Forensic Chemistry: Science Serving Justice

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Forensic Chemistry and Chemistry are fundamental parts of Forensic Science, that, in its broadest sense, can be defined as the application of techniques and principles of Science for the purpose of administration of criminal justice system [1].

From an historical point of view, the chemical analysis of poisons can be considered the beginning of Forensic Science; as a matter of fact, Egyptians, Greeks and Romans used poisons both for murder and for the execution of death penalty. As well known, the philosopher Socrates was sentenced to death by drinking hemlock in 399 B.C., arsenic was a very popular poison in Roman times, and over the centuries, poisoning has been a popular way to eliminate a rival in true and imaginary stories, remember the fictional Sleeping Beauty.

To ascertain someone's guilt, circumstantial and hearsay evidence was generally used before the development of systematic scientific criminal investigation procedures. The first instance of an actual chemical test for poison is the Blandy trial conducted March 3, 1752, that was of some forensic interest because of the expert testimony about the arsenic poisoning presented by Anthony Addington. He was the doctor who had treated Francis Blandy, the father of Mary who poisoned him with arsenic, but was claiming that she thought the arsenic was a love potion that would make her father approve of her relationship with an army officer William Henry Cranstoun. Addington put a sample of the powder Mary had given her father into cold water: a part remained on the water surface, while most of it remained on the bottom undissolved, the same behavior of a known sample of arsenic. Moreover, the powder tossed onto a red-hot piece of iron sublimated without burning, rising up in garlic-smelling white clouds just as arsenic did. Although rudimentary by today's standards, the possibility of testing traces of arsenic was quite fascinating in the 18th century and allowed Addington to develop a brilliant career.

In recent years, Wilmer Souder, shown in Fig.1, helped pioneer the field of Forensic Science while working at the National Bureau of Standards, the forerunner of the National Institute of Standards and Technologies. This new Science is largely a matter of metrology, the science of measurements, and Souder anticipated several of today's questions, calling for more precise measurement methods and more stringent standards overall.

He helped send countless murderers, bootleggers, gangsters and thieves to prison, while keeping a low profile partly out of concern for his and his family's safety, thus exerting an influence that was not as great as it might have been on the developing field of Forensic Science. He was one of the experts in the Trial of the Century, which ended on February 13, 1935 with the sentence of Bruno Richard Hauptmann, for kidnapping and killing the 20-month-old son of aviator Charles Lindbergh. The handwriting exhibited as procedural evidence at trial was analyzed by Wilmer Souder who testified that it

Fig. 1. Wilmer Souder developed a technique still in use today to assess if bullets are fired from the same gun: the comparison by means of a comparison microscope of the rifling marks left on the bullets [2].

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was attributable to Hauptmann, thus contributing the accused being sent to the electric chair.

Modern Forensic Science is today an interdisciplinary field: various disciplines such as engineering, computer science, entomology, anthropology, pathology, physics, nursing, and psychology, etc. all contribute to it. As a matter of fact, any discipline, profession, or trade with an expertise that can help in crime solving activities will fall under the umbrella of Forensic Science.

Remembering that chemistry is the branch of science that deals with the study of the composition of matter and of its different transformations, Forensic Chemistry is a specialized sub-field of Forensic Science that involves the application of techniques and principles of chemistry to the field of forensic investigation, to aid in the resolution of legal matters [3]. Forensic Chemistry involves complex procedures of chemical analysis that are used to identify unknown substances, to detect the presence or absence of controlled substances. The identification procedures are based on the physical and chemical properties of the unknown substance supported by the analytical data [4].

As a matter of fact, many forensic scientists are chemists, who employ their knowledge of chemistry to analyze evidence that can be found on materials such as drugs, fibers, paint, soil, charred debris, glass, documents, paper, tool marks, firearms, explosives, etc. Forensic Chemists, thanks to their knowledge in toxicology, fingerprints, footwear impressions, tire impressions, hair analyses, etc., may perform different analyses by means of traditional and innovative analytical techniques to determine the nature and composition of evidence collected from the crime scene and compared with the control samples, when required. Forensic Chemists, when called on in the courts, have to provide testimony as expert witnesses.

The first principle of crime scene investigation is that every contact leaves a trace. Consequently, for a correct evaluation of the crime scene, it is fundamental that physical evidence is properly sampled, packaged and sealed in special containers. The integrity of evidence has to be maintained and any further contamination has to be avoided, except for their natural contaminants such as dirt and debris that are often present.

Every substance that is collected from the scene of crime has a unique composition that can ultimately be identified. Arsonists, as an example, often use accelerants such as kerosene or gasoline to accelerate the rate of combustion, and each accelerant has its own unique composition. A Forensic Chemist may search for and collect burnt and unburnt material samples, extract the volatile hydrocarbons from them, and may use gas chromatography to separate the components of these samples.

