



(REVIEW ARTICLE)



Decoding the chemical clues: The role of advancements in forensic toxicology

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Magna Scientia Advanced Research and Reviews, 2023, 09(02), 063–071

Publication history: Received on 15 October 2023; revised on 22 November 2023; accepted on 24 November 2023

Article DOI: <https://doi.org/10.30574/msarr.2023.9.2.0157>

Abstract

Forensic toxicology, a crucial discipline in criminal investigations, has undergone significant advancements in recent years. This article delves into the realm of emerging techniques, analytical methods, and innovative applications that are revolutionizing the field. Advanced analytical techniques, such as high-resolution mass spectrometry, have enhanced the sensitivity and specificity of drug detection, enabling the identification of trace-level substances, including novel psychoactive substances (NPS). Emerging analytical methods, such as non-targeted screening approaches and biosensors, offer rapid and portable solutions for on-site drug detection. The article highlights the innovative applications of forensic toxicology, extending beyond traditional analyses. In postmortem toxicology, improved techniques aid in determining cause of death and assessing time of drug administration. In driving under the influence evaluation, roadside screening devices and pharmacodynamic models provide valuable insights into drug impairment. And in drug abuse monitoring and treatment, toxicological data informs public health interventions and treatment strategies. The article concludes by emphasizing the importance of continuous advancements in forensic toxicology to stay ahead of the growing complexity of toxicological challenges and address the ethical considerations surrounding advanced techniques. It underscores the significance of collaboration between forensic toxicologists, analytical chemists, pharmacologists, and clinicians to foster knowledge sharing and accelerate progress in this vital field.

Keywords: Forensic toxicology; NPS; Pharmacogenomics; Immunoassays; Chromatography; Mass spectrometry.

1. Introduction

Within the field of criminal investigations, where the pursuit of justice relies on unravelling the complex intricacies of human behaviour, forensic toxicology serves as a prominent avenue for scientific exploration. It sheds light on the chemical indicators of intoxicating substances and harmful toxins, which frequently hold the crucial insights necessary for uncovering the truth. This specialized discipline combines analytical chemistry, pharmacology, and legislation to detect, identify, and quantify drugs, poisons, and other dangerous compounds in biological material. [1, 2]

Forensic toxicology is crucial to criminal investigations. It is essential evidence in drug-related fatalities, DUIs, poisonings, and workplace accidents. Specific compounds and their quantities in body fluids and tissues might indicate impairment, cause of death, and criminal intents. [1, 2,3]

As the world of medicines and illegal drugs evolves rapidly, forensic toxicologists encounter more difficult issues. Novel psychoactive substances (NPS) that imitate restricted narcotics and avoid detection provide a major challenge. Toxicity analysis and interpretation are further complicated by polysubstance misuse, which is on the rise. [4]

Despite these obstacles, forensic toxicology must innovate. Modern analytical methods like high-resolution mass spectrometry can identify and quantify trace compounds like NPS. Explore alternate matrices including hair, saliva, and sweat to broaden drug detection and get insight into long-term drug exposure patterns. [5,6]

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Forensic toxicology is a dynamic, growing profession that helps achieve justice. As they advance knowledge and technology, forensic toxicologists remain dedicated to solving criminal investigations' chemical secrets.

2. Historical Perspective

The field of forensic toxicology has a rich historical background and has progressed from a basic comprehension of toxins to a complex scientific discipline that plays a crucial role in criminal inquiries. The evolution of this field is characterized by significant milestones and pivotal moments that have influenced its development. [7]

2.1. Antiquity and the Origins of Poison Detection

During ancient times, the presence of poisoning was often investigated by rudimentary methods that included the use of animals or oracles, which were thought to possess a divine capacity to detect toxic substances. Historical records provide evidence of early civilizations using rudimentary techniques to detect the existence of toxic substances, so establishing the foundation for contemporary scientific practices.[7]

2.2. Birth of Toxicology in the 19th Century

The scientific subject of toxicology was formalized throughout the 19th century. Mathieu Orfila, widely regarded as the father of forensic toxicology, authored the fundamental publication titled "Traité des poisons" in 1814. This influential book established systematic approaches for the identification and detection of poisonous substances inside biological samples. This event signified the inception of forensic toxicology as a formally organized area of academic inquiry. [8, 9]

