Investigative Frontiers Integration of Science Transforming Criminal Investigation

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Weapons of Evidence: Scientific Methods in Firearms, Toolmark, and Ballistic Investigation

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Abstract

Firearm, toolmark, and ballistic investigations are critical areas of forensic science that can provide evidence that is scientifically reliable in the reconstruction of firearm related crimes and for the judicial decision making process. This review discusses the scientific principles and fundamental techniques used in firearm examination, tool mark identification, and ballistic investigation, and their forensic value. It covers the classification of firearms, the examination of evidence, gunshot residue analysis, comparison microscopy, three dimensional surface analysis, and the use of advanced laboratory techniques to examine toolmarks on the firearm. The review also examines the use of automated ballistic identification systems, digital imaging, and the new technologies that are increasingly improving the objectivity and effectiveness of forensic examinations, like artificial intelligence and machine learning. Current issues, such as evidence variability, standardization, examiner bias, and technological validation, are also discussed. The assimilation of scientific approaches and state-of-the-art technologies remains to enhance the reliability, accuracy and evidentiality of the firearm and toolmark investigation in modern forensic practice.

Keywords; Firearm examination; Toolmark identification; Ballistic investigation; Gunshot residue; Forensic science.

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1 Introduction

"Weapons of Evidence" is an expression of the fact that firearms and physical evidence are both used in the course of forensic investigations. A firearm can cause injury or death, but it can also provide unique scientific information that can aid in identifying the gun, help establish the chronology of events, and link suspects, victims and crime scenes. Together, bullets, cartridge cases, toolmarks, and gunshot residue are silent witnesses that can capture microscopic and physical features that help forensic scientists piece together the events of a firearm-related crime.[2]

Firearm, toolmark and ballistic investigation is a specialized sub-discipline of forensic science that involves the scientific examination, identification and interpretation of evidence related to firearms, ammunition and tools involved in the commission of a crime. Firearm examination involves the identification of firearms, ammunition, cartridge cases and gunshot residue, while tool mark examination involves the microscopic impressions or striations created when a tool comes in contact with a surface. Ballistic investigation involves internal, external, and terminal ballistics, examining the behavior of a projectile before, during, and after it's fired and using that information to make connections between a firearm, ammunition, victims, and crime scenes.[3]

Scientific examination of firearms has grown from a simple visual comparison of weapons, bullets, and cartridge cases into sophisticated methods that include three-dimensional surface topography, digital imaging, automated comparison systems and statistical interpretation. Firearms evidence is critical in the investigation of homicide, armed robbery, terrorism and other violent crimes and is used to identify a firearm based on the ammunition components and/or toolmark recovered from the crime scene. Firearm examination, toolmark examination and ballistic investigation work synergistically to create an all-encompassing scientific approach to crime scene reconstruction and the presentation of credible forensic information to a court.[4]

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[2] E. J. A. T. Mattijssen, W. Kerkhoff, R. Hermsen, and R. A. G. Hes, "Interpol review of forensic firearm examination 2019–2022," Forensic Sci. Int. Synerg., vol. 6, p. 100305, 2023, doi: https://doi.org/10.1016/j.fsisyn.2022.100305.

[3] R. P. Sebuan, "IMPLEMENTATION OF FORENSIC BALLISTICS LABORATORY ACTIVITIES AND STUDENTS' PERFORMANCE: INPUTS FOR AN ENHANCED INSTRUCTIONAL DELIVERY," GET Int. Res. J., vol. 2, pp. 109–123, 2024, doi: https://doi.org/10.5281/zenodo.13748440.

[4] N. Scurich and T. D. Albright, "Assessing the foundations of forensic identification evidence: A critical examination of proficiency test design and results," PNAS, vol. 123, no. 27, pp. 1–9, 2026, doi: https://doi.org/10.1073/pnas.2528192123.

