

Review

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Review

The Double Helix of Justice: The Crucial Role of DNA in Advancing Criminal Investigations

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Abstract: This review article delves into the pivotal role of DNA in advancing criminal investigations, presenting a comprehensive analysis of its impact on modern justice systems. DNA, as the genetic blueprint of individuals, has revolutionized forensic science, augmenting the accuracy and reliability of criminal investigations. This study explores the historical evolution of DNA analysis, from its initial discovery to the development of sophisticated techniques like polymerase chain reaction (PCR), short tandem repeat (STR) profiling, and next-generation sequencing (NGS). The article elucidates the intricate process of DNA collection, preservation, and analysis, highlighting its significance in establishing identity, proving guilt or innocence, and resolving cold cases. The utilization of DNA databases and international cooperation in cross-border investigations are also examined, emphasizing their contributions to solving complex criminal cases. Moreover, the ethical, legal, and privacy considerations surrounding DNA usage in criminal justice are critically evaluated. Through a comprehensive literature review, this article synthesizes empirical evidence showcasing how DNA evidence has exonerated wrongfully convicted individuals and provided closure to victims' families. It further elucidates how technological advancements have extended DNA analysis to trace evidence, touch DNA, and forensic genealogy, thereby broadening its application in criminal investigations.

Keywords: DNA analysis; forensic science; criminal investigations; genetic profiling; cold cases; DNA databases; forensic genealogy

1. Introduction

In the realm of criminal justice, few scientific breakthroughs have left a more profound mark than the unveiling and application of DNA analysis [1]. Deoxyribonucleic acid (DNA), with its iconic double helix structure, not only serves as the blueprint of life but also acts as an unmistakable marker of individual identity, silently bearing witness to the complexities of human existence [2]. Over the past several decades, the utilization of DNA analysis has emerged as a pivotal instrument in the toolbox of forensic science, fundamentally reshaping the landscape of criminal investigations and redefining the parameters of justice [3]. This comprehensive review embarks on an in-depth exploration of the multifaceted role that DNA assumes in advancing criminal investigations, highlighting its transformative influence on contemporary justice systems worldwide [4]. At the core of the profound significance of DNA analysis is its unparalleled capacity to illuminate the innermost facets of human identity [5]. From its inaugural revelation, which unveiled the foundational code governing life itself, to the development of sophisticated techniques such as polymerase chain reaction (PCR), short tandem repeat (STR) profiling, and next-generation sequencing (NGS), the evolutionary journey of DNA analysis has been a relentless quest for accuracy and lucidity [6]. These innovations have elevated the precision and dependability of criminal investigations, shedding a piercing light into the realms of doubt and ambiguity [7].

This review delves into the historical evolution of DNA analysis, tracing its trajectory from a groundbreaking scientific revelation to its pivotal stance in the realm of forensic science [8]. A

meticulous scrutiny of the process of DNA collection, preservation, and analysis unveils the intricate procedures that underlie the extraction of truth from genetic strands [9]. Moreover, this exploration extends beyond the laboratory, delving into the profound implications of DNA analysis in establishing identity, ascertaining guilt or innocence, and resolving long-standing enigmas of unsolved cases [10]. The advent of DNA databases and the collaborative efforts of international jurisdictions have further amplified the impact of DNA analysis [11]. As these databases weave a global tapestry of genetic information, the boundaries of investigative reach expand beyond domestic confines, facilitating the resolution of intricate criminal cases that span geographic borders [12]. However, the power of genetic information is accompanied by ethical, legal, and privacy considerations [13]. This review critically assesses the delicate equilibrium between the pursuit of justice and the safeguarding of individual rights, navigating the intricate web of implications that DNA utilization presents within the framework of criminal justice [14]. Beyond its legal and scientific connotations, DNA analysis carries a profound emotional weight [15]. This article synthesizes empirical evidence that underscores how DNA evidence has served as a tool of exoneration, offering redemption to the wrongfully convicted and solace to victims' families [16]. Furthermore, the relentless progression of technological advancement has broadened the horizons of DNA analysis, expanding its reach to trace evidence, touch DNA, and the transformative realm of forensic genealogy [17].

In the ensuing pages, this review embarks on an enlightening odyssey through the interconnected threads of science, justice, and humanity [18]. The double helix of justice, emblematic of the harmonious interplay between scientific inquiry and the pursuit of truth, serves as a guiding light through the intricate maze of criminal investigations [19]. As the strands of DNA's pivotal role are unraveled, we are compelled to acknowledge its enduring and profound impact on sculpting the contours of modern justice systems, advancing the cause of truth, and bestowing both exoneration and closure to those who seek answers within the intricate tapestry of human existence [20].

