forensic firearm identification should routinely involve the use of independent peer-review by another firearms expert to verify that the conclusion drawn from any comparison is correct. However, at present, the protocol employed varies between laboratories globally with some employing verification only for identifications. Such verification protocol can again lead to the incorporation of confirmation bias [47] as the peer-reviewer already assumes that the comparison has been classified as an identification. As a measure to reduce the potential for confirmation bias, some laboratory protocols require peer-review across the full range of possible initial examiner conclusions (elimination, inconclusive and identification). In addition, to remain independent, peer-reviewers should not be informed of the initial examiner's conclusion. Such necessary changes in protocol are being employed, but may take years to be common practice worldwide as in many routine cases such action may be an un-necessary finance and human resource [48].

The development and use of forensic comparison databases (Section 4.2) have also been introduced to forensic firearm identification, which can reduce bias to some extent. Automatic database comparisons utilise algorithms in computer software to blindly assess objective criteria and quantitative data between samples electronically stored within it resulting in a ranked list of potential matches. However, humans are still required to undertake the final assessment from a short-list of possible matches so randomisation protocol should be employed to reduce bias resulting from ordinal ranking of the samples [46]. Recent research using competence test sets still supports that more accurate comparative conclusions arise from firearm examiners than using the 'more objective' blind algorithm-based comparison method when sample data is stored electronically within a database [43].

Although the author strongly recommends that subjective interpretation in casework is evidenced by objective quantitative data to demonstrate and scientifically justify the interpretation, at this time, there needs to be some compromise between ideal and realistic approaches. Currently, resourcing and capacity limitations experienced by many examiners across the world mean that they may be unable to meet ideal levels of objective reporting in casework and further improvements need to be implemented to make this more achievable for all. Understandably these advances will take considerable time and funding to ascertain and implementation is typically beyond the control of firearm examiners, but lies with government offices and policy makers [49]. As a minimum there has been a move to improve consistency in quality of forensic practice by introducing procedural standards and laboratory accreditation (Section 3.3) as well as increased requirements for proficiency and competency testing (Section 3.4). However, it should not be acceptable for laboratories to ignore recommendations supported by research from other scientific disciplines.

3.3. Procedural standards and accreditation

The 21st century has seen significant changes in the expectations of many laboratories and their employees to undertake procedures according to national (e.g. Laboratory Accreditation Board of the American Association of Crime Laboratory Directors [ASCLD/LAB]) and international standards of practice (e.g. International Organisation for Standardisation [ISO] 17025 and 17020 for laboratories and crime scene units respectively). The United Kingdom Accreditation Service (UKAS) is a profit based organisation that accredits against ISO, whereas ASCLD/LAB is non-for profit and seeks to provide an enhanced ISO 17025 standards in their accreditation programme. The costs associated with the assessment of such accreditation can be very high and thus not all regions have the finances to acquire such recognition. In addition, conforming to such standards can limit the use of available equipment for research and non-standard (or new) methods of testing and analysis, which may stifle the progress of in-house research in forensic disciplines by practitioners internationally. If a unit/laboratory does not have ISO accreditation this does not mean it is not operating to appropriate standards and practice, just that it has not yet been assessed to be. The policies for employing standardisation of practice vary from country to country, but there are improvements and developments being introduced every year to improve this. In the UK, the Forensic Science Regulator stipulated in the Codes of Practice and Conduct [50] that all firearms and toolmark based examination and analysis should be undertaken in ISO 17025 accredited laboratories by April 2012. Until a body or government places compulsory requirements on all laboratories/units to acquire such accreditation then this will not be sought by all.

To encourage and facilitate dissemination of best practice between practitioners US governments have funded Scientific Working Groups (SWG) in various forensic disciplines e.g. SWGGUN. In 2014, SWGs were replaced by the Organization of Scientific Area Committees (OSAC) to more effectively strengthen the scientific basis of forensic science disciplines in the US as well as create consistent documentary standards and guidelines for dissemination within each discipline. The initiative was established by National Institute of Standards (NIST) and Department of Justice (DOJ) and the OSAC community, comprising of 24 sub-committees [51], is comprised of both experienced practitioners and relevant professionals from agencies, academia and industry. The two relevant sub-committees for the firearm discipline are firearms and toolmarks and gunshot residue.