During any investigation, the most probative evidence is sent to the forensic laboratory, after the crime scene personnel may perform initial screening tests called presumptive tests at the crime scene. These tests allow investigators to narrow the field of the possibilities to a certain class of substances although they are not specific enough to confirm the presence of specific compounds. This procedure helps to speed up the investigation.

Fields of Analysis

Forensic Chemistry deals with the chemical analysis of a wide variety of physical evidence deriving from homicides, arsons, assaults, robberies, frauds, etc. as shown in Fig. 2.

Due to the fact that organic and inorganic analyses have to be performed, a wide range of analytical techniques are generally employed in forensic analyses, to conduct both presumptive and confirmatory tests that serve as the basis for criminal proceedings and help to determine sentencing for convicted offenders. The choice of the proper technique and instrumentation to be used depends on the type of sample to be analyzed.

The Method of Analysis

All of the above-mentioned analyses are based on the principles of the scientific method, which begins with observations: Forensic Chemists attempt to organize observations and look for trends or patterns, suggest a hypothesis that tentatively explains what is being observed and devise a plan to test the hypothesis. They carry out the plan, making further observations, and if the new observations contradict the original hypothesis, a new hypothesis is suggested and tested, and the cycle continues until the hypothesis has been sufficiently validated.

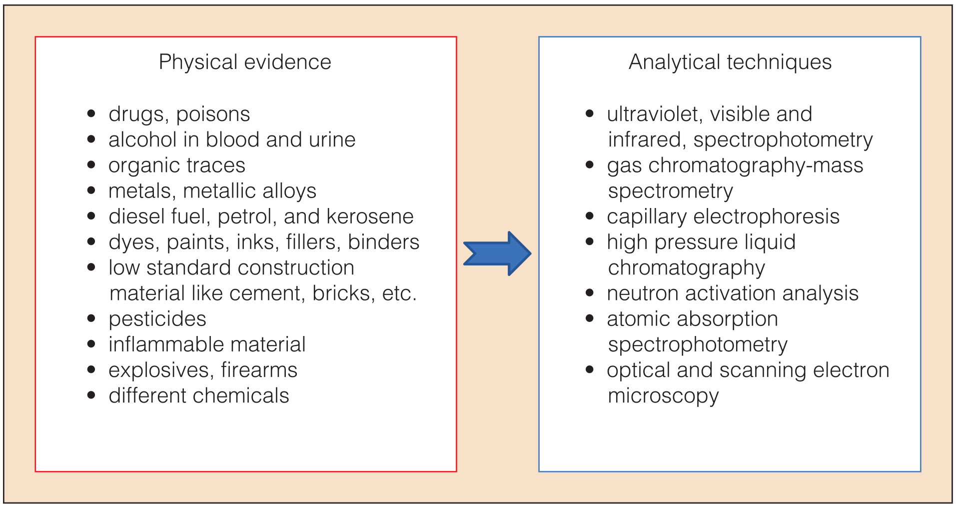


Fig. 2. Forensic Chemistry: physical evidence collected on the crime scene and analytical techniques utilized by Forensic Chemists for their analysis.

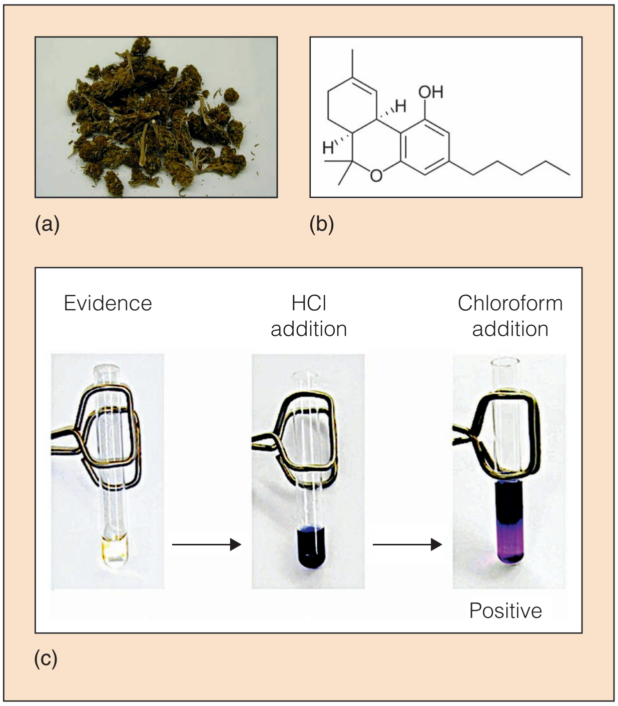


Fig. 3. Physical evidence. (a) Crushed vegetable; (b) Cis-delta-9-tetrahydrocannabinol, the main psychoactive constituent of cannabis; and (c) The detection with the Duquenois-Levine test, a screening test for marijuana [5].