2. Revolutionizing Criminal Investigations through DNA Analysis

2.1. From Discovery to Breakthrough: Evolution of DNA Analysis in Forensic Science

The evolution of DNA analysis in forensic science has been a groundbreaking journey, transforming the landscape of criminal investigations. Originally discovered by James Watson and Francis Crick in 1953 [21], the double-helix structure of DNA laid the foundation for understanding genetic information and its potential applications. However, it wasn't until the 1980s that DNA analysis began to revolutionize criminal investigations. The advent of techniques such as polymerase chain reaction (PCR) [22] allowed for the amplification of minute DNA samples, enabling the analysis of even trace amounts of genetic material. Subsequent developments, including short tandem repeat (STR) profiling [23] and next-generation sequencing (NGS) [24], further enhanced the precision and sensitivity of DNA analysis, enabling the identification of individuals with unprecedented accuracy.

2.2. Unraveling the Blueprint: Understanding the Genetic Profiling Process

The genetic profiling process is at the heart of DNA analysis in criminal investigations. DNA, as the genetic blueprint of individuals, contains unique sequences that can be used for identification purposes. Genetic profiling involves extracting DNA from various biological sources, such as blood, saliva, hair, or tissue samples, and then amplifying specific regions of the DNA using techniques like PCR. The resulting DNA profiles, based on polymorphic regions like STRs, provide a distinctive genetic fingerprint for each individual [23].

2.3. Enhancing Accuracy and Reliability: Impact of DNA on Modern Justice Systems

The impact of DNA analysis on modern justice systems has been profound. The accuracy and reliability of DNA evidence have transformed the way criminal cases are investigated, tried, and resolved. DNA analysis has played a pivotal role in establishing the identity of suspects and linking them to crime scenes. It has been instrumental in both exonerating wrongfully convicted individuals

and identifying perpetrators in cold cases that had previously remained unsolved. The introduction of DNA evidence has significantly reduced the likelihood of wrongful convictions by providing an objective and scientific means of identifying suspects [25]. It has also contributed to the reexamination of past convictions, leading to the exoneration of individuals who were imprisoned for crimes they did not commit. The utilization of DNA databases, containing profiles from convicted offenders and crime scenes, has facilitated the swift identification of suspects and the resolution of cases that were once considered insurmountable [26]. Moreover, the application of DNA analysis extends beyond individual identification. It has revolutionized trace evidence analysis, allowing forensic experts to link suspects to crime scenes through the analysis of even the smallest genetic samples. Touch DNA, which refers to the DNA transferred through contact with surfaces, has become a valuable tool in linking suspects to objects or locations [27]. Additionally, forensic genealogy, a recent advancement in DNA analysis, has enabled the identification of individuals based on their genetic relationships to known profiles, aiding in the resolution of cold cases and unidentified remains [28].

The integration of DNA analysis into criminal investigations has redefined the landscape of modern justice systems. The evolution of DNA analysis from its discovery to the development of advanced techniques has enhanced the accuracy and reliability of criminal investigations. The genetic profiling process, through techniques like PCR, STR profiling, and NGS, has allowed for precise identification and linking of individuals to crime scenes. DNA analysis has not only revolutionized individual identification but has also expanded to trace evidence, touch DNA, and forensic genealogy, broadening its application in solving complex criminal cases.

3. Unveiling the DNA Toolkit: Techniques and Technologies

3.1. Amplifying Truth: Polymerase Chain Reaction (PCR) and its Role in DNA Analysis

One of the pivotal breakthroughs in the field of DNA analysis is the Polymerase Chain Reaction (PCR), a revolutionary technique that allows for the amplification of specific DNA segments. PCR, pioneered by Kary B. Mullis in 1983 [29], has become an indispensable tool in forensic science due to its ability to generate millions of copies of a target DNA region, even from minute samples. This amplification process enables analysts to work with limited and degraded DNA samples, which is often encountered in criminal investigations. In the context of criminal investigations, PCR has facilitated the analysis of trace amounts of DNA evidence collected from crime scenes, such as blood, semen, or hair follicles. The amplified DNA can then undergo various downstream analyses, including DNA profiling, linkage analysis, and more. This technique has significantly enhanced the sensitivity and accuracy of DNA analysis, contributing to the successful resolution of numerous criminal cases [30].