2 Scientific Methods in Firearms Investigation

Firearms investigation involves the scientific analysis of firearms to determine the weapon, match a bullet or cartridge case to a particular gun, reconstruct gunshots, and interpret gunshot-related evidence found at a crime scene. The examination process involves an understanding of firearm mechanics, microscopic comparison, material science and analytical chemistry to make reliable associations between firearms and criminal incidents. Modern firearm investigation has evolved from visual comparisons of the weapon to instrument-based techniques and methodologies that are more objective and supported by advanced imaging equipment, laboratory protocols and validated analytical techniques. In the study of homicides, armed robberies, terrorist attacks, accidental shootings and other gun crimes, these scientific techniques play a key role, while at the same time ensuring that the forensic findings are scientifically valid and admissible in court.[5]

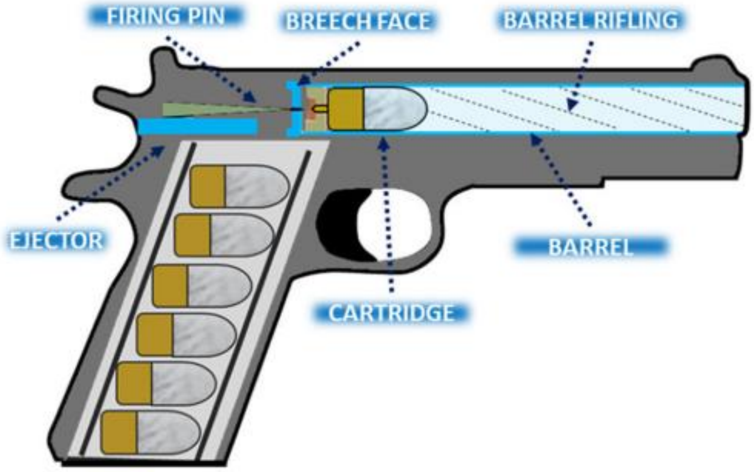

Figure 10: Main components of a firearm that leave traces on cartridge cases (Breech Face, Firing Pin, Ejector, Cartridge, Barrel) and projectiles (Barrel, Barrel Rifling)[6]

[5] S. Shil, D. Dey, T. C. Singh, S. Aayush, H. K. Pratihari, and A. D. Roy, "Investigation of country-made firearms in forensic relevance," Interactions, vol. 245, no. 280, 2024, doi: https://doi.org/10.1007/s10751-024-02124-4.

[6] L. Guarnera, O. Giudice, S. Livatino, A. B. Paratore, A. Salici, and S. Battiato, "Assessing forensic ballistics three-dimensionally through graphical reconstruction and immersive VR observation," Multimed. Tools Appl., vol. 82, pp. 20655–20681, 2023, doi: https://doi.org/10.1007/s11042-022-14037-x.

A. Firearm Classification and Operating Mechanisms

Firearms are usually designated into handguns, rifles, shotguns, or automatic/semi-automatic based on their design, characteristics of their barrel, and how they operate. They work by a series of operations where various parts of the firearm interact with the ammunition, which include loading, chambering, firing, extraction, and ejection. These mechanisms allow a forensic examiner to understand the functioning of a firearm, the type of weapon used to create marks, and the meaning of the marks created during the firing process.

B. Firearm Evidence

Typical evidence associated with a firearm consists of a firearm, fired bullets, cartridge cases, unfired bullets, fragments of the bullets, shotgun pellets, wads, and gunshot residue. These exhibit micro- and physical features which help the investigators determine the type of weapon used, reconstruct the shots and tie multiple crime scenes or suspects together through scientific comparison.[7]

C. Scientific Principles of Firearm Identification

Firearm identification relies on comparison of class characteristics (calibre, rifling pattern, number of lands and grooves) and individual characteristics resulting from minute irregularities formed in the manufacturing of the firearm and its use. These special markings are transferred onto bullets during firing and are the scientific basis for correlating ammunitions components with a specific firearm.

D. Laboratory Examination Methods

The examination of bullets and cartridge cases from a crime scene is primarily done through comparison microscopy, which involves comparing the recovered items with ones produced by a controlled test fire of a suspected firearm. Test-fired ammunition is checked for similarities in firing pin impressions, breech face marks, extractor marks, ejector marks and rifling impressions. Three dimensional imaging and digital comparison technologies are taking the place of the traditional microscopic examination to enhance objectivity and reproducibility, especially as the number of comparisons increases.

