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HAIR AS EVIDENTIARY MATERIAL IN FORENSIC SCIENCE

Abstract

The article provides an overview of the use of hair as forensic evidence in criminal investigations, emphasizing its unique physical, chemical, and genetic properties that allow for the detection of drugs, toxins, and other substances over long periods. It outlines the scientific basis of hair analysis, describes advanced techniques like SEM, IMS, and FISH, and presents forensic case reports demonstrating its practical forensic applications. The article concludes by discussing future developments and the growing importance of hair analysis in integrating molecular biology, analytical chemistry, and forensic science.

Keywords

hair analysis, forensic evidence, scanning electron microscopy, ion mobility spectrometry, fluorescence in situ hybridization, toxicology, DNA profiling, drug detection, forensic case reports

Introduction

Modern forensic science, as an interdisciplinary field integrating achievements in the natural sciences, technology, and law, continually faces challenges related to the precise identification of perpetrators of criminal acts. The crime scene constitutes a complex evidentiary environment, rich in potentially significant information about the course of the offense. Every detail, even one that may initially seem insignificant, can prove crucial in reconstructing the sequence of events. In this context, biological traces play a fundamental role in the evidentiary process by enabling the identification of the perpetrator. Among these traces, hair holds a special place. Its distinctive structure, resistance to degradation, and ability to retain both genetic and chemical information make it a valuable source of answers to questions that, until recently, seemed beyond reach[1].

The application of modern techniques such as DNA analysis, isotope spectrometry, scanning electron microscopy (SEM), ion mobility spectrometry (IMS), and fluorescence in situ hybridization (FISH) has significantly expanded the interpretative capabilities in hair analysis. In particular, molecular techniques like polymerase chain reaction (PCR) have revolutionized the process of analyzing biological material, enabling its use in precise individual identification[2]. The uniqueness of hair lies not only in its durability but also in its ability to accumulate a wide range of information about the host organism (from genetic traits and health status to aspects of lifestyle). It is precisely this multidimensional informational potential that makes hair an increasingly valued trace in forensic investigations[3].

This article focuses on the multidimensional significance of hair as a biological trace, analyzing its use both in the context of identity identification and as a carrier of information about a person's life and related circumstances. The conclusions presented aim to highlight the growing importance of advanced hair analysis in modern investigative procedures, as well as the need for continued development of technologies that support this field.

The beginnings of hair analysis research

A significant place in the history of hair research as evidentiary material is held by the work of Mateo José Bonaventure Orfila, regarded as the father of modern toxicology. As early as 1835, he published the first studies on hair analysis in the context of its usefulness in legal proceedings. Orfila not only laid the groundwork for the development of chemical analysis of biological traces but was also among the first

1 R. Włodarczyk, *Rozwój i współczesne możliwości wykorzystania śladów biologicznych*, Lublin 2018, p. 50.

2 M. Mańczuk, *Wykorzystanie nowoczesnych technologii do badania włosów celem uzyskania informacji o popełnionym przestępstwie*, p. 103.

3 I. Sołtyszewski, *Badania kryminalistyczne. Wybrane aspekty.*, Olsztyn 2007, p. 16–17.

scientists to recognize the evidentiary value of hair in detecting poisonings and identifying perpetrators of crimes[4].

The first practical case involving the use of hair as biological evidence occurred in 1847, when a hair was discovered on the surface of a firearm used in the murder of the Duchess de Praslin. This event is considered one of the earliest moments in the forensic application of hair[5].

In 1857, J.L. Lassaigne published a chapter titled *De l'examen physique des poils et des cheveux* in *Annales d'hygiène publique*, which represented one of the first attempts to systematize the study of human hair using physical and chemical methods. Another breakthrough came in 1869, when Emil R. Pfaff released the monograph *Das menschliche Haar in seiner physiologischen, pathologischen und forensischen Bedeutung.* This publication was the first attempt at a comprehensive description of hair in terms of its presence on different parts of the body. Pfaff argued that the analysis of the chemical properties of hair (such as the rate at which it dissolves in alkaline solutions) could provide information about the age of the individual from whom the sample originated[6].