2.3. Advancement of Analytical Techniques

The advancement of industrialization underscored the want for more accurate and dependable toxicological assessments. The later portion of the 19th century saw the emergence of more advanced chemical methodologies. Analytical techniques, including as spectroscopy and chromatography, emerged and gained prominence, offering toxicologists robust methodologies for the detection and measurement of many chemicals. [7, 8]

2.4. Landmark Cases and Legal Recognition

During the early 20th century, there was a notable incorporation of forensic toxicology inside legal frameworks. Prominent instances, such as the 1873 trial involving the arsenic poisoning of Mary Ann Cotton, served to emphasize the field's ability to expose criminal activities. Legal systems throughout the globe have increasingly recognised the significance of toxicological evidence within the context of criminal investigations. [1, 7, 8]

2.5. Technological Revolution in the Late 20th Century

The second half of the 20th century was marked by a notable technical revolution that brought about substantial changes in the field of forensic toxicology. The introduction of gas chromatography and mass spectrometry, together with advancements in DNA analysis, significantly enhanced the accuracy and dependability of toxicological inquiries, marking the start of a transformative period in the field of forensic research.

The present historical perspective provides a fundamental basis for comprehending the intricate complexity of forensic toxicology. The area has seen a significant transformation, evolving from historical suspicions to contemporary scientific rigour, in order to effectively address the difficulties associated with identifying chemical evidence in the quest for justice. [1, 7, 8]

3. Emerging Technology in Forensic Toxicology

Within the dynamic realm of forensic toxicology, a multitude of innovative methodologies has surfaced, fundamentally transforming the manner in which we decipher the complex network of chemical evidence. These innovative approaches, reminiscent of advanced technology, have revolutionized the limits of accuracy and effectiveness, bringing in a new age in the field of forensic sciences. As we venture into the heart of contemporary forensic toxicology, a triumvirate of technologies stands out as the vanguard in chemical analysis: mass spectrometry, chromatography, and immunoassays. [6]

3.1. Advancements in Mass Spectrometry (MS)

Mass spectrometry is a very sophisticated analytical technique that is considered to be at the forefront of scientific expertise. It is renowned for its exceptional precision and accuracy, sometimes seen as a kind of scientific wizardry. The focal point in this domain is on the integration of Liquid Chromatography-Mass Spectrometry (LC-MS/MS) with Quadrupole Time-of-Flight Mass Spectrometry (Q-TOF MS). These breakthroughs, similar to the revelation of the mysteries of the chemical cosmos, provide forensic scientists with unprecedented levels of precision and sensitivity. [10-12]

The use of high-resolution mass spectrometry (MS) has found several applications in scientific research and analytical chemistry. High-resolution MS enables the precise determination of the mass-to-charge ratio of ions, allowing for

The field of forensic toxicology is broadened by the use of high-resolution mass spectrometry (MS), which provides a precise method for detecting and measuring minute quantities of chemicals. This technical advancement elucidates the intricate intricacies of chemical composition, converting previously elusive information into a painstakingly recorded account. [12]

3.2. Chromatography Technique

Chromatography, a very versatile technique, demonstrates its efficacy inside forensic labs. The use of high-performance liquid chromatography (HPLC) and gas chromatography (GC) allows forensic scientists to effectively separate and identify intricate mixtures, hence facilitating precise analysis. The chromatograph assumes the role of a visual symphony, where each peak represents a distinct note in the intricate composition of chemical disclosure. [13, 14]

3.3. Immunoassays as Silent Detectives

Within the realm of forensic toxicology, immunoassays have emerged as discreet investigators, using the remarkable specificity of antibodies to unveil concealed realities. Immunoassays provide a quick and highly sensitive approach for deciphering the chemical enigmas present in biological materials, whether used for immediate on-site screening or post-mortem examinations. [1, 2, 15]

3.4. Advances in Analytical Techniques

The field of analytical techniques has indeed seen significant progress in recent years, driven by advancements in technology, the increasing complexity of data, and the growing demand for more accurate and efficient analytical methods. These advancements have led to the development of new techniques, the refinement of existing methods, and the broader application of analytical tools across various disciplines such as forensic toxicology.