When an unknown substance is submitted to a crime laboratory, the Forensic Chemist observes the properties of the substance. As an example, in the presence of a crushed and dried green-leafy material, the chemist can make hypothesis that the unknown substance is marijuana. He devises a plan to test the hypothesis: to view the substance under the microscope looking for properties of crushed marijuana leaves, and if the microscopic observations validate the hypothesis, he will make the reaction with the Duquenois-Levine reagent, a widely used presumptive test for tetrahydrocannabinol and other cannabinoids. The Duquenois-Levine reagent is a solution containing 2% vanillin and 1% ethanal, and after the addition of concentrated hydrochloric acid and chloroform, the chloroform layer becomes red purple if the drug is present, as shown in Fig. 3. If the result is negative, the Forensic Chemist makes another hypothesis, such as the unknown substance could be oregano, and tests this hypothesis with a proper analysis. If the hypothesis is not verified, the Forensic Chemist goes on with another hypothesis and so on, until a positive match is obtained.

Over the past decade, new and more dangerous synthetic drugs entered the market. Their identification is a noteworthy challenge because their chemical composition is continuously altered by producers in the attempt to circumvent the law and to avoid prosecution.

The Important Case of Blood Stains and Urine Analysis

Forensic Chemistry considers a wide range of evidence, and one of the most important and frequently performed types of analysis is the search for traces of drugs or poisons in samples of blood stains or urine [6]. Considerable effort is spent on drug screening of people, as employees or athletes for example, to detect the presence of performance-enhancing drugs. In this case, the role of Forensic Chemists is to discriminate, by means of accurate and cost-effective tests, between the external addition of illegal drugs and metabolites coming from foods like poppy seeds or from drugs intentionally taken at the suggestion of a doctor. Moreover, from a scientific point of view, drug metabolites exist in hair as the result of complex processes that probably include combination of incorporation and metabolism in hair/hair bulb.

These tests may be simple color tests or may involve different instrumental techniques more or less complex [7]. Paper or thin-layer chromatography, gas chromatography, or electrophoresis may be employed for the analysis of different toxins. In cases of deaths from unknown causes, samples of blood, lungs, urine, stomach contents and vitreous humor of the victims are examined for traces of poisons. Furthermore, insects found on dead bodies are another source of information, because they not only may absorb drugs or poisons from the body in trace amounts but maintain them even when the concentrations in the body have decreased.

From a single drop of blood, by analyzing the chemical compounds as well as measurable morphological characteristics of the resulting bloodstains, interesting information about the source of bleeding, impact surface and mechanisms of the formation of bloodstains can be obtained.

Long before DNA analysis, blood samples were collected and analyzed in crime laboratories with tests based on peroxidase, an enzyme found in blood, that acts as a catalyst for the reagent added to the blood and gives a characteristic color to the solution of dried blood and water: blue for the addition of benzidine or pink for the addition of phenolphthalein, as shown in Fig. 4.

An immunochromatographic procedure for the qualitative indication of human blood is intended for selective use when human origin of suspected bloodstains is questionable and/or when the determination of the indication of human origin is time sensitive. Limited sample size may preclude the use of this test to allow future DNA testing.

More specific tests are then applied to determine if the blood is human. The evidence available through blood typing is not as convincing as genetic fingerprinting, but it can readily prove innocence or increase the probability of a defendant being guilty. All humans belong to one of four blood groups (A, B, AB, O), based on genetically determined antigens (A and/or B) that may be attached to the red blood cells. These antigens may be present or absent in blood, and by adding specific antibodies (anti-A or anti-B), the presence or absence of A and B antigens can be determined.

If a person accused of a homicide has type AB blood and it matches the type found at the crime scene of a victim, the evidence for guilt is more convincing than if a match was found for type O blood, because only 4% of the population has type AB blood. The higher the number of rare factors in

Fig. 4. Human Blood Identification test (ABACard® Hematrace): left strip shows a positive reaction to human blood, while the right strip indicates a negative reaction; the upper, darker purple line is a control band indicating that the test worked properly, and the lower, lighter purple band, visible only on the positive reaction to the left, is the test band that appears if human blood is detected.

the blood of an accused person, the more convincing is the evidence.