An important milestone in the development of hair research was the publication, in 1884, of an atlas by the German anatomist J. Waldeyer, which included the first microscopic photographs of human and animal hair. The next step came with the 1889 publication by E. von Hofmann, *Handbook of Forensic Medicine*, in which a chapter dedicated to hair analysis provided practical guidance for investigators of the time. a significant contribution to the advancement of microscopic techniques was also made by G. Popp, who in 1904, while directing the Institute of Chemical Technology and Hygiene in Frankfurt, used an optical microscope to analyze hair in the case of the murder of Eva Disch. This case was widely publicized in the press as a groundbreaking example of the use of microscopy in a criminal investigation. In 1910, W. Balthazard of the Sorbonne Chair of Forensic Medicine published *Le poil de l'homme et des animaux*, a work that for decades served as a foundational textbook on the forensic analysis of human and animal hair[7].

In Polish forensic literature, the issue of hair analysis has appeared both in theoretical works and in the context of practical investigative cases. In the second half of the 19th century, L. Blumenstok-Halben, head of the Department of Forensic Medicine at the Jagiellonian University, published pioneering studies on methods of hair analysis. At the same time, H. Czerwiński emphasized their evidentiary significance, noting that the examination of a suspect's hair and facial features could be crucial in solving a crime. One of the earliest examples of hair being used as evidence in Polish forensic practice was the 1867 murder of Agnieszka Żychowiczowa, described by J. Widacki, in which the presence of hair in the victim's hands helped

4 R. Włodarczyk, *Historia, teraźniejszość i perspektywy kryminalistycznych badań włosów ludzkich*, Szczytno 2007, p. 10.

5 Ibid.

6 R. Włodarczyk, *Rozwój i współczesne…*, op. cit., p. 50-65.

7 R. Włodarczyk, *Historia, teraźniejszość…*, op. cit., p. 11.

establish key investigative facts. Interest in hair analysis as evidentiary material grew more broadly following the publication of J. Bednarski's book *Outline of the Most Important Principles of Forensic Science*, which at the time served as a fundamental compendium of knowledge in the field. In particular, Chapter X of the book focused on the potential use of hair in identifying perpetrators of crimes[8].

Structure of hair

Hair, which consists of keratinized fibers, is a unique product of epidermal cells characteristic of mammals, serving various protective functions. In humans, hair is mainly found on the scalp, in the underarm areas, and in the intimate regions. The hair covering the skin of the fetus, known as lanugo, consists of fine hairs whose development is closely linked to the activity of endocrine glands during fetal development. The hair organ comprises the hair follicle, sebaceous gland, and apocrine gland. The hair itself is made up of the shaft, root, bulb, and hair papilla, which work together in the process of hair growth and regeneration[9].

The hair root consists of several important structures: the hair shaft proper, the hair sheath, and the hair follicle. The upper part of the hair, known as the shaft or stem, ends with a free tip, while the lower part, embedded in the follicle, constitutes the root, whose key component is the matrix. The matrix contains living hair cells where intense metabolic processes and cell divisions take place. These cells, as a result of division, move upward, dying off, losing their nuclei, and undergoing keratinization. The shaft is composed of dead, keratinized cells in which no biological processes occur. It is worth noting that hair lacks blood supply and nerve endings. The interior of the hair is filled with a sulfur-containing protein called keratin, and at the center of the hair is the medulla (a residual structure made up of vacuoles containing glycogen and proteins rich in the amino acid citrulline). The vacuoles are separated by air-filled spaces. The hair cuticle, which forms the outer layer, consists of a single layer of flat cells, whose shape, polygonal nature, and arrangement are crucial in identification studies. These microscale structural features of hair can provide valuable information about the identity and individual characteristics of the person to whom the hair belongs[10].

The average number of hairs on the human scalp is about 120,000. Hair can be classified as straight, wavy, or curly, each with different cross-sectional shapes: straight hair has a round cross-section, wavy hair is oval, and curly hair is twisted along its long axis and has a kidney-shaped cross-section. Hair on the scalp typically forms one, and sometimes two, whorls, which can be either left- or right-handed; their position and direction are hereditary. The average lifespan of a hair is between

8 Ibid., p. 12-13.

9 I. Łuczak-Zielkiewicz, M. Szutowski, *Wartość diagnostyczna włosów*, 2013, p. 56-64.

10 B. Młodziejowski, I. Sołtyszewski, Ślady biologiczne [in:] *Ślady kryminalistyczne. Ujawnianie, zabezpieczanie*, ed. M. Goc, J. Moszczyński, Warszawa 2007, p. 125-184.