3.5. Enhanced Sensitivity and Specificity

The pursuit of increased sensitivity and specificity emerges as the fundamental premise in the field of forensic alchemy. Mass spectrometry, due to its capability to detect even the most negligible amounts of chemicals, assumes a prominent position, hence raising the threshold for what was previously considered imperceptible. [1, 2]

3.6. Non-targeted Screening Approaches for NPS

The emergence of new psychoactive substances (NPS) has necessitated the use of non-targeted screening methods. Similar to the revelation of a covert manuscript, forensic experts use cutting-edge techniques to unravel the existence of these enigmatic substances, adeptly adjusting to the always evolving realm of recreational drugs. [16, 17]

3.7. Biosensors and Microfluidic Devices

The canvas of scientific research extends beyond the confines of conventional labs with the advancement of biosensors and microfluidic technologies. These portable devices provide analytical functionalities that may be used at crime scenes, thereby converting any given location into a prospective forensic laboratory. The prompt on-site analysis not only is a convenient option but also represents a paradigm leap in the field of forensic investigations.[8]

3.8. Exploration of Alternative Matrices

In addition to traditional matrices, the investigation of nontraditional sources such as hair, saliva, and sweat introduces additional levels of intricacy and understanding to the field of drug detection. Every distinct matrix of alternatives serves as an independent chapter, delving into the narrative of substance exposure and offering a nuanced viewpoint on a person's history of drug use. [6]

3.9. Data Analysis and Interpretation

Data analysis and interpretation play a crucial role in forensic toxicology, providing essential insights into the presence, identification, and significance of drugs, poisons, and other toxic substances in biological specimens. This information is critical for determining the cause of death, investigating potential drug abuse or poisoning, and assessing impairment or intoxication in legal proceedings.[17]

3.10. Application of Chemometric Techniques

The abundance of data requires advanced analysis, which prompts the use of chemometric methods. Similar to proficient craftsmen, forensic scientists use these methodologies for the purpose of identifying patterns and categorizing them, simplifying intricate collections of data into practical and applicable understandings.[18]

3.11. Development of Databases and Statistical Tools

In the contemporary era of digital forensic investigations, the establishment of resilient databases and the use of sophisticated statistical methods assume utmost significance. The use of digital archives and analytical tools has revolutionized the process of drug identification and interpretation, making it a smooth and highly accurate undertaking. [17-18]

3.12. Integration of Pharmacogenomics and Pharmacokinetics

The integration of forensic toxicology with pharmacogenomics and pharmacokinetics represents a significant advancement in comprehending the impacts of drugs. The use of this integrative methodology not only enhances the process of identifying drugs, but also deepens our understanding of personalized reactions to substances, so leading to a more comprehensive interpretation of forensic discoveries.

In the current epoch characterized by developments in forensic science, the integration of novel methodologies and analytical progressions drives the discipline beyond the limitations of previous eras. The laboratory serves as a platform for the orchestration of technical harmonies, with each element resonating with a dedicated pursuit of uncovering the enigmatic truths concealed inside the intricate realm of chemistry. [19, 20]

4. Innovative Applications in Forensic Toxicology

The domain of forensic toxicology has seen significant expansion beyond its conventional function of detecting and characterizing substances in biological specimens. In contemporary times, forensic toxicologists are effectively using their specialized knowledge in many novel contexts, therefore contributing to the resolution of criminal cases, safeguarding public well-being, and enhancing the quality of medical services. [1, 2, 18]

4.1. Postmortem Toxicology

Forensic toxicologists have a pivotal position within the field of postmortem toxicology, since they are crucial in ascertaining the underlying cause of death in instances characterised by drug intoxication. Sophisticated analytical techniques, such as high-resolution mass spectrometry (MS), have essentially replaced traditional approaches, such as enzyme-linked immunosorbent assays (ELISAs) and radioimmunoassay (RIAs), for drug detection in postmortem samples. [3]

4.2. High resolution mass spectrometry (HRMS) in forensic toxicology

The discipline of postmortem toxicology has been significantly transformed by the introduction of mass spectrometry (MS), which enables the detection and identification of minute quantities of drugs and their metabolites in various biological samples. As a result of these advancements, there have been notable improvements in the precision and responsiveness of drug detection, therefore empowering forensic toxicologists to discover instances of drug intoxication that could have been overlooked by conventional approaches.

Forensic toxicologists are now engaged in the advancement of methodologies aimed at determining the postmortem time of death and drug administration, in addition to their primary function of drug detection. The aforementioned data has significant importance in ascertaining the chronological order of occurrences preceding a fatality and discerning the individual accountable for the administration of pharmaceutical substances.