The first instance in which the forensic analysis of bloodstains was used in the conviction of a criminal was in the beginning of the last century for the Mad Carpenter, Ludwig Tessnow a German serial killer known also as the Monster of Rügen. In 1895, in Lechtingen, he abducted and killed two young girls, leaving their bodies dismembered and butchered in some nearby woods. Tessnow was identified as having been in the vicinity of the murder scene, but when questioned about the stains on his clothing, Tessnow claimed the spots were from wood dye, not unusual for a man whose trade was carpentry. In 1901, when he committed murders again, pioneering precipitin testing enabled Forensic Chemists to prove his clothing had been extensively stained with both human and animal blood, despite his claims to the contrary. Tessnow was arrested, convicted and executed in 1904.

Thallium and Arson

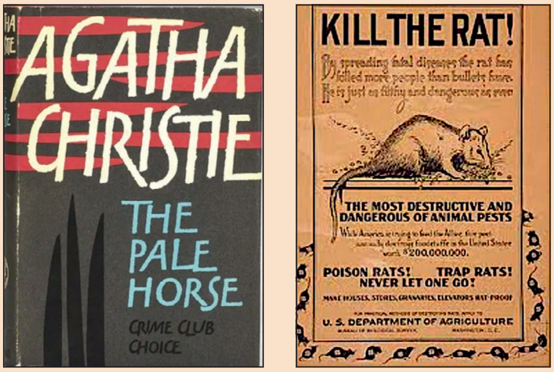
It might be interesting to discuss two examples related to crimes involving a poison and fire that resulted in the culprit being executed.

The Thallium

George Trepal, also known as the Mensa Murderer because he was a member of the high intelligence quotient (IQ) Society Mensa, committed the almost perfect crime. As well-known, Mensa is the largest and oldest non-profit organization open to people who score at the 98th percentile or higher on a standardized, supervised IQ or other approved intelligence test. Trepal lived in Florida and had noisy neighbors, at whom for years he yelled to turn their music down. Then, suddenly the members of the family came down with a mysterious illness, one of them died and the others were in critical condition. The doctors, with the help of Forensic Chemists, ultimately determined the cause to be thallium poisoning. As a matter of fact, residue of thallium was found in Coke bottles found in the house of the victims and coincidentally in the house of Trepal, where it was possible to find chemistry books and equipment, poison information, a bottle-capping machine and a copy of the novel *The Pale Horse* by Agatha Christie, a story in which a family is poisoned by thallium (Fig. 5a). The murderous genius was taken to a trial and sentenced to death.

In terms of detection, once spotted, thallium poisoning can be confirmed via tests on the victim's urine. A rapid test can be carried out on a urine sample using bismuth nitrate, nitric acid and sodium iodide, which gives a red precipitate in solution if thallium is present. However, on occasion, false positives can be obtained from this test, so instead atomic absorption spectrophotometry is more commonly used. Thallium gives a characteristic absorption of light using this method that can be utilized to identify its presence.

The toxicity of thallium, widely used as a pesticide mostly for killing rats, is due to its similarity in properties to potassium and sodium ions (Fig. 5b). Potassium ions have a number of roles in the body, including the transmission of messages through nerves; however, the body cannot distinguish between thallium and potassium, and the incorporation of thallium ions instead means that these roles cannot be carried out. Unless given in a high dose, thallium is an agent that exerts its effects slowly. Its early symptoms are very non-specific, including gastrointestinal problems, such as vomiting, or merely nausea. Two weeks into the poisoning, the patient



(a) (b)

Fig. 5. Thallium poison. (a) *The Pale Horse*, a work of detective fiction by Agatha Christie first published in the UK by the Collins Crime Club on 1961; (b) Advertising poster of 1930 on thallium used as a pesticide for killing rats.

starts to exhibit a symptom that is typical of thallium poisoning: a dark pigmentation will begin to appear around the roots of the hair. This symptom rapidly progresses to complete loss of the hair and alopecia. For this reason, the United States Central Intelligence Agency, in addition to several hundred unsuccessful attempts to assassinate Fidel Castro, tried to organize a *Character assassination* using thallium salts spread on the shoes, to destroy Castro's famous beard [8].

There is no real antidote for thallium poisoning, in the sense that there is no known agent that will remove thallium from the body once it has already been absorbed in the gastrointestinal tract. However, a number of agents can be administered to prevent it from being absorbed or reabsorbed. The primary agent used in cases of poisonings is Prussian blue, although it is toxic itself and must be administered in moderate doses.

Arson

Arson is a serious crime that affects society through cost, property damage, and loss of life. Everybody nowadays has heard of the terrible arsons that occurred in several part of the world and in particular in the last few years that involved the Amazonian forest and the Australian continent. A well-studied case, which brought to arrest the arsonist is reported, although it is not as impressive as those presented before.

