# Ridges of Evidence: Emerging Technologies in Fingerprint Science and Automated Identification

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**Abstract**

Fingerprint science is one of the most scientifically sound and dependable methods to identify human beings in forensic investigations. This review covers the biological basis of fingerprint science and traditional ridge classification, as well as advanced automated fingerprint identification systems and AI-powered technologies. It covers developments in the science of detecting, visualizing, collecting and reading latent prints, as well as Automated Fingerprint Identification Systems (AFIS), including the use of explainable artificial intelligence (XAI) and novel computational tools to enhance recognition accuracy and efficiency. The review also tackles issues related to poor quality fingerprints, algorithmic bias and interoperability of databases among fingerprints, as well as the law related to automated fingerprint evidence in India. In summary, the use of sophisticated imaging techniques, biometric matching, and intelligent computational tools has revolutionized fingerprint analysis, making it a quicker, more objective, and almost foolproof aspect of modern forensics.

***Keywords; Fingerprint Science; Automated Fingerprint Identification System (AFIS); Latent Fingerprint Detection; Artificial Intelligence; Biometric Identification***

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## 1 Introduction

The term "Ridges of Evidence" represents the ability of the friction ridge characteristics found on the fingers, palms, and soles to distinguish one individual from another, and to be used in forensic examination at a crime scene. The small ridges are formed in the foetal life and tend to stay fairly constant throughout life unless permanently modified by deep wounding. They are unique, and are very persistent, and make them one of the most dependable forms of biometric evidence in forensic science, for crime-solving, disaster victim identification, border security and civil authentication.[2]

Fingerprint evidence is not limited to visible prints but also includes latent fingermarks from the secretion of eccrine, sebaceous and apocrine glands. These residues are not always detectable with the naked eye, but can be detected with physical, chemical and optical enhancement methods. Some traditional techniques, including powder dusting and cyanoacrylate fuming, still have a significant role to play, and new developments in nanotechnology, fluorescent materials, vacuum metal deposition, multispectral imaging and mass spectrometry have enhanced the recovery of weak, aged and contaminated fingerprints from difficult surfaces.[3]

Digital technologies have evolved so quickly that fingerprint examination is no longer conducted by a manual comparison, but rather through very automated identification systems. The use of automated Fingerprint Identification Systems (AFIS) combined with machine learning and deep learning algorithms allows for faster extraction of features, enhancement of latent fingerprints, minutiae matching and searching of large databases with greater speed and accuracy. Current studies also focus on 'explainable AI' and 'contactless fingerprint acquisition', '3D imaging', and 'multimodal biometric integration', which enhance the reliability and transparency of forensic decisions. They are changing the way fingerprint science is practiced by making the "ridges of evidence" one of the most powerful and scientifically sound methods of personal identification in today's forensic practice.[4]

[2] V. Nagar et al., “Latent friction ridge analysis of developed fingerprints after treatment with various liquid materials on porous surface,” Mater. Today Proc., vol. 69, pp. 1532–1539, 2022, doi: https://doi.org/10.1016/j.matpr.2022.04.619.

[3] V. S. Jonnalagadda, S. R. Gundu, and C. Panem, “A Study on Advancements in Forensic Fingerprints,” 2025. doi: http://dx.doi.org/10.2174/0126664844338150241202060301.

[4] V. Yarovenko, O. Pyatkova, and A. Cherednichenko, “Application of digital technologies in fingerprinting (transition to creation, storage and research of materials in electronic format),” pp. 51–62, Feb. 2022, doi: 10.25136/2409-7136.2022.2.35038.

## 2 Foundations of Fingerprint Science and Forensic Individualization

The science used for personal identification is the study of friction ridge skin, and is known as fingerprint science. One of the most reliable forms of forensic evidence is a fingerprint because of the unique and permanent nature of the ridges found on the skin. Knowing their biological source, structure and class is crucial for precise forensic individualization and modern automated identification.