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[7] D. H. Kaye, "Firearm-mark Evidence: Looking Back and Looking Ahead," PennState Dickinson Law, 2018, [Online]. Available: https://insight.dickinsonlaw.psu.edu/fac_works/364

E. Gunshot Residue (GSR) and Shooting Distance Determination

Gunshot residue is a mixture of inorganic and organic particles that come out of a gun and onto the shooter's hands, clothing, target, and other surfaces. The scanning electron microscopy and energy-dispersive X-ray spectroscopy (SEM-EDS) techniques are commonly used for GSR analysis. The process of shooting distance determination involves studying the soot patterns on the inside of the bullet hole, the powder tattoo, and the distribution of residue around the bullet hole to determine the distance the gun had been fired and the circumstances surrounding a shooting incident.[8]

3 Scientific Methods in Toolmark Investigation

Toolmark investigation is an invaluable part of forensic science which involves the examination and comparison of marks made when a tool comes in contact with another object. This kind of evidence is often found in burglary, forced entry, vehicle theft, homicide and vandalism crimes. The scientific background of toolmark examination is the impression of unique microscopic characteristics that occur in tool materials at the surface during manufacture and are then transferred to the surface of the material under contact. The new approach to toolmark investigation integrates classic comparison microscopy with advanced 3D (3 dimensional) surface metrology, which enhances the objectivity, accuracy and reproducibility of forensic toolmark comparisons. The toolmark analysis, therefore, offers valuable associative evidence in helping to relate the tools to the crime scene and reconstruct the activities of the criminals.[9]

A. Types and Characteristics of Toolmarks

Toolmarks are usually divided into impressed, striated and combination marks. Impressed marks are formed by the impact of a tool on a softer material, while striated marks are formed by the sideways movement of a tool over a surface, creating parallel shallow scratches. Combination marks are mixed, having characteristics of both types. Every toolmark will have class and individual characteristics, which are due to the design and manufacture of the tool, and

[8] C. Weyermann et al., "(Re-)positionning forensic research & development for increased impact in gunshot residue examination," Forensic Sci. Int., vol. 375, 2025, doi: https://doi.org/10.1016/j.forsciint.2025.112560.

[9] A. S and R. G. SUGITHKUMAR, "FORENSIC TOOLMARK ANALYSIS OF 3D IMAGING APLLICATION IN BURGLARY CASE," INDIAN J. Leg. Rev., vol. 5, no. 14, pp. 338–349, 2025, doi: https://doi.org/10.65393/PNUY4319.

microscopic imperfections, wear, corrosion and accidental damage that have been caused during use.[10]

B. Scientific Basis of Toolmark Identification

The scientific principle of tool mark identification is based on the assumption that no two tools have the same microscopic surface characteristics. These special features are imparted to the contact material during contact, leaving the material with consistently repeated marks that can be compared to marks made by a suspected tool. The correspondence of class characteristics and individual characteristics is assessed by the examiner, based on standard comparison criteria and quality assurance procedures, to determine if the questioned mark was made by a particular tool.

C. Evidence Collection and Preservation

To ensure the integrity of the toolmark evidence, proper collection and preservation is critical. If possible, the entire object with the tool mark should be recovered, not altering the surface that was marked. High quality casts are made with a silicone based impression material and detailed photographs are taken, if removal is impractical. When the chain of custody is carefully packaged, handled, and maintained, contamination and damage to the microscopic features that must be analyzed in the lab are minimized.

D. Laboratory Comparison Methods

Conventional laboratory examination utilizes comparison microscopy, which allows for the side-by-side viewing of questioned and test toolmarks to compare similarities between the micro striations and impressions. Recent developments have seen the introduction of three-dimensional (3D) surface analysis, such as optical profilometry and confocal microscopy, which are able to quantitatively measure surface topography and improve the objectivity of toolmark comparisons. In modern forensic laboratories, these digital methods are used in conjunction with traditional microscopy for statistical evaluation, to enhance reproducibility, and to aid in the evaluation of traditional microscopy techniques.[11]

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[10] J. Patteet and C. Champod, “Striated toolmarks comparison and reporting methods: Review and perspectives,” Forensic Sci. Int., vol. 357, p. 111997, 2024, doi: https://doi.org/10.1016/j.forsciint.2024.111997.

[11] M. Cuellar, S. Gao, and H. Hofmann, “An algorithm for forensic toolmark comparisons,” Forensic Sci. Int. Synerg., vol. 9, p. 100543, 2024, doi: https://doi.org/10.1016/j.fsisyn.2024.100543.