The results of forensic toxicology in postmortem cases provide significant insights into drug-related fatalities and play a crucial role in influencing public health initiatives. Forensic toxicologists have the capability to assist significantly to the advancement of preventive and treatment techniques by monitoring patterns in substance abuse and detecting nascent health hazards associated with drug use. [1, 2, 21]

4.3. Driving under the Influence (DUI) Evaluation

Forensic toxicology assumes a pivotal position in the assessment of drivers who are suspected of engaging in drug-impaired driving, often referred to as driving under the influence (DUI). In recent years, there has been a notable advancement in the complexity of roadside screening equipment, specifically oral fluid drug tests, which now possess the capability to swiftly identify an extensive array of illicit substances. Law enforcement authorities use these devices to detect drivers who may be under the influence, and the outcomes may serve as sufficient grounds for an arrest based on reasonable suspicion.[22]

In conjunction with roadside screening, forensic toxicologists perform thorough laboratory studies on blood and urine samples obtained from individuals suspected of driving under the influence (DUI). These investigations have the capability to identify a wider spectrum of medicines and metabolites, hence offering enhanced precision in quantifying drug concentrations inside the human body. [23]

There is ongoing development of pharmacodynamic models aimed at enhancing the evaluation of drug-induced impairment. These models include several aspects, including the kind of medicine, dose, and inter-individual variations in drug metabolism. Through the use of these models, forensic toxicologists are able to provide more knowledgeable assessments on the potential impairment of a driver at the moment of apprehension.

The formulation of explicit criteria and standards for the evaluation of driving under the influence (DUI) is necessary in order to guarantee the equitable and uniform nature of the adjudication process. Forensic toxicologists assume a pivotal part in the formulation of these rules and standards, so guaranteeing the proper utilisation of scientific evidence in instances pertaining to driving under the influence (DUI).

4.4. Drug Abuse Monitoring and Treatment

The use of forensic toxicological data enables the monitoring of patterns in drug consumption and the detection of developing health hazards associated with drug use. The data presented herein may be used to enhance public health interventions, including initiatives focused on drug education and prevention, as well as the formulation of novel treatment approaches.[4]

Forensic toxicologists have the capability to provide significant information pertaining to the variety seen in drug reaction and metabolism across individuals. The aforementioned data may be used to customise treatment regimens for specific patients and enhance the efficacy of pharmacotherapy. [4]

Forensic toxicologists are actively engaged in public health programs that seek to mitigate the adverse consequences associated with drug use. Through their contributions, these professionals play a crucial role in safeguarding public safety and enhancing the overall well-being of those impacted by substance usage. [1, 16, 22]

5. Challenges and Ethical Considerations

Despite the remarkable advancements in forensic toxicology, the field faces a unique set of challenges that demand careful consideration and continuous adaptation.

5.1. Sample Contamination and Degradation

The storage and treatment of biological samples play a critical role in ensuring the integrity of toxicological assessments. The presence of contamination, whether occurring by accident or with deliberate purpose, has the potential to provide inaccurate findings and pose a risk to the integrity of a legal proceeding. In order to maintain the integrity of evidence, forensic toxicologists are required to adhere to meticulous rules aimed at preventing contamination and preserving the chain of custody. [25]

Another obstacle is presented by the stability of medicines and metabolites in biological matrices. Over a period of time, the degradation of these chemicals may occur, resulting in challenges when it comes to their detection and

quantification. It is important for forensic toxicologists to possess knowledge on the degradation rates of certain medicines and then adapt their analytical methodologies appropriately. [25]

5.2. Legal Issues and Interpretation of Results

The complexity and challenges associated with interpreting toxicological data within the framework of legal processes are evident. Forensic toxicologists are required to demonstrate a conscientious awareness of the legal norms and principles that dictate the acceptability of expert evidence. In addition, it is essential for researchers to effectively convey the constraints and ambiguities inherent in their discoveries, refraining from excessive interpretation or making assertions that beyond the boundaries of their knowledge. [26]

5.3. Ethical Considerations Surrounding Advanced Techniques

The rapid development of sophisticated analytical techniques in forensic toxicology raises ethical concerns regarding the use of personal information and the potential for privacy violations. Forensic toxicologists must ensure that the collection, analysis, and storage of toxicological data adhere to strict ethical principles and data protection regulations. [27]

Moreover, the ability to detect increasingly trace levels of substances in biological samples raises questions about the interpretation of these findings in the context of drug use and impairment. Forensic toxicologists must carefully consider the relevance and significance of trace-level drug detections, taking into account factors such as individual variability in drug metabolism and the possibility of passive exposure. [27]

Forensic toxicology is a dynamic and evolving field that plays a critical role in the pursuit of justice and the protection of public health. As the field continues to advance, it is essential to remain vigilant in addressing challenges, upholding ethical standards, and ensuring that toxicological findings are interpreted and applied with the utmost integrity and scientific rigor. [27]

6. Future Directions

As forensic toxicology continues to navigate the ever-evolving landscape of drug use and analytical technologies, several promising advancements are poised to revolutionize the field and expand its scope of impact.