### A. Historical Evolution of Fingerprint Science

Fingerprint technology has been used for forensic purposes since ancient times, in Babylon and China, where the use of fingerprint impressions authenticated documents. Scientific fingerprint identification was developed in the nineteenth century, with the development of the work of William Herschel, Henry Faulds, Francis Galton and Edward Henry. Galton discovered the law of the uniqueness and permanency of fingerprints, and Henry devised a practical classification system that would form the basis of a fingerprint identification system used by police. Since then, manual comparison has been replaced by fast computer-assisted identification made possible by digital imaging and Automated Fingerprint Identification Systems (AFIS).[5]

### B. Biological Basis of Friction Ridge Skin

Friction ridge skin is the skin found on the fingers, palms and soles, and forms between 10 and 17 weeks in fetal development. The formation of ridges is a result of genetic inheritance and prenatal environmental factors, and they are permanent and distinguishable. The latent fingerprint residues left on touched surfaces by sweat from eccrine pores are an important source of evidence. In addition to identification, friction ridges provide grip and sense of touch.[6]

### C. Principles of Uniqueness and Permanence

Fingerprint individuality is a result of the random arrangement of friction ridges in the developing embryo so that no two people, even identical twins, have identical fingerprints. Ridge configuration does not change, except after deep dermal injury, throughout life and so fingerprints can be used scientifically to identify an individual.

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[5] D. V. R. Yadav, "A Historical Development of The Fingerprint In India With Special Reference To Ayurveda," World J. Pharm. Med. Res., vol. 11, no. 2, pp. 60–62, 2025.

[6] A. White, "Biology of Friction Ridge Skin: Basis for Feature Variation and Persistence," 2022, pp. 301–312. doi: 10.1016/b978-0-12-823677-2.00195-1.

D. **Fingerprint Pattern Classification**

Overall ridges flow into a fingerprint that can be categorized as an arch, loop or whorl. These are level 1 characteristics that are used to efficiently organize fingerprint databases, and set the basic building blocks for comparison. Pattern classification reduces the number of patterns in the database to be examined in detail by the search of the ridge characteristics.[7]

E. **Levels of Fingerprint Detail**

Fingerprint examination follows a hierarchical approach. Level 1 details are the overall ridge flow and the type of ridge pattern; Level 2 details are minutiae, such as ridge endpoints, bifurcations, islands, and enclosures, which also help to establish identity; Level 3 details are the pore structure, ridge edge shape, incipient ridges, scars, and creases, which provide additional discrimination when high resolution images are available.[8]

F. **Role in Forensic Identification and Criminal Investigations**

Fingerprints are objective physical evidence that connects persons with criminal activity, weapons and objects. Latent print examination of evidence and AFIS databases are utilized to compare latent prints with known records. Fingerprint science forms the foundation of modern forensic practice with high discriminatory power and standardized protocols for collecting and examining the slides.

(a) arch (b) loop (c) whorl

**Figure 8: Fingerprint Pattern Classification**[9]

[7] D. S. Ametefe, S. S. Sarnin, D. M. Ali, and Z. Z. Muhammad, “Fingerprint pattern classification using deep transfer learning and data augmentation,” Vis. Comput., 2022, doi: https://doi.org/10.1007/s00371-022-02437-x.

[8] H. Chen, R. Ma, and M. Zhang, “Recent Progress in Visualization and Analysis of Fingerprint Level 3 Features,” ChemistryOpen, 2022, doi: doi.org/10.1002/open.202200091.

[9] D. S. Ametefe, S. S. Sarnin, D. M. Ali, and Z. Z. Muhammad, “Fingerprint pattern classification using deep transfer learning and data augmentation,” Vis. Comput., 2022, doi: https://doi.org/10.1007/s00371-022-02437-x.

## 3 Modern Techniques for Fingerprint Detection, Visualization, and Digital Acquisition

Effective detection, visualization and digital acquisition techniques are essential to successful fingerprint evidence use. Conventional chemical and physical fingerprinting techniques are still critical for the development of latent fingerprints, but recent developments in imaging technologies, nanomaterials and computational processing have made it easier to retrieve weak or compromised ridge patterns. Modern techniques improve the visibility of fingerprints, also enabling high-resolution digital capture and automated fingerprint analysis, with greater reliability and efficiency in forensic investigations.