Accreditation and best practice alone is not sufficient to ensure the accuracy of the interpretation of casework undertaken by examiners, however, UKAS for example, assesses and audits the laboratory or department as a whole to ensure that employees follow the laboratory's standard operating processes and procedures. However, UKAS does not assess individuals specifically to determine whether they carry out the procedures and interpret results competently. This is where qualifications (Section 3.4), training and additional and regular testing of individuals (Section 3.5) are required.

3.4. Higher education qualifications

Employment of firearm examiners with higher education based academic qualifications has been increasing over the last 50 years. The greatest change in provision of such qualifications in forensic science has been since late 1990s where public interest in forensic science increased and higher education institutes (universities) began offering degrees in areas of forensic science, dramatically raising competition for forensic-related jobs. In the field of firearms and ballistics, this change has resulted in the employment of an increasing proportion of entry level technicians and trainee examiners with science degrees (at undergraduate and postgraduate level) thus demonstrating a deeper initial scientific understanding and having some prior experience in undertaking forensically significant research prior to starting work. Interestingly there has also been a significant rise in the number of qualified female firearm examiners being employed in this discipline over the last 10 years.

Heard [7] mentions that there are two best professional qualifications currently offered in the Firearms and Toolmark Examination which involve no 'taught' elements and rely solely on the candidate's (practitioner's) prior training and casework experience in the relevant discipline. Only one is an academic qualification; the UK's Forensic Science Society (now the Chartered Society of Forensic Sciences [CSFS]) Professional Postgraduate Diploma (Strathclyde University) with an optional Masters level research-based Top-Up Qualification (Staffordshire University). The other programme is offered by AFTE and is discussed further in Section 3.5.

Due to the increasing expectation and scrutiny of outcomes from the criminal justice system and the NAS [2] report, very experienced practitioners are seeking further research-based and practice-based

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qualifications in areas of firearms and ballistics to deepen their knowledge and provide new evidence to evaluate and validate the science underpinning this field. Dr James Hamby and the author have been awarded their research PhDs in Forensic Firearm Identification [52,53]. There are now other experienced firearms practitioners pursuing their PhDs specifically focussing on publishing novel research and advanced validation studies to support challenging casework in the firearms arena. In addition, there has been increasing interest from practitioners to collaborate with academic institutions to advance and expand research in this field that is not linked to academic qualification.

3.5. Examiner training and competence

Globally, firearm examiner training is typically undertaken by bringing in external qualified experts to teach courses in the various areas of firearm examination and identification with in-house support through mentoring. There has been some move to create agency funded national programmes, such as the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) funded National Firearm Examiner Academy to try to ensure depth and consistency of training, but they only have funding and capability to train approximately 10 new examiners each year. In addition, a basic electronic training programme was published in 2008 by the National Forensic Science Technology Centre (NFSTC [54]) with National Institute of Justice (NIJ) funding, but this requires continual input and mentoring from a trained examiner to support the training process.

So why is training in firearm identification so important to identify a comparative match? A match is only identified when the number of striations that are dimensionally and spatially comparable exceeds those observed in a best known non-match. The best known non-match is primarily built up during the examiner's training period, but will continue to develop over their career. Training initially involves the examiner comparing the individual characteristics on the surfaces of numerous fired ammunition components from the same known firearm (known match). The individual characteristics on fired samples are then compared to those test-fired from as many other firearms of the same manufacturer and model as well as other manufacturer–model combinations (known non-matches).

The closest non-match comparisons of individual characteristics will typically arise from test-firings generated from consecutively manufactured firearm components. Such components are manufactured with the same tool surface and thus may exhibit the highest chance of subclass characteristics. Subclass characteristics may be confused as individual characteristics as they are striae that are typically very deep and therefore may carry over from one manufactured surface to another. As a result, these striae are not individual to one firearm component and may have the potential to interfere with comparison and identification. However, just because a manufactured component may exhibit subclass characteristics, that does not mean that these toolmarks are transferred to the surface of fired ammunition, especially if the toolmarks are striated and not impressed.

To determine a best known non-match, the examiner is required to assess the natural test-fire to test-fire variability of known matches, differentiate individual characteristics from any potential subclass characteristics in known non-matches and thus identify that the fired sample has come from one specific weapon rather than another. The best known non-match therefore is established when the individual characteristics are sufficiently similar that they could be incorrectly identified as being from the same source without sufficient training and experience, but it is known that the individual characteristics produced have been created by firing from two different sources. Objective computerised methods of examination are unable to identify striae as being subclass or individual in nature, therefore subjective human opinion will always be required to interpret this potential during matching.