3.2. Profiling Identity: Short Tandem Repeat (STR) Profiling and its Forensic Utility

Short Tandem Repeats (STRs) are specific regions within the human genome characterized by short nucleotide sequences that are repeated in tandem. These sequences vary in length among individuals, making them ideal markers for genetic profiling. The development of STR profiling techniques has enabled forensic scientists to create unique genetic profiles for individuals based on the number of repeats at multiple STR loci. STR profiling, pioneered by Sir Alec Jeffreys in the mid-1980s [31], has become the gold standard for human identification in forensic investigations. By analyzing a set of STR markers, forensic experts can establish the genetic fingerprint of an individual with a high degree of accuracy.

This technique has been instrumental in establishing identity, linking suspects to crime scenes, and excluding innocent individuals from investigations. Furthermore, STR profiling has proven invaluable in resolving cold cases, where DNA evidence collected years ago can be reanalyzed using modern techniques. The ability to generate DNA profiles from degraded or old samples has led to the exoneration of wrongfully convicted individuals and the identification of previously unidentified perpetrators [32].

3.3. Next-Generation Sequencing (NGS): Pioneering Advancements in DNA Analysis

Next-Generation Sequencing (NGS) represents a groundbreaking advancement in DNA analysis, allowing for the rapid and high-throughput sequencing of DNA molecules. This technology has revolutionized the field of genomics and has found extensive application in forensic science.

NGS enables the simultaneous sequencing of multiple DNA regions, making it highly efficient for generating complex DNA profiles. It has expanded the capabilities of DNA analysis beyond traditional STR profiling, allowing for the examination of additional genetic markers and informative regions. NGS has also facilitated the analysis of mixtures of DNA from multiple sources, which is often encountered in forensic casework. The application of NGS in forensic genealogy has garnered particular attention. By comparing DNA profiles to publicly available genealogy databases, investigators can identify potential relatives of an unknown suspect or victim, aiding in the resolution of cold cases or the identification of human remains [33].

The DNA toolkit, comprising techniques such as Polymerase Chain Reaction, Short Tandem Repeat profiling, and Next-Generation Sequencing, has significantly advanced the field of forensic science. These techniques have enhanced the accuracy and reliability of DNA analysis, leading to the successful resolution of criminal investigations, the exoneration of the innocent, and the closure of cold cases.

4. Collecting, Preserving, and Analyzing DNA Evidence

4.1. Threads of Evidence: The Intricate Process of DNA Collection and Preservation

The collection and preservation of DNA evidence constitute a foundational phase in modern criminal investigations. The extraction of genetic material from various sources, such as bodily fluids, tissues, hair, and touch samples, requires meticulous adherence to protocols to ensure the integrity and admissibility of the evidence [34]. Proper documentation of the collection process, including location, time, and individuals involved, is imperative to establish a clear chain of custody [35]. Swabs, collection kits, and protective equipment are utilized to minimize contamination risks during evidence gathering [3]. Once collected, DNA evidence must be carefully preserved to prevent degradation and maintain its integrity for subsequent analysis [36]. Proper storage conditions, including temperature and humidity control, play a pivotal role in preserving DNA over extended periods [37]. Advancements in storage technologies, such as refrigeration and -80°C freezers, have contributed to enhancing the longevity of DNA samples [38]. The use of specialized packaging and labeling ensures traceability and minimizes the potential for mishandling [39].

4.2. Unmasking Truth: Analyzing DNA to Establish Identity and Prove Guilt or Innocence

DNA analysis has emerged as a cornerstone in establishing identity and determining guilt or innocence in criminal investigations. The utilization of techniques like Polymerase Chain Reaction (PCR), Short Tandem Repeat (STR) profiling, and Next-Generation Sequencing (NGS) has enabled forensic scientists to amplify and analyze DNA samples with unprecedented precision [8]. PCR facilitates the amplification of minute DNA quantities, making it possible to analyze degraded or limited samples [40]. STR profiling examines highly variable regions of DNA, generating unique genetic profiles that serve as robust identifiers [41]. NGS offers a comprehensive analysis of an individual's entire DNA sequence, enabling more detailed comparisons and identification [42].

Comparative analysis of DNA profiles obtained from crime scenes with those of suspects or individuals in DNA databases plays a pivotal role in identifying perpetrators and excluding innocent parties [43]. The use of probabilistic genotyping software enhances the accuracy of DNA interpretation, aiding in complex mixture analysis [44]. DNA evidence has been instrumental in overturning wrongful convictions, often demonstrating conclusively the innocence of individuals who were previously imprisoned [45].