3 and 5 years[11]. The hair growth cycle consists of several phases that determine its growth and development. In men, the anagen phase (active growth) lasts from 16 months to several years, while in women it can last from 20 months up to 5 to 7 years. After the anagen phase comes the catagen phase, lasting 2 to 3 weeks, during which the lower part of the hair follicle and the papilla degenerate. The catagen phase transitions into the telogen phase, or resting phase, which lasts from 2 to 6 months. After the telogen phase, the hair falls out and the cycle begins anew[12]. Hair growth is a cyclical process; it is estimated that scalp hair grows about 1 cm every 28 days. This growth is not continuous but depends on the activity of the hair follicle. The total number of hairs on an adult human body is approximately 4 to 5 million; however, their number and activity decrease with age[13].

Hair consists of numerous substances, both inorganic and organic. Analysis of hair ash has revealed the presence of sulfur (S), nitrogen (N), calcium (Ca), phosphorus (P), sodium (Na), potassium (K), magnesium (Mg), iron (Fe), copper (Cu), manganese (Mn), cobalt (Co), nickel (Ni), and other trace elements. Among the organic compounds, keratin, melanin, lipids, and carbohydrates predominate. The presence of creatinine as well as sulfur- and nitrogen-containing compounds is also significant, as they form strong bonds that protect the skin from harmful external factors[14].

The presence of melanin in hair determines its classification into three main pigment groups: xanthism, melanism, and erythrysm. Light hair, referred to as xanthism, includes various shades of blonde, ranging from very light to medium-dark, characterized by high abundance and a fine structure. Dark hair, classified under melanism, encompasses shades of light brown, dark brown, brunette, and black, and can have medium to coarse thickness. Red hair, categorized as erythrysm, appears in a wide range of shades, from pale to intensely bright, fiery, and chestnut. Its color is determined by the presence of trichosiderin (an iron-containing pigment)[15]. For example, hair of individuals of the Caucasian race (white) exhibits a circular cross-sectional shape, whereas hair of individuals of the Mongoloid race (yellow) has an oval cross-section[16].

Detection and preservation

During the investigation of crimes, both sexual and other types, hairs from the perpetrator and the victim can be found in various locations related to the course of events — at the crime scene, along the path of approach and departure, on the bodies of those involved, their clothing, and objects used. It is practically impossible for a perpetrator to avoid leaving behind hairs, especially due to contact with rough

11 J. Sokołowska-Pituchowa, *Anatomia człowieka, Podręcznik dla studentów medycyny*, Warszawa 2003, p. 775.
12 R. Włodarczyk, *Rozwój i współczesne…*, op. cit., p. 91.
13 Ibid., p. 91-95.
14 Ibid.
15 Ibid., p. 159.
16 B. Młodziejowski, I. Sołtyszewski, op. cit., p. 125-184.

surfaces in the environment and the natural process of hair shedding (the average daily natural hair loss is between 50 and 100 hairs). Additionally, because of their small size and low weight, hairs are easily displaced by air movement[17].

In the search for hairs, there are no specific detection methods that allow for their easy localization. Therefore, it is important to conduct a thorough examination of the crime scene, preferably using strong angled light. Alternatively, wide adhesive tape can be used to detect hairs. The detection process involves meticulous inspection of items such as clothing parts, combs, sinks, as well as parts of the human body, including nails, hands, and interdigital spaces. After identifying hairs, they should be removed from the surface using disposable tweezers or forceps (preferably with rubber tips to prevent damage). In the case of wet hairs, they should be air-dried at room temperature before being sent for analysis, without cleaning. The evidence material must be secured in drying envelopes or paper bags, accompanied by a properly completed evidence documentation[18].