The number of comparisons that an examiner needs to undertake to determine a best known non-match is a non-quantifiable amount. The degree of individual characteristic similarity between two sources may vary depending on the manufacturing production of the firearm surface and the type of ammunition being fired. It also depends on the training requirements of the institution and the types of firearms typically encountered during casework in that region. The range of firearms and ammunition (including modern and historic) encountered in casework between regions is likely to differ significantly due to availability, legislation, cost and intended usage. With the vast numbers of manufacturer–model combinations worldwide it is unrealistic for an examiner to be able to compare test-fires from all of these, therefore the organisation may initially focus training on the manufacturer–model combinations that examiners will see routinely in casework, whilst ensuring that all types of firearm and a range of manufacturing methods and ammunition cartridges are observed and compared. The time spent undertaking such comparisons to build up an extensive catalogue of known match and non-match comparisons is typically why firearm examiner training usually takes a minimum of 2 years. Examiners should therefore appreciate the variables that influence quality and reproducibility and what constitutes a best known non-match to enable firearm identification. Without such training using appropriate scientific operating processes and good working practices it is likely that an individual would not be deemed competent to undertake casework unsupervised.

Lack of quality training and use of sub-standard practice has resulted in misidentifications and miscarriages of justice. The recommended way to demonstrate, monitor and rigorously test individual examiners' skills is through the use of competency testing that simulates casework, usually at additional cost to employers and/or employees. Currently, there is no compulsory requirement for examiners to undertake competence assessments or be retested within a specific timeframe [55]. Some demonstration of assessment of staff proficiency and competency is recommended and usually required within standard operating processes to achieve accreditation, but this assessment could be internal and/or external. Ideally examiners should be undertaking annual competence-based assessments that are more robust than proficiency assessments and are assessed by both internal and external organisations to ensure independence from the results.

One externally assessed method demonstrating both written and practical competence is offered by AFTE through their NSFTC assessed certification programme in the examination and identification of three areas; toolmarks evidence, firearms evidence and gunshot residue (GSR) evidence. A practitioner is only eligible to take the test if they are a regular AFTE member or higher, have a total of 5 years of experience in the area of certification and from 2014, also have an undergraduate degree [56]. Post-nominal letters of TM, FA and/or GSR-AFTE illustrate an individual successfully completing the AFTE Certification in each of the disciplines respectively. Successful candidates are listed on the AFTE certified members list [57] and the individual must be recertified every 5 years. A limitation to this programme is that elements of assessment are undertaken in the US, so for international practitioners this option is not typically affordable. Also, there are additional competencies undertaken by firearms professionals that are not currently offered through this programme. Other proficiency tests are available from independent companies, such as collaborative testing services providing ISO 17043 accredited tests, that try to fill some of this gap and will ship internationally; however, these still do not cover all key competencies of firearms professionals.

Internationally, forensic science provision has seen increasing levels of privatisation resulting in an increasing number of independent practitioners or smaller laboratories operating across a range of forensic disciplines. These practitioners or laboratories are not able to develop regular internal proficiency or competency testing and therefore seek sources of external testing. Such privatisation occurred in the UK in 2012 with the demise of the Forensic Science Service (FSS). As a result, there was an increasing need for the UK-based professional body, The Chartered Society of Forensic Sciences (CSFS; formerly the Forensic Science Society) to provide external competency testing in a range of

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skills undertaken by practitioners such as firearms professionals that was affordable to those working in the UK and covered relevant competencies in their discipline. The Society is an international professional body dedicated to forensic practitioners in all disciplines with members in more than 60 countries. In 2014, the Society was awarded a Royal Charter demonstrating the organisation's importance, constancy and longevity working in this particular field [58]. Consequently, the Society can now provide experienced practitioners the Chartered title of CSFS membership, which demonstrates an individual's high level of professionalism and conduct in their discipline. As a route to becoming a Chartered practitioner in a firearms related discipline, from 2015 UK practitioners can sit Certificates of Professional Competence (CoPC) in legal classification, firearms function testing, comparison microscopy and/or GSR analysis using SEM/EDX microscopy to demonstrate practical competence in court. Practitioner members with either the Accredited or Chartered status are also listed on the CSFS Register of Accredited Forensic Practitioners [59].