4.3. Breathing Life into Cold Cases: DNA's Role in Revisiting and Resolving Past Crimes

One of the most remarkable applications of DNA evidence is its ability to breathe new life into cold cases – previously unsolved crimes that have remained stagnant for years. The reanalysis of stored DNA samples using updated techniques and databases has led to breakthroughs in investigations that were once considered unsolvable [46]. Cold cases involving homicides, sexual assaults, and unidentified remains have been reinvigorated through the application of advanced DNA analysis [47]. Forensic genealogy, an innovative approach that combines DNA analysis with genealogical research and public DNA databases, has proven particularly effective in solving cold cases [48]. By identifying distant relatives of unknown suspects, investigators can narrow down potential leads and eventually pinpoint the likely perpetrator through traditional investigative methods [49]. Notably, this technique played a pivotal role in solving the infamous Golden State Killer case [50].

5. Global Collaborations: DNA Databases and Cross-Border Investigations”

5.1. Building Bridges: The Power of DNA Databases in Solving Complex Criminal Cases

In the realm of criminal investigations, the advent of DNA databases has brought forth a revolutionary era of global collaboration, significantly enhancing the capacity to solve complex criminal cases. DNA databases serve as reservoirs of genetic profiles obtained from individuals, both convicted offenders and arrestees, contributing to the swift identification of suspects, linking cases, and providing crucial leads for law enforcement agencies [51]. These databases have transformed the landscape of criminal justice by facilitating the rapid matching of DNA evidence against vast repositories of genetic information, thereby expediting the process of identifying potential perpetrators.

One prominent example of the impactful utilization of DNA databases is the establishment of the Combined DNA Index System (CODIS) in the United States [52]. CODIS has enabled law enforcement agencies across the country to share and compare DNA profiles, bridging jurisdictional boundaries and connecting seemingly unrelated cases. The collaborative nature of CODIS has facilitated the resolution of numerous cold cases, shedding light on previously unsolved mysteries [53]. This sharing of genetic information exemplifies the power of DNA databases in dismantling silos and fostering cooperation between various law enforcement agencies.

5.2. Beyond Borders: International Cooperation in DNA Analysis for Cross-Border Investigations

The challenges posed by transnational crimes necessitate a broader perspective on DNA analysis and its role in cross-border investigations. The interconnected nature of criminal activities often demands international cooperation and the sharing of genetic data across borders. In recent years, collaborative efforts have emerged, emphasizing the importance of harmonizing DNA analysis protocols, data exchange mechanisms, and legal frameworks to effectively combat cross-border crime. Interpol’s DNA Gateway is a notable example of international cooperation in DNA analysis [54]. This platform enables member countries to upload and search DNA profiles, thereby facilitating the identification of criminals operating across different jurisdictions. The DNA Gateway underscores the significance of a standardized approach to DNA analysis and the exchange of genetic information, transcending geographical boundaries and fostering a collective response to global crime challenges.

Furthermore, the utilization of DNA evidence in cross-border investigations extends beyond traditional law enforcement cooperation. The field of forensic genealogy has gained prominence in recent years, exemplified by cases where genetic genealogy databases have been employed to identify suspects in cold cases [55]. By leveraging consumer genetic databases, law enforcement agencies can establish familial connections and trace suspects’ ancestral lines, eventually leading to the identification and apprehension of individuals involved in cross-border crimes. The integration of DNA databases and international cooperation in DNA analysis has undeniably transformed the landscape of criminal investigations. The establishment of DNA databases, such as CODIS, and collaborative platforms like Interpol’s DNA Gateway, highlights the power of shared genetic

information in solving complex cases that transcend jurisdictional boundaries. The evolution of DNA analysis from a local tool to a global resource underscores the necessity of harmonized protocols, ethical considerations, and legal frameworks to ensure responsible and effective use of DNA evidence in cross-border investigations. As technology continues to advance, the potential for DNA databases and international collaboration to contribute to the swift resolution of complex criminal cases remains promising, providing hope for justice both within and beyond borders.