Throughout the 1980s and 1990s, California was plagued by a series of arson fires: one of the fires resulted in the loss of 65 houses, and another fire in an hardware store killed four people. Investigators combed the areas and searched for clues; however no clear pattern was found. An investigator noticed the odd coincidence that the pattern of arsons was occurring near the city of Fresno that was the host city of a convention of arson investigators. The police started with a list of 55 possible suspects that after several years and fires was finally narrowed down to John Orr, a respected arson investigator, who was convicted of four murders and sentenced to life plus 20 years in prison without the possibility of parole. Arson investigators and criminal profilers defined Orr the Pillow Pyro, one of the worst serial arsonists of the 20^{th} century. Orr used the same incendiary device for all of his nearly 2000 blazes: a cigarette attached to a book of matches wrapped in paper with cotton and bedding, hence the nickname, secured with a rubber band; the cigarette would burn down, and the matches would ignite the paper and bedding.

The methods and technologies applied by fire investigators in detection of evidence and subsequent analyses had considerable advances since 1950, increasing their degree of reliability and sensitivity, and were more and more subject to rigorous quality control and assurance. The classification of ignitable liquids is continuously updated to include many new categories due to developments in the petroleum industry. Techniques such as steam or vacuum distillation and gas chromatography (GC) with flame ionization detection considered acceptable, even a benchmark, forty years ago, are nowadays generally disfavored, to the extent that their implementation may almost be considered as ignorance in the field. The advent of readily available mass spectrometric techniques has revolutionized the field of fire debris analysis, noteworthy increasing the degree of sensitivity and discrimination [9]. Multi-dimensional GC, particularly GC x GC, Comprehensive Two-dimensional gas chromatography, while not yet widely applied, is rapidly gaining recognition as an important technique [10].

In the field of investigation of arson fires there is a continuous research of more efficient and sensitive vapor collection methods as this one that involves the dynamic adsorption of headspace vapors on short porous layer open tubular (PLOT) columns maintained at low temperature, around -40 °C. The collection sensitivity is high, below 1 part per billion (ppb). The low temperature is achieved using a vortex tube connected to compressed air, with no moving parts, good for use in environments with explosive or flammable materials. After vapor collection, the PLOT capillaries can be heated, up to 160 °C, releasing the vapor. The PLOT-cryo method can be used to simultaneously test for up to eight different ignitable liquids from a single sample, allowing investigators to take multiple samples from each of several locations in a fire scene in a short time.

Fires, Explosions

In may be interesting to underline that the Forensic Chemistry approach is important in assessing liability for events such as fires that are not always intentional arsons, as described before, or explosions. As a matter of fact, the use of explosives may be legitimate, as in mining activities and military operations, or may be illegal, to cause death and destruction by criminals and terrorists. Consequently, the main goal of an investigation on explosives is to assess if the event is accidental or deliberately set up. Several analytical techniques are used to analyze the post-blast explosive residues; the most popular are infrared spectroscopy, Raman spectroscopy, gas chromatography/mass spectrometry, and energy dispersive X-ray analysis.

An accurate investigation of the blast site is of outstanding importance, from structural damages to injuries, to the collection of fragments, such as circuit boards, switches, or timers possibly coming from the exploded device, accelerants, tampered utilities, specific burn patterns in case of fires, and residues of the explosive. To identify the chemical composition of the explosive, Forensic Chemists may utilize *in situ* analytical techniques, such as ion-mobility spectrometry (IMS), commonly used to separate and identify ionized molecules in the gas phase on the basis of their mobility in a carrier buffer gas. In particular, hand-held IMS detection devices are used to characterize residues present around the blast site [11].

Dealing with fires, in addition to ultraviolet, infrared and nuclear magnetic resonance spectroscopy to identify accelerant components, the most widely used technique is gas liquid chromatography, which is able to separate and detect trace amounts of volatile hydrocarbons in complex mixtures, such as the four most common accelerants petrol, kerosene, mineral turpentine and diesel. Even if the samples are evaporated and contaminated, Forensic Chemists are confident in identifying these compounds on the basis of their gas chromatograms.

However, to make a positive identification, a large number of the components present has to be identified, and their ratios have to be very similar to that of a standard.

Lithium-ion Batteries

Due to the outstanding development of their technology over the last three decades, lithium-ion batteries are now extensively used in electronic devices, both of industrial interest and consumer-grade portable systems. These devices mostly safe, however they carry a risk of explosion, and the resulting injuries range in severity from superficial burns of low entity to death in the most unlucky situations [12]. The U.S. Consumer Safety Commission reported in February 2018 that in the previous five years, over 25,000 overheating or fire incidents occurred involving a wide range of devices. Meanwhile the Federal Aviation Administration (FAA) reported, in January 2020, that lithium-ion batteries were involved in 280 incidents on aircraft or in airports since January 2006 [13]. Moreover, in October 2016, the FAA banned passengers from carrying Galaxy Note 7 devices on commercial aircraft after a series of fires were caused by the phones. Samsung, the manufacturer, recognized that errors in design and manufacturing in the batteries were the cause of fires and took actions to induce customers to stop using their phones.