In 2014, UK practitioners also highlighted the need to bridge the gap between education and training and therefore the CSFS have worked with forensic practitioners and academics to create the Pre-Employment Assessment of Competence (PEAC). The PEAC is a competence based written and practical assessment in crime scene and/or laboratory skills to demonstrate day-one competence of individuals seeking to work in the respective fields. The PEAC aims to act as an independent assessment centre to allow employers to assess the competence and potential of a perspective employee prior to employment and commencement of further training. The first PEAC assessments commenced in June 2015 and the outcome of evaluation of this programme will be published at a later date.

The organisations highlighted in this article, including AFTE, OSAC and CSFS are only some examples of those dedicated to continuing to develop the standards of practice and competence of practitioners and professionals working in the firearms and toolmark discipline. Recommendations and requirements of practitioners and their employers are continuing to develop each year and the author is sure that confidence in the use of forensic evidence analysis in court will be re-established with continuing collaboration and research, dissemination and standardisation of good working practices and developing methods of reporting (Section 4).

4. Advances in firearm identification

One of the frequent misperceptions regarding research in forensic disciplines is that research is not undertaken frequently. Within the field of forensic firearm identification, AFTE published a number of articles [60,61] to compile and highlight research undertaken in the field as one way to begin addressing the criticisms highlighted in the NAS report and National Research Council (NRC) report [1] respectively. In addition, Mattijssen [62] reviews the latest research across the discipline between 2010 and 2013 and the SWGGUN Admissibility Resource Kit [30] continues to be populated by AFTE members.

Investigation and research is typically a key component of undertaking casework. In the UK, for example, the former government funded FSS had a research and development budget to undertake novel studies in forensic departments. In comparison to a researcher or academic, publishing research is not identified as a key role for practitioners. Due to high caseloads and other priorities, results, analysis and outcomes from scientific investigations frequently undertaken by practitioners are typically not externally published. At times, it may also be important not to disclose research outcomes into the wider public domain. In addition, articles may be published in a wide range of scientific journals due to the interdisciplinary nature of research in this field and different target audiences for practitioners and academics. Fragmented dissemination of the literature typically makes research inaccessible for practitioners. The most accessible source of literature for practitioners is available through the AFTE journal, however, some criticise the journal's peer-review process due to variability in depth and standard of scientific reporting within some of the articles published.

To some extent the NAS [2] report has had a positive impact on practitioners' opinions regarding the value and importance of publishing their research. There has been some noticeable increase in the encouragement to support research in some agencies and laboratories to further build the body of knowledge and evidence underpinning pattern recognition-based disciplines. There have also been increased levels of engagement between academia and industry over recent years to undertake collaborative research and share knowledge between scientific disciplines. However, significant human and financial resources are required to be successful in further increasing research outputs in forensic disciplines and to ultimately establish these fields as ‘scientific’ in the minds of critics. The principal areas of continuing and expanding research related to firearm identification focus on undertaking validation studies to provide error rates (Section 4.1), utilising 3D surface metrology systems and bespoke mathematical automated comparison algorithms (Section 4.2) and incorporating Bayesian statistics into reporting to support evidential findings (Section 4.3).

4.1. Validation studies and error rates

As previously discussed, there is appropriate research published using both subjective and objective methods to support the theory of identification. Bunch et al. [63] therefore identify that the relevant question for the courts and the science relating to firearm identification is not whether toolmarks are unique or not, but “Can a trained human or machine reliably distinguish between toolmarks made by one tool versus toolmarks made by other tools?”. Such a question can be answered and empirically determined with comprehensive and blind validation studies to quantify the potential for incorrect conclusions (error) using quality assured samples created from known sources. To confidently estimate error rates within casework, those sitting the test must be fully qualified and complete testing blind with limited context regarding the aim of the test to reduce bias in their conclusions. Practitioner testing should also reflect casework where no prior assumptions are made about the samples under comparison. In addition, test makers should not know which test set has been sent to which candidates (double blind) and should design the test to reduce confirmation bias typically evident in proficiency tests when the candidate may have come to assume that all the unknown samples must come from the reference samples provided in the test. Examples of good practice using appropriate validation study design were employed during research undertaken by Kerkhoff et al. [64] reporting no misleading conclusions in a limited test set of 10 cases and Fadul et al. [65] producing an error rate (where an examiner made a misidentification) of less than 1.2 %.