4 Scientific Methods in Ballistic Investigation

Ballistic investigation is a sub-field of forensic science which involves the examination of the evidence produced by the firing of a gun or weapon to establish the direction of fire, association between the gun, ammunition and shooting scene, and the reconstruction of a shooting incident. Ballistic investigation is a field of science that combines the knowledge of physics, engineering, and forensics, allowing investigators to use these principles to explain the flight path, direction, and impact of bullets, and to develop a time line of events in a firearm-related crime. The use of digital imaging, automated ballistic identification systems and computational reconstruction techniques has greatly enhanced the accuracy and efficiency of ballistics exams, and they have become essential tools in today's criminal investigation.[12]

A. Internal, External, and Terminal Ballistics

There are three parts to ballistics: internal, external, and terminal. Internal ballistics deals with the action taking place within the gun from the time the propellant is fired until the time the projectile is fired from the gun. This includes the generation of pressure and the acceleration of the bullet. External ballistics is the study of the flight of a projectile after it has left the muzzle, taking into account the factors of gravity, air resistance, and the effects of the environment on the path of the projectile. The interaction of the projectile with the target, such as penetration, deformation, fragmentation, and energy transfer, is studied in terminal ballistics to understand the characteristics of wounds and the behavior of the impact.

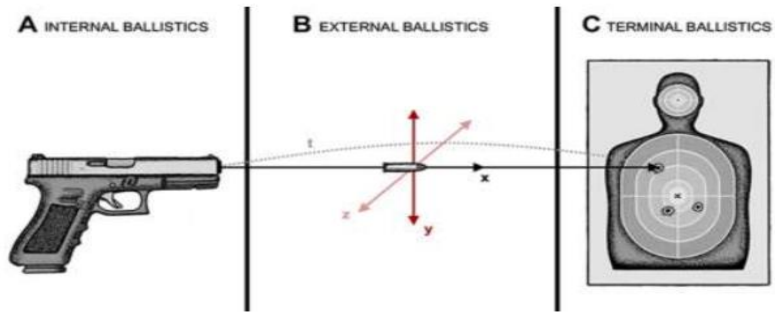

Figure 11: Phases of ballistics[13]

[12] S. V, "Forensic Ballistics and Shooter Profiling in Firearm Crime Investigations," Int. J. Recent Dev. Eng. Technol., vol. 15, no. 06, pp. 943–955, 2026.

[13] I. M. M. Cunha et al., "Analysis of Terminal Ballistics on Medical Forensics: Criteria and Challenges in the Forensic Area in Brazil," Int. J. Res. Publ. Rev., vol. 5, no. 2, pp. 2159–2169, 2024, doi: https://doi.org/10.55248/gengpi.5.0224.0535.

Table 5: Types of ballistics, focus area, and key factors

Type	Focus Area	Key Factors
Internal Ballistics	Inside the barrel	Propellant burn rate, pressure curves, barrel harmonics
External Ballistics	Projectile in flight	Drag coefficients, Coriolis effect, gyroscopic stability
Terminal Ballistics	Target impact	Penetration depth, energy transfer, wound ballistics

B. Bullet Trajectory Analysis and Crime Scene Reconstruction

Bullet trajectory analysis uses the path of a bullet to determine the shooting direction and the shooter's position and sequence of the shots. Investigators utilize trajectory rods, laser alignment device, photogrammetry, and three dimensional crime scene documentation to examine bullet holes, impact marks, ricochets and the location of projectiles recovered. The combination of these observations, autopsy results, and witness testimony helps forensic scientists determine the truth of a firearm-related incident and assess alternative hypotheses about the event.[14]

C. Ballistic Imaging Systems and Databases

Modern forensic laboratories use automated ballistic identification systems like Integrated Ballistic Identification System (IBIS) and National Integrated Ballistic Information Network (NIBIN) for the comparison of digital images of bullets and cartridge cases. These systems examine microscopic markings in detail, quickly locate a potential match and connect firearms-related evidence found in separate crime scenes. Automated databases greatly improve the efficiency of investigations because they can make massive comparisons and also keep them in a standardized digital format for future analysis.[15]

[14] S. Giovine, "The Science behind Ballistics Analysis in Criminal Investigations," J. Med. Toxicol. Clin. Forensic Med., vol. 9, pp. 1–2, 2023, doi: 10.36648/ 2471-641.9.3.59.

[15] E. Camci and F. Findik, "Recent developments in ballistics," Def. Secur. Stud., vol. 6, no. 2, pp. 132–141, 2025, doi: https://doi.org/10.37868/dss.v6.id291.

D. Interpretation of Ballistic Evidence in Forensic Investigations

The interpretation of ballistic evidence is a process of synthesizing firearm examination, trajectory analysis, laboratory result, and crime scene observations to reach conclusions that are based on science. The consistency of the ballistic evidence with the investigative information is assessed and factors such as projectile deformations, intermediate targets, ricochets and environmental influences are taken into account. Applying validated analytical techniques, quality assurance protocol and objective interpretation provides reliability, repeatability and admissibility of ballistic evidence in judicial proceedings.