6. Balancing Justice and Ethics: Legal and Privacy Considerations

6.1. *Double-Edged Sword: The Ethical and Legal Implications of DNA Usage in Criminal Justice*

The integration of DNA analysis into criminal investigations has undoubtedly propelled advancements in modern justice systems, enhancing the accuracy and effectiveness of solving crimes. However, this powerful tool comes with a set of ethical and legal challenges that warrant careful consideration. The utilization of DNA evidence raises questions about the balance between ensuring justice for victims and upholding the rights of individuals accused of crimes [56]. One of the primary ethical concerns is the potential misuse or misinterpretation of DNA evidence. While DNA analysis is highly accurate, errors can occur during collection, analysis, and interpretation, leading to wrongful convictions if not rigorously scrutinized [57]. The imperative to avoid such miscarriages of justice calls for stringent quality control measures and transparent reporting of methodologies [58]. Furthermore, the concept of “genetic determinism” must be addressed, as attributing criminal behavior solely to genetic factors could oversimplify complex sociological and environmental influences [59]. Striking a balance between the weight of genetic evidence and other contextual factors is pivotal to ensuring a fair and just legal process.

From a legal perspective, the use of DNA evidence prompts discussions surrounding the admissibility of such evidence in court [60]. Courts must grapple with challenges related to the authentication of DNA samples, chain of custody, and the reliability of the analytical techniques employed [61]. Additionally, privacy concerns arise regarding the potential intrusion into an individual’s genetic information without their informed consent [62]. Clear legal frameworks need to be established to govern the collection, retention, and disposal of DNA samples, as well as the sharing of such data across jurisdictions [63].

6.2. *Genetic Privacy in the Age of DNA Analysis: Striking the Balance between Investigation and Individual Rights*

The advent of DNA databases has raised significant privacy concerns. The creation of expansive DNA databases, containing profiles of both suspects and individuals not directly linked to crimes, prompts debates over the potential for genetic surveillance and the erosion of personal privacy [64]. Striking the right balance between the investigative utility of DNA databases and the protection of individual rights necessitates robust regulations [65]. In the digital era, the protection of genetic privacy involves safeguarding not only the physical DNA samples but also the digital data derived from DNA analysis. Encryption and secure storage of genetic data are critical to prevent unauthorized access [66]. Additionally, mechanisms should be in place to ensure that DNA data are not used for purposes other than criminal investigations, such as insurance discrimination or employment decisions [67]. The challenges of cross-border investigations further complicate genetic privacy and legal considerations. International cooperation in sharing DNA data demands harmonization of legal standards to prevent misuse and unauthorized data transfers [68]. Developing international frameworks for genetic data sharing can promote effective collaboration while respecting individual privacy rights.

So, the integration of DNA analysis into criminal investigations has brought about a paradigm shift in modern justice systems. However, this progress must be accompanied by a keen awareness of the ethical and legal implications surrounding DNA usage. Striking the delicate balance between justice and individual rights requires robust regulations, transparent practices, and careful consideration of the potential risks and benefits of DNA evidence in criminal proceedings.

7. DNA's Impact on Exoneration and Closure"

7.1. *Redemption through Science: Empirical Evidence of DNA Exonerations and Wrongful Conviction Reversals*

DNA analysis has proven to be a powerful tool in the pursuit of justice by facilitating the exoneration of individuals who were wrongfully convicted. Empirical evidence highlights numerous cases in which DNA evidence has played a pivotal role in exonerating innocent individuals who were unjustly imprisoned. These cases underscore the significance of DNA analysis in rectifying miscarriages of justice and restoring the freedom and dignity of those who were wrongly accused. One landmark study conducted by the Innocence Project, a non-profit legal organization dedicated to exonerating wrongfully convicted individuals, revealed that DNA evidence was crucial in overturning convictions in approximately 367 cases in the United States alone [69]. These cases spanned a range of offenses, including rape, murder, and other serious crimes. The study demonstrated that DNA analysis not only helped identify the real perpetrators but also brought to light flaws in the criminal justice system, such as eyewitness misidentification and unreliable forensic evidence.

Further supporting the impact of DNA analysis on exoneration, research by Neufeld and Scheck [70] provides a comprehensive analysis of the role played by DNA evidence in cases of wrongful conviction. The authors detail how advancements in DNA technology have revealed instances of erroneous convictions and prompted systematic reevaluation of forensic practices.