The NAS [2] study made criticism that there are insufficient validation studies undertaken in the field of firearm identification. Prior to the NAS report, Nichols [66] summarised some of the work related to validation that had been undertaken to this date using the traditional comparison macroscopy approach. Since then, further research has been funded, especially in the US, to increase the extensiveness of validation studies in the field [65] together with more objective validation studies utilising 3D imaging methods [67,68] from samples fired through consecutively manufactured components. The outcome from these studies continues to support the theory of identification and uniqueness using individual characteristics to identify toolmarks to a specific common source i.e. a specific gun. Error rates associated with each study vary, but are typically less than 4% [62,63].

The type of manufacturing and surface finishing processes employed when creating a particular firearm component impact on the quantity and quality of the toolmarks left on the surface, which can be ultimately transferred during the cycling and/or firing process. The shallower the gross features of class characteristics and the finer the individual striations, the more difficult the comparison and potential for larger error rates to occur [67]. However, the nature of the examination should render a conclusion as inconclusive if the examiner feels that the individual characteristics are insufficient to make an identification.

Certainly over the last 5 years there has been increasing change to the research design and methods have been conducted in firearm identification. Stroman [69] discusses and recommends the most appropriate research designs for use in the field moving forward. The author agrees that further research incorporating comprehensive, declared tests with multiple blind elements within the validation methods and an open design (i.e. unknown samples may not all match known reference samples for comparison) should continue to be undertaken to more sufficiently represent the diversity of factors and levels of complexity seen in firearm identification based casework. Unfortunately, due to the time consuming and potentially expensive nature of research, publications using such recommended research methods will not immediately become available. The single blind research publications currently available still have value in supporting the ability of examiners to correctly undertake casework, although the limitations in the research design need consideration when used. In the author's opinion there is insufficient published scientific research to generically rule firearm identification evidence as inadmissible in court.

4.2. 3D imaging, databases and comparison algorithms

Since 1980s databases have been researched, developed and implemented for electronically storing, searching and comparing class and individual characteristics important for firearms investigation and identification. The most prevalent examples include the General Rifling Characteristics (GRC) Database and Integrated Ballistics Identification System (IBIS). With increasing technological advancements since the invention of the comparison macroscope and application of the striagraph [70], firearm identification databases such as IBIS have moved away from comparing 2D images of toolmarks on fired ammunition components alone and incorporated non-contact sensors to acquire 3D surface topography data and complex comparison algorithms to automatically compare fired evidence samples. Brinck [71] established that comparison capabilities were significantly enhanced by using a combination of 2D images and 3D surface data within correlation algorithms. NIST have also designed and produced standard reference materials (SRM) from real fired bullets and cartridge cases; SRM 2460 [72] and 2461 [73] respectively, which are used to establish laboratory protocols for gathering 3D data in a quality assured manner that meet ISO 17025 requirements [74].

Bespoke firearm identification comparison software has been written for specific 3D data formats generated by imaging with different surface metrology technologies [75]. IBIS Trax3D, EvoFinder and ALIAS are examples of commercially available 3D comparison ballistics imaging systems that provide firearm examiners with increased examination objectivity and time-efficiency compared to using a comparison macroscope alone. Surface features can be orientated and contextualised in a wider field of view, depth profiles of contours under evaluation are objectively compared with numerical data and software may allow virtual exaggeration and magnification smaller features of interest. However, comparison algorithms cannot automatically determine whether the samples compared have been generated by the same source, they can only evaluate the similarity of the surfaces compared. Human interpretation is required to make the final comparative conclusion, as previously discussed.

Some laboratory protocols use firearm identification systems as a screening tool to improve workflow efficiency. Representative samples of test-fires and evidence samples may be routinely imaged by trained technicians and stored in the laboratory's database for past, present and future comparison. When comparisons are run during the screening process, the firearm examiner may only review the top 10 or 20 closest database entries, but a confirmed identification can only be achieved when the examiner physically compares the samples under the comparison macroscope. Use of screening protocols may result in missed opportunities by only examining the top 10 or 20 comparisons. However, limitations arising from missed opportunities usually negatively impacts current investigations rather than leading to miscarriages of justice.