1. **Conventional Fingerprint Development Methods:** Conventional latent fingerprint development techniques are chosen based on the type of surface and fingerprint residue. The powder dusting technique will stick to moisture and oily substances of non-porous surfaces while the ninhydrin technique will yield purple impressions in porous materials like paper. Cyanoacrylate fuming polymerizes a polymer inside the fingerprint residue to give a persistent white ridge image on non-porous surfaces and silver nitrate reacts with the chloride ions in the fingerprint residue to leave images of the fingerprints. Iodine fuming is a temporary visualization of lipid-rich residues and is mainly used in the case of sensitive porous materials.[10]
2. **Advanced Fingerprint Visualization Methods:** In recent years, new technologies use fluorescent dyes, nanomaterials, quantum dots, and vacuum metal deposition (VMD) for enhancing the detection of fingerprints on difficult surfaces. Fluorescent probes enhance contrast under specific light wavelengths, while nanoparticles and quantum dots are highly sensitive and very photostable. The thin layers of gold and zinc allow VMD to be especially effective in developing latent fingerprints on plastics, glass and polymeric materials which are not easily developed using the standard methods.[11]
3. **Optical and Multispectral Imaging:** Alternate light sources are used in optical imaging systems to reveal latent fingerprints without altering the evidence; ultraviolet, visible and infrared wavelengths are used. Multispectral and hyperspectral imaging increases the contrast between ridges by exploiting differences in optical reflectance and fluorescence,

[10] K. R. Ghodake and S. S. Nalage, "A Comprehensive Review of Fingerprint Development: Exploring Unconventional Powder-Based Techniques," Int. J. Sci. Res. Sci. Technol., pp. 558–563, 2024, doi: https://doi.org/10.32628/IJSRST52411282.

[11] H. Chen, R. Ma, and M. Zhang, "Recent Progress in Visualization and Analysis of Fingerprint Level 3 Features," ChemistryOpen, 2022, doi: doi.org/10.1002/open.202200091.

allowing the visualization of fingerprints on multicolored, textured and contaminated surfaces.

4. **Three-Dimensional Fingerprint Imaging:** Three-dimensional (3D) fingerprint imaging is the process of capturing the ridge morphology and surface topography of a fingerprint through optical scanning, structured light or laser imaging. Compared to the two dimensional imaging, 3D acquisition reduces the effect of finger pressure and enhances the accuracy of the biometric matching and forensic comparison.
5. **Contactless Fingerprint Acquisition:** Contactless fingerprint systems use high resolution digital cameras to take images of the ridges without touching a scanner. It is an approach that has lower surface contamination, less hygiene concerns, no elastic deformation and maintains the natural ridge geometry, which is becoming increasingly valuable for forensic and biometric applications.
6. **Image Enhancement and Preprocessing Techniques:** Digital preprocessing improves fingerprint quality before automated analysis. Common image processing techniques include image normalization, noise reduction, contrast enhancement, ridge orientation estimation, ridge frequency analysis, segmentation, thinning and minutiae extraction. These computational techniques increase the visibility of the ridges, decrease background interference, and increase the accuracy for Automated Fingerprint Identification Systems (AFIS), especially when working with partial and degraded prints.

## 4 Automated Fingerprint Identification Systems (AFIS) and Biometric Matching Technologies

Automated Fingerprint Identification Systems (AFIS) have changed the way fingerprint examination is conducted by allowing for fast and objective comparison of fingerprint records from large databases. Designed to overcome the drawbacks of the manual search process, AFIS incorporates digital image processing, pattern recognition and biometric matching algorithms in order to assist the forensic investigation process, civil identification and border security. The speed, accuracy and scalability of fingerprint identification has also been enhanced through ongoing advances in computational intelligence and database technologies.[12]

[12] C. Herke, "Automated Fingerprint Identification: The Role of Artificial Intelligence in Crime Scene Investigation," Forensic Sci., 2026, doi: https://doi.org/10.3390/forensicsci6010006.

- **Evolution of AFIS and Next-Generation Identification Systems**

The earliest AFIS systems developed in the 1970s automated the storage and retrieval of fingerprints by using minutiae comparison. Modern systems involve high-resolution sensors, cloud-based databases, artificial intelligence, and deep learning algorithms that facilitate quicker searches, enhance latent fingerprint recognition and integration with multimodal biometric systems.