Preliminary examination

The initial morphological analysis of hair is a crucial stage in the identification process, allowing for the determination of physical characteristics and the assessment of the evidential value of the material for further investigation. This procedure includes both macroscopic and microscopic examinations. In the first step, it is established whether the examined material originates from a human or an animal. In the case of animal hair, it is possible to identify the species and, in some instances, assign the sample to a specific individual using DNA analysis. Human hair length generally exceeds that of animal hair, with a diameter ranging from 0.05 to 0.15 mm, whereas animal hair diameter may be smaller or larger. Animal hairs rarely show signs of dyeing or other cosmetic treatments. a significant difference is also found in the structure of the medulla: in animals, it is complex, regular, and often geometric in shape, with cells arranged in parallel rows. Human hairs have an interrupted medulla or lack one altogether, and the ratio of the medulla diameter to the total hair diameter (medullary index) is less than 1/3 for human hair and more than 1/3 for animal hair. Additionally, animal hair roots have a brush-like morphology, while human hair roots are bulbous or ribbon-like. The tips also differ: human hair, especially scalp hair, usually has frayed or cut ends, whereas animal hair tips are sharply pointed[19].

The next stage of the analysis is the identification of the body site from which the hair originates. This process involves assessing characteristics such as length, shape, color, degree of curliness, pigmentation, and the structure of the hair medulla.

17 R. Włodarczyk, *Historia, teraźniejszość…*, op. cit., p. 90.

18 L. Koźmiński, W. Miś, L. Szplit, *Podstawowe czynności techniczno-kryminalistyczne podczas oględzin miejsca zdarzenia,* Piła 2015, p. 56.

19 R. Pawłowski, *Medyczno-sądowe badanie śladów biologicznych*, Kraków 1997, p. 84.

Microscopic examinations also allow for the determination of the ethnic origin of the individual from whom the hair came by analyzing the cross-sectional shape, pigment distribution, and degree of waviness. Additionally, it is possible to distinguish hairs originating from children and elderly individuals. Children's hair is characterized by greater delicacy and fineness, whereas hair from older people exhibits reduced pigmentation and a distorted cross-section. Examination of the hair tips also provides important information regarding their origin (a shed hair, telogen, typically has a small sheath of surrounding tissue cells or is completely devoid of it, whereas a forcibly removed hair may contain attached tissue fragments)[20].

Macroscopic analysis of hair provides important information about its condition. Hair luster is an indicator of health (shiny hair suggests a proper balance of elements and trace minerals, while dull hair may indicate underlying health issues). Hair shape and elasticity are primarily determined by genetic and ethnic factors, as well as environmental influences and cosmetic treatments. Hair color can undergo various modifications due to chemical and physical factors. For instance, UV radiation often leads to hair lightening, while exposure to high temperatures or contact with substances such as copper or cobalt can alter the color to greenish or bluish tones. Additionally, pathological conditions and postmortem changes may also affect hair pigmentation[21].

The examination of hair collected from a deceased individual enables the identification of characteristic postmortem changes. a key element in this process is the assessment of the possibility of retrieving the root portion, approximately 1 cm in length, for further genetic analysis. To precisely select material for analysis, fluorescence microscopy is employed, during which the specimen is stained with DAPI. This substance binds to DNA, indicating areas of its highest concentration. For many years, morphological-comparative analysis served as the basis for forensic casework, complemented by serological testing and protein polymorphism analysis. Based on similarities and differences in hair characteristics, experts attempted to associate evidentiary samples with reference samples. The conclusions were drawn from the analysis of these features, taking into account factors such as diseases, parasites, or environmental damage[22].

Comparative examination

To obtain reference samples for the morphological analysis of hair (such as shape, thickness, length, color, etc.), approximately 10 hairs are either plucked or thoroughly combed from five different body regions, such as the scalp, beard, mustache, sideburns, armpits, torso, and pubic area. For genetic testing, only a few hairs or biological samples such as blood, saliva, or an oral swab are sufficient.