The success in solving gun crime and implementing such expensive objective systems in casework is not down to using technology alone [49]. Organisations such as ATF, Federal Bureau of Investigation, Interpol and National Ballistics Intelligence Service (based in the UK) utilise IBIS for example to share and compare data and intelligence both in their laboratories and even internationally through Integrated Ballistics Information Networks (IBIN). King et al. [76] has evaluated the use of IBIN in the US demonstrating variable results in effectiveness depending on how the system was integrated into investigation and casework protocols. Although, not all countries or regions will deem searching of international databases a routine requirement [77]; more targeted searches based on intelligence are currently recommended in Europe for example. The NRC [1] publication focusses in detail on the development and potential for forensic ballistics databases although the value of adopting shared databases is likely to remain debated for some time whilst inter-agency policies are adapted, implemented and evaluated in each region. Objective and automated advancements in imaging and comparison will hopefully further reduce potential for human error resulting in misidentifications, but examiner training, experience and competence will continue to be fundamental, especially as the majority of laboratories do not have the financial resources to implement such technology.

4.3. Statistical reporting to support evidential findings

When fired cartridge cases and/or projectiles are recovered from scenes and there are insufficient individual characteristics to permit the conclusion of identification, then inconclusive is likely to be reported. However, an inconclusive conclusion has not lost all its probative value to a case. The likelihood ratio (one element of Bayes' rule) can be used to measure the relative strength of support for two opposing propositions considered by the examiner in casework; a suspect weapon or another unknown weapon as being responsible for firing the evidence exhibits. For example, Bunch and Wevers [78] use class characteristics of the firearms evidence and known frequencies of rifling characteristics in the GRC database to estimate the likelihood ratio and determine which end of the 'inconclusive' range the evidence is more likely to support; more inclusive or eliminatory. However, the GRC database does not reflect all the possible examples of class characteristics in existence worldwide. Approximately 4700 combinations were contained in the 2008 version of the database, but this number is continuing to increase annually. In addition, the exact number of weapons that have ever been produced for each manufacturer–model combination is unknown and neither is the precise number or frequency of weapons of these characteristics present in the region 'local' to the crime scene [78]. As a result, any calculation of likelihood in this manner should utilise an over estimate of the true frequency of weapons in the population [79] to ensure the strength of the interpretation is not too strong for the evidence provided. More useful frequency data can be incorporated into likelihood ratio calculations by processing information contained in laboratory case submission records, resulting in more reliable and precise estimates of probability assigned to analysis findings. However, acquisition of such data from records is not typically a routine, fast or automated process at present and further work needs to be undertaken to facilitate this statistical approach.

New Zealand have been using the calculation of likelihood ratio to estimate the probability of uncertainty and support their reporting of interpretations from evidence in court reports for over 20 years across all forensic science disciplines. The European Network of Forensic Science Institutes (ENFSI) have recently published reporting guidelines [80] to encourage European forensic science laboratories to use likelihood ratio calculations to support their interpretations and the guidelines have been adopted for firearms evidence in The Netherlands

[64], for example. Currently, the US generally appears to be trailing in the routine use of likelihood ratio in firearm identification based casework. Bunch and Wevers [78] discuss the advantages and disadvantages of using the likelihood ratio approach in firearm identification casework for both class and individual characteristics. They conclude with logical scientific support for using the approach above the traditional method so the examiner can utilise all information available to them during the examination. However, the paper highlights the importance for continual training in the use of the likelihood ratio, not only for firearm examiners and legal professionals but also for juries to ensure the approach is understood and utilised correctly in both the laboratory and in court. Research in other disciplines such as fingerprint analysis has also demonstrated that using statistical assessment tools in the examiner's decision making processes did not appear to influence the overall comparison conclusion, although using such tools did improve the accuracy and consistency of the features selected for comparison [81].

4.4. Continuing developments and research

Over the last 20 years there have been some significant advancements in knowledge and technology applied within this field, but this is not sufficient and should not stagnate. Research into non-contact 3D imaging technologies and comparison algorithms are continuing to advance objective approaches for firearm identification. NIJ for example are funding Cadre Research Labs to develop a novel gel-based sensor and NIST to create an open-access research focussed resource called the Reference Ballistic Tool Mark Database [82] to enable those without imaging equipment to develop more advanced pattern recognition algorithms. In an ideal world, co-operative polices should be in place to enable all practitioners to access a ballistic identification system to provide objective evaluation and comparison of firearms evidence in casework. Unfortunately implementation of such policies is unlikely to be achievable in the foreseeable future, therefore research into less-expensive objective methods using traditional comparison macroscopy is also required. Such research could be facilitated through more extensive collaboration between research-based institutions and practitioner laboratories.