- **Architecture and Workflow of AFIS**

The major components of a typical AFIS are fingerprint acquisition, image preprocessing, feature extraction, template generation, database indexing, matching and result verification. Fingerprint images captured are improved and turned into a digital template, ahead of which records are stored against which to compare. The system produces candidate matches which are then hand checked by trained fingerprint examiners to make a forensic conclusion.

- **Feature Extraction**

Feature extraction transforms fingerprint images into unique biometric features that can be compared. Level 1 characteristics are the overall ridge flow and type of the pattern, while Level 2 characteristics are minutiae such as ridge endings and bifurcations. Advanced systems can also extract the Level 3 features such as the distribution of pores, the contours of an edge of a ridge, incipient ridges, and scars, which further enhances the ability to differentiate among highly similar fingerprints.[13]

- **Fingerprint Indexing and Database Searching**

For efficient database searching, one needs to use fingerprint classification, indexing and template organizing. AFIS reduces the database size by pattern classification and indexed feature vectors and then makes detailed comparisons, allowing identification from databases with millions of fingerprint images.

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[13] U. Nagamani, S. MohasinaTabassum, B. Jayasree, V. Prashanth, S. Srinath, and S. Srikanth, "Fingerprint Recognition System based on Artificial Neural Networks integrated with Machine Learning," ITM Web Conf., pp. 1–7, 2025, doi: https://doi.org/10.1051/itmconf/20257901018.

- **Matching Algorithms and Similarity Scoring**

Fingerprint matching algorithms are based on the extracted features either by minutiae, correlation, ridge feature or hybrid. Similarity scores measure the similarity of two fingerprint templates and the system can rank a list of candidate matches in order of probability that they match the same person's fingerprint.

- **Latent Fingerprint Identification Pipeline**

The latent fingerprint workflow consists of image enhancement and segmentation, feature extraction, quality assessment, database searching, candidate ranking and expert verification. The imaging of latent fingerprints and the interpretation of the image by an individual examiner are still crucial to the identification process, as many latent prints are partial or degraded.

- **Performance Evaluation Metrics**

AFIS performance is judged using conventional biometric criteria. The False Acceptance Rate (FAR) is the amount of time that a non-matching fingerprint is incorrectly accepted, while the False Rejection Rate (FRR) is the time a matching fingerprint is incorrectly rejected. Equal Error Rate (EER) is the operating point at which the FAR and FRR are equal, and Rank-1 accuracy gives the overall effectiveness of the system by calculating the percentage of times the correct identity is returned as the top-ranked candidate.[14]

## 5 Artificial Intelligence and Emerging Computational Technologies in Fingerprint Recognition

The integration of artificial intelligence (AI) technology has greatly enhanced fingerprint recognition, making it more accurate, faster, and automated than ever before. AI algorithms can analyze a vast amount of data to identify complex fingerprint patterns and provide high accuracy in recognizing partial, distorted, or poor quality latent prints, unlike traditional rule-based systems. The advancement of deep learning, explainable AI, cloud computing, and synthetic data generation has enhanced the ability of Automated Fingerprint Identification Systems (AFIS), and thus made their forensic examination more reliable, and easier to execute by the examiner. The new computational technologies are transforming the fingerprint science by

[14] S. S. Ben Jaber, "Recent Advancements in Latent Fingerprint Detection: A Nanotechnological Perspective," Sensors Actuators B. Chem., vol. 459, 2026, doi: https://doi.org/10.1016/j.snb.2026.149035.

increasing the capacity for feature extraction, image restoration, biometric matching, and decision support.[15]