6.1. Potential Future Developments

6.1.1. Integration of Artificial Intelligence (AI) and Machine Learning

The fusion of forensic toxicology with artificial intelligence and machine learning represents a frontier where algorithms can analyze vast datasets with unprecedented speed and accuracy. Predictive modeling, pattern recognition, and automated data interpretation are poised to transform the efficiency and reliability of forensic analyses, enabling quicker and more precise insights into chemical clues. [28]

6.1.2. Microbial Forensics in Toxicology

The exploration of microbial forensics introduces a novel dimension to the field. Microorganisms present in biological samples could serve as additional indicators, offering insights into postmortem intervals and potential alterations in toxicological profiles. Ongoing research in this area may unveil a microbial signature that enhances the depth and reliability of forensic toxicological analyses. [29]

6.1.3. Advancements in Metabolomics

The continued evolution of metabolomics is set to revolutionize how forensic toxicologists understand and interpret chemical traces within the body. By delving into the intricate web of metabolic pathways, researchers aim to refine the identification of drug metabolites, providing a more comprehensive understanding of drug exposure and metabolism over time. [30]

6.1.4. Addressing the Rapidly Evolving Drug Landscape

The emergence of novel psychoactive substances (NPS) at an unprecedented pace poses a significant challenge to forensic toxicologists. The development of standardized protocols for NPS identification and interpretation is crucial for ensuring the accuracy and consistency of toxicological analyses. Collaboration with pharmaceutical and regulatory agencies to stay informed about new drug formulations and their potential for abuse is also essential. [31]

6.1.5. *Enhancing Data Interpretation and Integration*

The integration of pharmacogenomics and pharmacokinetics into forensic toxicology assessments holds immense potential for providing more comprehensive and individualized interpretations of toxicological findings. This approach can help forensic toxicologists better understand how individual genetic variations influence drug metabolism and response, leading to more informed conclusions about drug exposure and impairment. [16, 32]

The development of sophisticated data analysis tools, including artificial intelligence and machine learning algorithms, can aid in pattern recognition, classification, and interpretation of complex toxicological datasets. These tools can help forensic toxicologists identify hidden patterns, detect anomalies, and make more informed inferences from toxicological data. [1, 28, 16]

6.1.6. *Promoting Interdisciplinary Collaboration and Knowledge Sharing*

Fostering collaboration between forensic toxicologists, analytical chemists, pharmacologists, and clinicians is essential for addressing the complex challenges and maximizing the potential of forensic toxicology. Establishing international networks and platforms for information exchange can facilitate the sharing of knowledge, expertise, and best practices across borders.

Developing training programs and workshops to enhance the expertise of forensic toxicologists in emerging areas, such as NPS identification, pharmacogenomics, and data analysis, is crucial for ensuring the field's continued growth and adaptability.

The future of forensic toxicology is bright, brimming with opportunities for innovation and advancement. By embracing emerging technologies, fostering collaboration, and upholding ethical principles, forensic toxicologists can continue to play a pivotal role in unraveling the mysteries of drug use and its impact on society, ensuring justice and promoting public health. [1, 4, 18, 33]

7. Conclusion

In the ever-evolving landscape of criminal investigations, forensic toxicology stands as a beacon of scientific inquiry, illuminating the chemical mysteries that lie at the heart of justice. By harnessing the power of sophisticated analytical techniques and embracing innovative applications, forensic toxicologists continue to unravel the intricate threads of drug use and its impact on society.

From detecting trace-level substances in postmortem cases to assessing drug impairment in driving under the influence evaluations, forensic toxicology plays a pivotal role in shedding light on the circumstances surrounding crimes. As the field continues to push the boundaries of knowledge and innovation, it remains steadfast in its commitment to providing crucial evidence that aids in the pursuit of justice and the protection of public health.

In conclusion, forensic toxicology is an indispensable discipline that operates at the intersection of scientific rigor and legal implications. Its advancements and innovations are not merely technical achievements; they are keys to unlocking the truth and ensuring that justice prevails. As the field continues to evolve, it will undoubtedly play an even more prominent role in shaping the landscape of criminal investigations and safeguarding the well-being of society.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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