20 R. Włodarczyk, *Historia, teraźniejszość…*, op. cit., p. 32–33.

21 K. Świech, *Ultrastrukturalne badania włosów metodą SEM,* Prokuratura i Prawo, No 10, 2012, p. 133-148.

22 E. Sadowska, I. Sołtyszewski, *Dowód z badań włosów ludzkich,* Prokuratura i prawo, No 7-8, 2011, p. 217.

The initial macroscopic assessment of hair includes an analysis of several key parameters that may provide crucial information in the identification process. Hair length is measured in millimeters or centimeters and should be straightened, if possible, to ensure the most accurate measurement. Hair color is determined using the EKR scale or a standardized hairdressing nomenclature system, which enables precise color classification. The degree of luster is categorized as very glossy, semi-matte, or matte, offering insight into the hair's health and possible grooming routines. The shape of the hair is assessed using the Martin scale or classified as straight, slightly arched, arched, S-shaped, coiled, or wavy, depending on the degree of waviness. Hair type is closely related to the area of the body from which it originates (e.g., eyebrow, eyelash, nasal, and ear hairs have specific shapes that are not found in hair from other body regions). Elasticity and tensile strength are evaluated based on the hair's flexibility, which helps determine its resistance to mechanical stress. Additionally, various surface contaminants may be present, such as glass particles, plant debris, blood, dust, pollen, or traces of disease or parasites. These can provide information about the environment in which the individual was present[23].

Toxicological Analysis

The origins of hair toxicological analysis date back to the 1940s; however, this field experienced significant development only in the 1970s and 1980s. Initially, the primary focus was the detection of heavy metals and metallic elements. As technology advanced, hair toxicology began to include the identification of xenobiotics, organic poisons, and particularly addictive substances. Furthermore, hair screening tests now allow for the detection of alcohol metabolites, making them a valuable tool in diagnosing alcohol-related disorders and in identifying individuals who consume alcohol, whether regularly or occasionally[24].

In judicial proceedings and investigations conducted by law enforcement agencies, traditionally used biological materials, such as blood and urine, require experts to carry out detailed analyses to detect drugs and other substances regulated under the Act of 29 July 2005 on Counteracting Drug Addiction (Ustawa o przeciwdziałaniu narkomanii z dnia 29 lipca 2005 r.; Dz. U. z 2012 r. poz. 124, z późn. zm.). However, these tests are characterized by a limited "detection window," typically up to three days from the time of substance exposure. In contrast, human hair serves as a biological material with a significantly longer retrospective detection period, allowing for the identification of psychoactive substances several months, even up to a year or more after their use[25].

23 B. Hołyst, *Kryminalistyka*, Warszawa 2024, p. 448.

24 www.kwartalnik.csp.edu.pl/kp/archiwum-1/2015/nr-22015/2682,Wlosy-jako-material-analityczny-w-badaniach-kryminalistycznych-Zastosowanie-bada.html, [06.05.2025].

25 Ibid.

Hair analysis is one of the most non-invasive methods for drug detection. Keratin, the main protein in hair, has the ability to bind metal ions and organic substances, enabling detailed analysis of a user's drug consumption history. Psychoactive substances and toxins accumulate in specific segments of the hair, allowing retrospective detection of drug use up to 10 months prior. In the context of forensic science, this method is referred to as a "wide detection window." However, hair analysis has certain limitations; it is time-consuming, labor-intensive, and costly compared to other biological sample testing methods. Moreover, direct detection of drugs immediately after use is not possible, as psychoactive substances first need to disperse throughout tissues and organs. Additionally, this method is less effective for individuals who have used drugs only once[26].

Toxicological examination of hair provides significant opportunities for detecting hard-to-detect substances, such as the so-called "date rape drug" (e.g., gamma-hydroxybutyric acid, GHB) and doping agents. These compounds have a short detection window in traditional biological materials, often becoming undetectable within just a few hours. Hair, due to its ability to permanently bind chemical substances at the keratin level, allows for the identification of traces of these compounds even several months after their intake. This represents a major advancement in prosecuting sexual offenses involving psychoactive substances. Similarly, hair analysis has been applied in the long-term monitoring of pharmacological doping (including the use of anabolic-androgenic steroids and other performance-enhancing substances). Thanks to advanced analytical techniques such as gas chromatography or liquid chromatography coupled with mass spectrometry (GC-MS, LC-MS/MS), it is possible to precisely determine the type, concentration, and pattern of substance use. This makes hair a valuable piece of evidence in forensic toxicology and an effective tool in combating unfair practices in professional sports[27].