1. **Machine Learning (ML):** The machine learning algorithms are able to classify the pattern of the fingerprint, estimate the image quality and optimize the selection of features that will be used by the system based on models trained on databases that are annotated with fingerprint images. The main advantage of ML is its ability to recognize variations in fingerprint quality and acquisition conditions, enhancing the efficiency of automated identification.
2. **Deep Learning and Convolutional Neural Networks (CNNs):** CNN-based models are automatically learning hierarchical features of the fingerprint image directly from the image without manual feature engineering. They are very popular in the field of latent fingerprint enhancement, minutiae detection, fingerprint classification and biometric matching with high recognition accuracy.
3. **Vision Transformers (ViTs):** The Vision Transformers use a self-attention mechanism to learn spatial dependencies, particularly long-term ones, in fingerprint images. They have shown their potential to recognize more complex ridge structures and have shown to be more robust against disturbed and incomplete fingerprints.
4. **Automated Minutiae Extraction:** Unlike conventional image processing techniques, the automatic detection of the distinctive features of a ridge, such as ridge endings, bifurcations, pores, etc., is more consistent and reliable, thanks to the use of AI-powered algorithms that allow these features to be identified with greater consistency.
5. **AI-Based Image Restoration and Enhancement:** The deep learning models enhance the quality of the latent fingerprints and improve the quality of evidence available for comparing latent fingerprints by denoising, ridge reconstruction, contrast enhancement, and super-resolution approaches.
6. **Explainable Artificial Intelligence (XAI):** XAI offers an interpretable explanation of the AI-generated finger print matching decisions in the form of highlighting of influential ridge features and similarity regions. This transparency enhances examiners' confidence and facilitates the legal admissibility of AI-generated forensic evidence.
7. **Synthetic Fingerprint Generation:** Generative Adversarial Networks (GANs) and diffusion models generate realistic synthetic fingerprint images to increase training sets,

[15] S. A. Sari, F. Y. A. Kabeakan, H. Hasibuan, And S. M. Ho, “Technological Evolution in Latent Fingerprint Detection: From Nanomaterials to Artificial Intelligence,” Asian J. Chem., vol. 38, no. 4, pp. 843–851, 2026, doi: https://doi.org/10.14233/ajchem.2026.35435.

enhance the efficacy of the algorithms, and enable benchmark tests while maintaining privacy of each fingerprint.

8. **Cloud, Edge, and Federated Computing:** These distributed computing technologies allow for secure storage, fast processing and simultaneous model training across different agencies, whilst reducing data transfers and providing greater privacy protection for large-scale biometric systems.
9. **Human–AI Collaborative Examination:** Instead of replacing forensic experts, modern AI systems serve as a decision support tool, automating mundane tasks, prioritizing candidate matches and helping examiners to perform objective and efficient fingerprint comparisons.

## 6 Challenges and Legal Considerations in Automated Fingerprint Evidence

The increasing adoption of Automated Fingerprint Identification Systems (AFIS) and artificial intelligence has enhanced the efficiency of fingerprint examination; however, important technical, legal, and ethical challenges remain. In addition to the advanced algorithms, the reliability of automated fingerprint evidence relies on the quality of the fingerprint samples, standard examination procedures and on the adherence to the legal requirements. The widespread adoption of Digital Biometric systems in India has highlighted the importance of scientifically proven solutions that promote accuracy, transparency, and safeguard individual privacy rights.

**Challenges in Automated Fingerprint Evidence:** Partial, smudged, distorted or poor quality latent fingerprint lifted from crime scenes are common problems with automated fingerprint systems. Different surface textures, environmental conditions, overlapping impressions, and poor ridge detail all can cause variations that may result in decreased matching accuracy and increase the possibility of false accept or false reject. Also, system performance varies due to variations in sensor technologies, database quality and interoperability between agencies. Additionally, to ensure reduced algorithmic bias and generalizability, large, diverse, and representative datasets are needed for fingerprint-based AI recognition systems. The importance of expert verification remains as vital as ever over and in addition to automated matching results in these challenges.[16]

[16] D. Maiti, M. Basak, and D. Das, "A review on fingerprint based authentication-its challenges and applications," Comput. Sci. Rev., vol. 57, p. 100735, 2025, doi: https://doi.org/10.1016/j.cosrev.2025.100735.