Improvements in technology have not only been made in the ability to examine and compare firearms evidence, but also in the manner in which firearm components are manufactured. Advances in modern manufacturing processes to increase both manufacturing tool and firearm component lifetime, accuracy and precision have resulted in finer individual characteristics that are significantly more challenging and time consuming for examiners to compare. Changes in manufacturing approach require particular research attention to evaluate the potential for subclass characteristics and reproducibility of individual characteristics that may influence the ability of examiners to accurately conclude a positive identification during casework. Any research requires funding for both equipment and manpower to improve the perceived reliability of this scientific discipline, however, funding sources worldwide vary significantly and funding available is becoming even more competitive with other forensic disciplines having priority.

Although some countries have sought quality assurance accreditation by implementing standard examination procedures and providing firearm examiner training programmes to improve consistency of practice, these approaches have yet to be employed worldwide. To reduce miscarriages of justice globally these practices need to be shared and individuals should be required to undertake frequent casework simulated competency assessments to demonstrate their ability in drawing correct conclusions for identifications, inconclusives and eliminations. With increased knowledge and scrutiny in the past, present and future judicial processes it is likely that reported incidents of miscarriages of justice will rise from earlier periods where sub-standard practice was employed in casework. It is therefore vital that the field continues to develop and adopt objective reporting practices to support their subjective interpretations through the use of quantifiable methods of comparison and/or statistical models of reporting in casework, such as calculation of likelihood ratio.

5. Summary

Miscarriages of justice arising from firearms misidentification are typically a result of inadequate standard protocol and/or incorrect interpretation of the firearms evidence rather than 'flaws' in the scientific underpinning. The practice of firearm identification through pattern matching is inherently a subjective process and consequently potentially prone to bias and human error, as in many other scientific processes. However, more objective quantitative methods should continue to be developed and implemented in casework to support subjective interpretations and improve consistency in reporting of the discrete range of conclusions. Such approaches include application of statistical reporting methods and application of non-contact surface measurement techniques.

Research has demonstrated the importance of training in firearm identification for a number of years before conducting casework unsupervised and regular demonstration of individual competence is recommended. Laboratory accreditation should also be sought to assess appropriateness and consistency of operational protocol and protocol should incorporate an independent peer-review process for all conclusions related to casework. In addition, examiners should seek expert witness training to develop skills in explaining the scientific knowledge underpinning the discipline and communicating the manner in which conclusions were obtained to laypersons in court. It should not be acceptable for an examiners to say 'I am the expert you just have to trust me' nor laypersons to make assumptions about the work undertaken by an expert in any field.

Responsibility for evidence admitted into the courtroom resides with all those involved in the legal process. Law enforcement is responsible for building a case against a suspect by collating intelligence and utilising expert evidence in the investigative process. The judge should act as gatekeeper to determine whether a forensic practitioner should be considered an expert witness and deem the evidence admissible in the courtroom. Legal counsel should be concerned with asking the right questions of witnesses both before the court case and during proceedings to ensure the judge and jury (if relevant) understand and correctly weigh up the evidence presented to them. Expert witnesses should ensure that they interpret evidence in a thorough, independent manner remaining impartial whether they are presenting evidence for the prosecution or defence.

Hopefully this article has helped to provide a critical review of the causes of and potential solutions to minimise instances of miscarriages of justice associated with forensic firearm identification evidence. For the future, it is recommended that legal professionals seek education and training from experts in relevant scientific disciplines to become more aware of the capabilities and limitations of evidence types they may encounter. Literature written and courses delivered by those without such scientific expertise unfortunately seem to propagate misunderstandings and misconceptions within forensic disciplines rather than aiming to recognise and clarify issues when they arise. The author therefore wants to request that legal professionals start communications with subject experts and appointed expert witnesses at the earliest opportunity to help them prepare critical and relevant questions when undertaking cross-examinations. Through two-way correspondence legal counsel can gain further insight into the specific procedures employed and conclusions drawn in individual cases to develop efficient cross-examination strategies and facilitate effective communication of the scientific evidence to laypersons in the courtroom. Creating suitable learning environments in court will inevitably assist the jury or judge to appropriately evaluate and weigh the evidence presented to reach a correct verdict in the first instance. If this approach to criminal proceedings evolves successfully this will ultimately build confidence in

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the scientific reliability of forensic evidence as well as the criminal justice system.

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