The investigations carried out in the framework of Forensic Science, and more specifically of Forensic Chemistry, of the incidents involving lithium-ion batteries are devoted to determine the cause, the possible manufacturing or design defect including review of safety devices, the inadequacy of the instructions or warnings given to the users, and the ignorance of the instructions by the users.

As a matter of fact, the forensic approach, in order to identify battery status, addresses the full range of critical characteristics, through the examination of the battery composition, morphology and fundamental chemical/physical properties by means of thermal analysis and electrochemistry assessment. In particular, after overheating, the composition of the materials or components may change, with a consequent swelling that results from the decomposition of electrolyte materials and leads to excess pressure within a cell. The porosity of the separator at different layers and different locations within a cell allows it to develop a profile of the distribution of the overheating conditions, and finally, the thermal properties may be changed due to the material degradation effect caused by aging. All the work carried out allowed several common causes of failure of lithium-ion batteries to be identified: defects of batteries and/or of charging equipment; battery damage or mechanical damage; and wrong charging, electrical abuse and thermal abuse [14].

As an example, Fig. 6 shows a Samsung Galaxy Note 7 device which contains a lithium-ion battery that caught fire during a test at the Applied Energy Hub Battery Laboratory of Singapore [15].

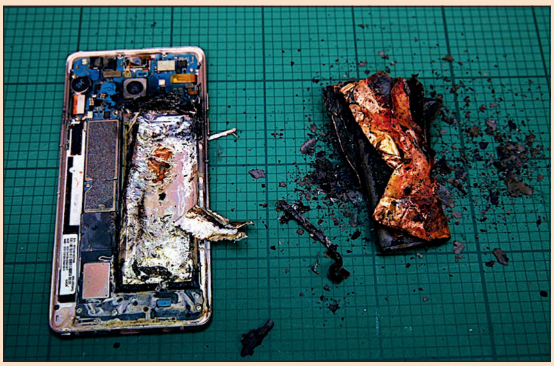


Fig. 6. Destructive test carried out in a controlled environment on a device containing a lithium-ion battery, which caught fire [15].

Forensic Chemistry for the Environment

In recent times, Forensic Chemists are more and more involved in systematic investigations of the polluted sites or accidents that badly impacted the environment [16]. In newspapers often it is possible to read about an environmental lawsuit, and from even small releases of pollutant, dramatic damages and large cleanup costs may derive. Petroleum, ubiquitous as an environmental contaminant, is frequently the subject of concern: from 2010 to 2020, the loss of 164,000 metric tons of oil occurred in more than 60 accidents, of which just 10 incidents were responsible for more than 90% of the spilled oil.

Due to its complex chemical composition, it is really difficult to determine the true nature and the origin of petroleum spills, and consequently, it is difficult to ascribe the responsibility for and ownership of contamination. Methods that are technically sound are needed to help in the elaboration of defensible opinions on the age and the sources of contamination in the field of environmental tort litigation.

Environmental chemistry techniques are employed to decipher the source and fate of pollutants as well as to determine their age [17]. For example, the Gas Technology Institute and META Environmental Inc. developed an extensive database of pyrogenic and petrogenic chemical fingerprints by using gas chromatography coupled with a flame ionization detector (GC/FID) or with a mass spectrometer (GC/MS). The chemical fingerprinting techniques are successful in discerning wastes from completely different sources, such as Manufactured Gas Plant (MGP)-type wastes from different plant operations.

In order to avoid the low sensitivity of these techniques in the identification of polycyclic aromatic hydrocarbon (PAH), a new analytical method for the measurement of urban background PAH contamination was developed. This method utilizes a gas chromatography isotope ratio mass spectrometer (GC/IRMS) to measure the compound-specific isotope ratio (CSIR) carbon and reveals a great potential as an environmental forensic method.

On Site Investigations

In the last ten years, the outstanding importance of collecting data on the crime scene in the first hours after the criminal event, to have insights on the identity of potential suspects, became more and more evident [18]. Consequently, real-time and on-site forensic investigations gained increasing popularity because they avoid the delays that occur when evidence has to be collected, delivered and analyzed in laboratory. On-site devices have revealed their usefulness in the investigations on sexual aggressions: a simple preliminary on-site DNA analysis could help to decrease the number of suspects, to focus the work of police authorities.

Recently, the number of presumptive tests for screening samples is noticeably increased due to the development of portable sensors, chip-based systems and handheld instruments for in-field analysis of forensic interest, as well as of robust and validated methods capable of providing reliable analyses on the crime scene. Miniaturized platforms including electrochemical sensors, paper-based analytical devices, microfluidic devices and portable instruments like mass, Raman and near-infrared (NIR) spectrometers allow this improvement in reliability of measurements, in the lower consumption of sample and reagents, in the low-cost per analysis and in the need for minimal instrumental training.