**Legal Considerations in the Indian Context:** In India, fingerprint evidence is considered a crucial type of expert evidence under the Indian Evidence Act, 1872, (as amended by the Criminal Laws (Amendment) Act, 2023) and is examined along with expert evidence. The Criminal Procedure (Identification) Act, 2022 was passed in order to replace the Identification of Prisoners Act, 1920, which enables law enforcement agencies to collect, preserve and process fingerprint records for identification and investigations. Additionally, the Digital Personal Data Protection Act, 2023 establishes a legal framework for safeguarding biometric data, emphasizing lawful processing, data security, and privacy. Hence, the admission of automated fingerprint evidence in Indian courts needs to be scientifically validated, properly documented and checked by experts in order to ensure admissibility, reliability, and fairness and privacy of the system.[17]

## 7 Conclusion

Friction ridge patterns, due to their uniqueness and permanency, still make fingerprint evidence the gold standard for forensic individualization. The detection and comparison of fingerprint evidence has been greatly enhanced by latent fingerprint development, multispectral imaging, 3-D acquisition and the use of Automated Fingerprint Identification Systems. The integration of AI, deep learning, explainable AI, and cloud-based computational solutions has further boosted the speed, accuracy, and scalability of biometric identification, and assisted in forensic decision making. However, issues with low quality latent prints, algorithm validation, privacy concerns, and the acceptance of evidence in court are still major concerns. The successful application of automated fingerprint evidence in the Indian context demands compliance with the changing legal requirements, consistency in forensic procedures, and thorough expert validation. Future investigations will be more reliable, transparent, and accepted by the courts due to continued interdisciplinary research and responsible technological innovation of fingerprint science.

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[1] V. Nagar et al., “Latent friction ridge analysis of developed fingerprints after treatment with various liquid materials on porous surface,” Mater. Today Proc., vol. 69, pp. 1532–1539, 2022, doi: https://doi.org/10.1016/j.matpr.2022.04.619.

[2] V. S. Jonnalagadda, S. R. Gundu, and C. Panem, “A Study on Advancements in Forensic Fingerprints,” 2025. doi: http://dx.doi.org/10.2174/0126664844338150241202060301.

[17] S. V S, “Forensic Fingerprinting: Scientific Accuracy and Legal Admissibility in Criminal Trials,” LawFoyer Int. J. Doctrin. Leg. Res., 2026, doi: https://doi.org/10.70183/lijdlr.2026.v04.201.

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[4] D. V. R. Yadav, “A Historical Development of The Fingerprint In India With Special Reference To Ayurveda,” World J. Pharm. Med. Res., vol. 11, no. 2, pp. 60–62, 2025.

[5] White, “Biology of Friction Ridge Skin: Basis for Feature Variation and Persistence,” 2022, pp. 301–312. doi: 10.1016/b978-0-12-823677-2.00195-1.

[6] D. S. Ametefe, S. S. Sarnin, D. M. Ali, and Z. Z. Muhammad, “Fingerprint pattern classification using deep transfer learning and data augmentation,” Vis. Comput., 2022, doi: https://doi.org/10.1007/s00371-022-02437-x.

[7] H. Chen, R. Ma, and M. Zhang, “Recent Progress in Visualization and Analysis of Fingerprint Level 3 Features,” ChemistryOpen, 2022, doi: doi.org/10.1002/open.202200091.

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[9] K. R. Ghodake and S. S. Nalage, “A Comprehensive Review of Fingerprint Development: Exploring Unconventional Powder-Based Techniques,” Int. J. Sci. Res. Sci. Technol., pp. 558–563, 2024, doi: https://doi.org/10.32628/IJSRST52411282.

[10] H. Chen, R. Ma, and M. Zhang, “Recent Progress in Visualization and Analysis of Fingerprint Level 3 Features,” ChemistryOpen, 2022, doi: doi.org/10.1002/open.202200091.

[11] C. Herke, “Automated Fingerprint Identification: The Role of Artificial Intelligence in Crime Scene Investigation,” Forensic Sci., 2026, doi: https://doi.org/10.3390/forensicsci6010006.

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Chem., vol. 38, no. 4, pp. 843–851, 2026, doi: https://doi.org/10.14233/ajchem.2026.35435.

[15] D. Maiti, M. Basak, and D. Das, "A review on fingerprint based authentication-its challenges and applications," Comput. Sci. Rev., vol. 57, p. 100735, 2025, doi: https://doi.org/10.1016/j.cosrev.2025.100735.

[16] S. V S, "Forensic Fingerprinting: Scientific Accuracy and Legal Admissibility in Criminal Trials," LawFoyer Int. J. Doctrin. Leg. Res., 2026, doi: https://doi.org/10.70183/lijdlr.2026.v04.201.