7.2. *Bringing Closure: DNA's Role in Providing Solace to Victims' Families*

In addition to its role in exonérations, DNA analysis has also been instrumental in providing closure to victims' families who have endured years of uncertainty and pain. When a crime remains unsolved for an extended period, the lack of resolution can exacerbate the emotional toll on those left behind. DNA evidence has emerged as a means to address this aspect of the justice process, offering a path toward closure and healing. The case of Julie Doe, a young woman whose murder went unsolved for over two decades, serves as a poignant example of DNA's role in providing closure to victims' families [71]. Through advancements in forensic genealogy, which involves the use of DNA databases to identify potential relatives of the unknown suspect, law enforcement was able to identify the perpetrator and bring a sense of closure to Julie Doe's family. This case exemplifies the transformational power of DNA analysis in resolving cold cases and offering solace to those affected by crime. The emotional impact of such resolutions cannot be overstated. Families of victims not only seek justice but also yearn for answers and closure. DNA analysis has enabled law enforcement agencies to bridge the gap between unresolved cases and emotional healing, demonstrating its profound humanitarian significance.

DNA analysis has had a transformative impact on the criminal justice system, not only in advancing investigations but also in promoting exoneration and closure. Empirical evidence from cases of wrongful conviction reversals highlights the critical role DNA evidence plays in rectifying miscarriages of justice. Moreover, DNA analysis has proven to be a powerful tool in providing solace and closure to the families of victims whose cases have remained unresolved for years. The application of DNA technology in these realms underscores its crucial role in shaping modern justice systems and fostering a more equitable and compassionate approach to criminal investigations.

8. Expanding Horizons: Tracing Evidence, Touch DNA, and Forensic Genealogy

DNA analysis has continuously evolved and expanded its scope within criminal investigations, reaching beyond traditional applications to unveil hidden evidence, unlock secrets through touch DNA analysis, and even unravel lineages through the innovative field of forensic genealogy. These advanced techniques have significantly enhanced law enforcement's ability to solve complex cases, identify perpetrators, and provide closure to victims' families. This section delves into the remarkable developments in tracing evidence, touch DNA analysis, and forensic genealogy, underscoring their transformative role in modern criminal investigations.

8.1. Unveiling Invisible Clues:

DNA Analysis in Tracing Elusive Evidence Tracing evidence plays a pivotal role in criminal investigations, often requiring the identification of minute and invisible traces left behind by perpetrators. DNA analysis has revolutionized this aspect of forensic science, enabling investigators to link suspects to crime scenes even in cases where conventional evidence might be scarce. Through the use of advanced techniques such as polymerase chain reaction (PCR) and short tandem repeat (STR) profiling [72], DNA extracted from trace amounts of biological material, such as skin cells, hair, or bodily fluids, can be amplified and analyzed. This has led to breakthroughs in cases where conventional investigative methods fell short, providing crucial links between suspects and crime scenes that might have otherwise gone unnoticed.

8.2. The Fingerprint of the Unseen:

Unlocking Secrets with Touch DNA Analysis Touch DNA analysis represents a significant leap forward in forensic science, allowing investigators to analyze DNA samples obtained from surfaces that have been touched by individuals. Even the slightest contact can leave behind trace amounts of DNA, which can now be extracted, amplified, and profiled [73]. This technique has been instrumental in solving cases involving items like weapons, clothing, and vehicles, where direct biological evidence might be lacking. Touch DNA analysis has the potential to uncover connections between suspects and objects, shedding light on their interactions and potential involvement in criminal activities.

8.3. Unraveling Lineages:

Forensic Genealogy and its Transformative Role in Criminal Investigations Forensic genealogy has emerged as a groundbreaking approach to identifying suspects and victims by exploring their familial connections through DNA analysis. This technique involves comparing DNA profiles to public and private genealogical databases, enabling law enforcement to trace family trees and pinpoint potential relatives of an unknown individual [73]. The application of forensic genealogy gained significant attention following its success in solving high-profile cold cases, such as the identification of the Golden State Killer. By combining DNA analysis with genealogical research, investigators can not only establish the likely identity of an individual but also provide crucial context to their criminal activities and relationships. Forensic genealogy's transformative potential extends to cases involving unidentified remains, missing persons, and decades-old mysteries. By leveraging DNA databases and genealogical records, law enforcement agencies can bring closure to families who have long sought answers. However, the use of forensic genealogy raises important ethical and privacy concerns, as it involves the use of genetic information for purposes beyond the scope of individual consent [74].

The expansion of DNA analysis techniques to tracing evidence, touch DNA analysis, and forensic genealogy has ushered in a new era of possibilities in criminal investigations. These advancements have proven instrumental in solving cases that were once considered unsolvable, providing critical leads, and redefining the boundaries of justice. Nevertheless, as these techniques continue to evolve, it is essential to strike a balance between their potential benefits and the ethical considerations surrounding privacy and consent.

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