Electrochemical methods satisfy most of the above-mentioned requirements for on-site and *in-situ* measurements, and furthermore, the use of sensor strips, e.g., screen-printed electrodes (SPE) instead of the conventional three-electrode electrochemical cells, overcame the difficulty in electrodes handling and the need for frequent calibration due to poor stability as a function of time due to electrode poisoning.

From one side, the detection of potentially explosive compounds and drugs will take advantage of different possible approaches, from paper-based devices to the electrochemical and microchips electrophoresis methods of similar sensitivity. From the other side, the constant development of portable mass spectrometers and NIR analyzers provides a powerful way to identify new substances. In any case, the portable instruments offer great advantages for forensic applications including rapid, sensitive and accurate analysis of abused drugs, banknotes, questioned documents, and signatures as well as the real possibility to use them at airports, seaports and police operations at borders between neighboring countries. Finally, the coupling of wireless data systems for data acquisition and transmission and simpler readout interfaces for operators to reduce subjectivity and allow rapid decision making will further increase the versatility of portable devices.

Measurement Uncertainty in Forensic Chemistry

Only in recent times in Forensic Chemistry and Toxicology has more attention been paid to measurement uncertainty of critical quantitative values, such as mass, concentration, purity, or volume, thus introducing a new level of anxiety among many forensic scientists. This reaction occurs with other unfamiliar concepts, notwithstanding the fact that ISO 17025-based accreditation programs have the essential requirement of uncertainty evaluation of a critical measurement for analytical laboratories seeking and maintaining accreditation [19].

Forensic Chemists, for example in the field of toxicology, carry out both quantitative and qualitative analytical measurements, but do not consider or provide the formalization of measurement uncertainty, although they have a conceptual understanding of measurement uncertainty. To actually compute a statistically valid estimate of uncertainty, taking into account all the relevant factors, is not easy, and Forensic Chemists prefer to report it in an intuitive form that is intelligible for a jury. As a matter of fact, the primary customers of forensic chemical analyses are the courts and members of the legal community, who previously were not too convinced of the relevance of measurement uncertainty. Nowadays, in several jurisdictions the legal community is becoming more and more aware of the concept and is now demanding uncertainty evaluation, in order to judge the quality and validity of the presented measurements. This renewed interest in measurement uncertainty is favored by reports such as the 2009 one of the National Academy of Sciences, that highly criticize the lack of a strong scientific foundation for the claims and practices of Forensic Sciences [20].

The study of uncertainties that arise in measurements and propagate through calculations and inferences are of noteworthy importance for arriving to reliable conclusions in DNA sequencing applications. The dramatic increase in the measurements made at the biochemical and molecular level has to be attributed to development of high-throughput DNA sequencing technologies. As a matter of fact, the different DNA-sequencing technologies produce data with their own platform-specific errors and biases which have a wide range of variation. Several statistical studies were performed with the aim of measuring error rates for basic determinations; however, no general scheme is sufficiently able to project these uncertainties to assess the reliability of the conclusions drawn about biological, genetic and epigenetic questions. Both uncertainty in the quantification in DNA sequencing applications and descriptions of the sources of error need to be deepened, as well as the proposal of methods that can be used for accounting and propagating these errors and their uncertainties through subsequent calculations [21].

As a final observation, in Forensic Chemistry and more generally in Forensic Sciences, there is, without any doubt, a need to address more widely the issue of measurement uncertainty and to develop competencies in computing, reporting and explaining this fundamental item.

Concluding Remarks

To conclude this brief introductory work, it is interesting to note that Forensic Chemistry is becoming more and more popular as shown by the diffusion all over the world of prime-time television programs such as CSI: Crime Scene Investigation, Law & Order, Criminal Minds, and Cold Case which all center on the criminal justice system. The vision that is conveyed in these programs, of being able to solve crimes through very complex investigations in one hour or less, is very optimistic although stimulating for the viewer. Unluckily, in real life the collection and analysis of evidence involves painstaking care and rigorous application of scientific principles.

In addition to these television shows, the media definitely contributed to the increase in attention paid to Forensic Science; as a matter of fact, the coverage of popular criminal cases has brought the crime scene investigation and forensic analysis out of the laboratories and into the public.

From a scientific point of view, Forensic Science has a promising future due to the utilization of new methods and technologies as well as the ability to capture and process huge amount of data [22]. For example, if the discovery and utilization of DNA has transformed current-day Forensic Science, the continuous evolution of detection technologies will further increase the understanding of trace DNA transfer, persistence, prevalence, and recovery. New discoveries can create incremental evolutionary changes or revolutionary changes that will reshape the face of Forensic Chemistry as well as Forensic Science altogether.