5 Emerging Technologies and Challenges

Firearms, toolmarks and ballistics examinations are rapidly changing in terms of accuracy, objectivity and efficiency as a result of advancements in technology. The traditional methods, which are mostly visual comparison, are being supplemented by the latest imaging systems, computational analysis and statistical methods that minimize subjectivity and enhance the scientific foundations of forensic conclusions. Simultaneously, these developments introduce new technical, operational and legal opportunities and challenges that must be constantly validated, standardized, and trained for by the examiner. Therefore, the challenge of keeping pace with technological advances while maintaining scientific accuracy is a significant research interest today in the field of forensics.[16]

A. Emerging Technologies

Recent advances in three-dimensional (3D) surface topography, confocal microscopy, scanning electron microscopy (SEM), and micro-computed tomography (Micro-CT) have proved useful for the precise characterization of firearm and toolmark evidence. Automated ballistic identification systems like IBIS and NIBIN can help to quickly compare digital images of recovered bullets and cartridge cases from various crime scenes. Furthermore, AI, machine learning, and statistical algorithms are being developed to support objective pattern recognition, similarity assessment, and probabilistic interpretation in the field of forensic analysis, improving the reproducibility and efficiency of forensic analysis.[17]

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[16] L. Guarnera, O. Giudice, S. Livatino, A. B. Paratore, A. Salici, and S. Battiato, "Assessing forensic ballistics three-dimensionally through graphical reconstruction and immersive VR observation," Multimed. Tools Appl., vol. 82, pp. 20655–20681, 2023, doi: https://doi.org/10.1007/s11042-022-14037-x.

[17] Y. Xin, Y. Tang, Y. Luo, and K. Wang, "A review of firearm toolmarks identification: Progress, challenges, and perspectives," Forensic Sci. Int., vol. 379, p. 112735, 2026, doi: https://doi.org/10.1016/j.forsciint.2025.112735.

B. Challenges

Even with such progress, there are still some obstacles to be overcome. Variations between the manufacturing process, wear on the manufacturing tools, damage to the evidence, or environmental influences can make forensic comparisons difficult. It is important for emerging technologies to be extensively validated, standardized, and quality assured before use, to guarantee consistent and reliable outcomes. Additionally, examiner bias, comparative interoperability of forensic databases, cost and logistical considerations, and legal challenges surrounding the validity and reliability of algorithm-derived conclusions remain themes for research to create more objective, scientifically defensible and transparent firearm and toolmark examination.[18]

6 Conclusion

The scientific techniques used in firearm and toolmark and ballistic analysis have made a huge mark on the ability of forensic science to identify weapons, match physical evidence to the criminal event and accurately and reliably reconstruct shooting incidents. Traditional methods such as comparison microscopy and test firing continue to be essential in forensic investigations; new methods such as three-dimensional surface metrology, automated ballistic identification systems, artificial intelligence and advanced imaging have enhanced the precision of analysis and minimised subjectivity. Firearm examination, toolmark analysis, ballistic reconstruction and gunshot residue analysis all comprise a complete system for understanding and interpreting firearm-related evidence and assisting in a criminal investigation. Nevertheless, issues such as the variability of the evidence, methodological standardization, examiner bias, and the validation of new technologies call for continued scientific research and international cooperation. Future work needs to focus on objective analytical approaches, standardized protocols, and well-designed quality control measures to further improve the accuracy, repeatability, and legal acceptance of firearm and ballistic evidence in forensic analyses.

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[18] R. Baril and L. Claro, “Exploring Forensic Firearm Examination Towards the Enhancement of the Practice in Forensic Firearm Examination,” Psychol. Educ. A Multidiscip. J., vol. 51, pp. 884–897, Jan. 2026, doi: 10.70838/pemj.510703.

7 Reference

[1] E. J. A. T. Mattijssen, W. Kerkhoff, R. Hermsen, and R. A. G. Hes, "Interpol review of forensic firearm examination 2019–2022," Forensic Sci. Int. Synerg., vol. 6, p. 100305, 2023, doi: https://doi.org/10.1016/j.fsisyn.2022.100305.

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[9] J. Patteet and C. Champod, "Striated toolmarks comparison and reporting methods: Review and perspectives," Forensic Sci. Int., vol. 357, p. 111997, 2024, doi: https://doi.org/10.1016/j.forsciint.2024.111997.

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