References

[1] C. Roux, F. Crispino and O. Ribaux, "From forensics to forensic science," *Current Issues in Criminal Justice*, vol. 24, no. 1, pp. 7-24, 2012.

[2] R. Press, "Who was detective X?" National Institute of Standards and Technology, Feb. 2017. [Online]. Available: www.nist.gov/featured-stories/who-was-detective-x.

[3] D. Rendle, "Advances in chemistry applied to forensic science," *Chemical Soc. Reviews*, vol. 34, no. 12, pp. 1021-30, 2006.

[4] R. Chophi, S. Sharma, S. Sharma and R. Singh, "Trends in the forensic analysis of cosmetic evidence," *Forensic Sci.*, vol. 14, 100165, Jun. 2019.

[5] Colorado Green Lab. [Online]. Available: www.coloradogreenlab.com.

[6] K. Pokupcic, "Blood as an important tool in criminal investigations," *J. Forensic Sci. Criminal Investigation*, vol. 3, no. 2, May 2017.

[7] B. Zanfrognini, L. Pigani and C. Zanardi, "Recent advances in the direct electrochemical detection of drugs of abuse," *J. Solid State Electrochemistry*, Jun. 2020.

[8] E. Fabián, *CIA Targets Fidel: Secret 1967 CIA Inspector General's Report on Plots to Assassinate Fidel Castro*. Melbourne, Vic., Australia: Ocean Press, 1996.

[9] M. P. V. Matos and G. P. Jackson, "Isotope ratio mass spectrometry in forensic science applications," *Forensic Sci.*, vol. 13, May 2019.

[10] G. Gruber, B. A. Weggler, R. Jaramillo, K. A. Murrell, P. K. Piotrowski and F. L. Dorman, "Comprehensive two-dimensional gas chromatography in forensic science: a critical review of recent trends," *Trends in Analytical Chem.*, vol 105, pp. 292-301, May 2018.

[11] R. Cumeras, E. Figueras, C. E. Davis, J. I. Baumbach, and I. Gracia, "Review on ion mobility spectrometry, part 1: current instrumentation," *Analyst*, vol. 140, no. 5, pp. 1376-1390, 2015.

[12] T. L. Palmieri, J. Yelon J. D. Shapiro, T. Duncan and D. Kuhls, "Lithium batteries: a technological advance with unintended injury consequences," *J. Trauma Acute Care Surgery*, vol. 85, no. 2, pp 406-409, 2018.

[13] "DOT bans all Samsung Galaxy Note7 phones from airplanes," Federal Aviation Administration (US), 10 March 2020. [Online]. Available: https://www.faa.gov/news/updates/?newsId=86685.

[14] A. R. Baird, E. J. Archibald, K. C. Marr and O. A. Ezekoy, "Explosion hazards from lithium-ion battery vent gas," *J. Power Sources*, vol. 446, no. 257, pp. 1-13, 2020.

[15] Z. Epstein, "Watching a samsung galaxy explode note 7 is terrifying," NY Post, Oct. 2016. [Online]. Available: https://nypost.com/2016/10/07/watching-a-samsung-galaxy-note-7-explode-is-terrifying/.

[16] D. L. Saber, D. Mauro and T. Sirivedhin," Applications of forensic chemistry to environmental work," *J. Ind. Microbiol. Biotechnol.*, vol. 32, pp. 665-688, 2005.

[17] S. A. Stout, A. D. Uhler, T-M. Nyamik, and K. J. McCarthy, "Environmental forensics: unraveling site liability," *Environmental Sci. Technol.*, vol. 32, 260A-264A, 1998.

[18] W. R. de Araujo, T. M. G. Cardoso, R. G. da Rocha *et al.*, "Portable analytical platforms for forensic chemistry: a review," *Analytica Chimica Acta*, vol. 1034, pp. 1-21, Nov. 2018.

[19] "ASCLD/LAB Policy on Measurement Uncertainty," American Society of Crime Laboratory Directors, Aug. 2011.

[20] *Strengthening Forensic Science in the United States: A Path Forward*, National Academy of Science, National Research Council. Washington, DC, USA: The National Academies Press, 2009.

[21] J. A. O'Rawe, S. Ferson and G. J. Lyon, "Accounting for uncertainty in DNA sequencing," *Trends in Genetics*, vol. 31, no. 2, pp. 61-66, 2015.

[22] J. L. Mnookin, S. A. Cole, I. E. Dror *et al.*, "The need for a research culture in the forensic sciences," *UCLA Law Review*, vol. 58, pp. 725-779, 2011.

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