Modern Technologies

Thanks to the use of advanced analytical technologies, hair constitutes one of the most valuable pieces of evidence in forensic investigations. One of the most sophisticated tools used in hair analysis is the scanning electron microscope (SEM), which employs a precise electron beam to provide detailed imaging of the hair's microstructure. SEM enables not only the assessment of the hair loss mechanism (allowing differentiation between hair that was pulled out, shed naturally, or damaged chemically or thermally) but also the identification of chemical residues and traces of contact with mechanical or thermal tools. Complementing SEM in the detection of toxic compounds and explosive residues is ion mobility spectrometry (IMS). This technique allows for rapid detection of molecules characteristic of

26 I. Krzyżewska, A. Kozarska, *Zastosowanie chromatografii gazowej do detekcji narkotyków w technice kryminalistycznej*, LAB Laboratoria, Aparatura, Badania, No 21(2), 2016, p. 12-20.

27 E. Sadowska, I. Sołtyszewski, op. cit., p. 7-9.

toxic substances or explosives that may have deposited on the hair surface through direct contact or secondary transfer in the gas phase. Meanwhile, fluorescence in situ hybridization (FISH) enables the analysis of genetic material contained in the hair follicle. This technique uses molecular probes labeled with fluorochromes that bind to specific DNA sequences, including chromosome fragments determining sex. This allows for the identification of X and Y chromosomes, thereby determining the donor's sex. The combined application of these three technologies significantly broadens the range of data obtainable from hair analysis, providing morphological, chemical, and genetic information, making it an invaluable tool in modern toxicology and forensic science[28].

Forensic case reports

A properly secured and analyzed biological trace, such as a hair containing genetic material, can constitute extremely important evidence in criminal proceedings, often decisively influencing the outcome of a case. In international case law, there are instances where a single hair subjected to DNA analysis played a key evidential role. One of the most well-known cases is that of the so-called "Vienna Strangler," a 44-year-old writer and journalist accused of murdering prostitutes across Europe. In connection with one of the victims (a woman murdered in Prague), the breakthrough evidence was a single hair found on the passenger seat cover of a BMW car. This vehicle, previously owned by the suspect, had been sold by him and subsequently scrapped. The seat covers, stored for approximately 1.5 years in a garage, were secured by law enforcement authorities. Detailed examination and specialist analysis of the hair revealed a DNA profile matching the victim's genetic profile, directly linking the suspect to the crime scene. The results of the hemogenetic analysis served as key evidence in the trial, leading to the conviction of the journalist not only for the murder in Prague but also contributing to establishing his responsibility for other victims[29].

One of the most high-profile cases in which a hair played a crucial role as forensic evidence was the disappearance of Caylee Anthony, a three-year-old girl from Florida. The incident began on July 15, 2008, when the child's grandmother, Cindy Anthony, reported her missing. It was established that the girl had not been seen for 31 days, and her mother, Casey Anthony, repeatedly misled law enforcement by providing false information about her daughter's whereabouts. During the investigation, one of the key pieces of evidence was Casey Anthony's car. After the vehicle was recovered from a tow lot, Cindy informed the police about a strong odor resembling a decomposing body. In response, investigators conducted a detailed examination of the vehicle, focusing particularly on the trunk to determine whether Caylee's remains might have been stored there before being abandoned in a wooded area. The

28 M. Mańczuk, op. cit., p. 103- 109.

29 M. Lewandowska, *Wykorzystanie dowodu z DNA na przykładzie postępowań karnych,* Palestra 2011, p. 72.

breakthrough came with the identification of a single hair found in the trunk. It was subjected to mitochondrial DNA analysis, which allows for the determination of maternal lineage. The results indicated a high probability that the hair belonged to Caylee Anthony, as the mitochondrial profile matched those of the child's mother and grandmother. Moreover, an FBI specialist testified that the hair exhibited morphological features characteristic of hair from deceased individuals (changes in the root area indicative of postmortem processes). Although this evidence was insufficient to definitively assign guilt, it significantly strengthened the hypothesis that the girl's body had been present in her mother's car trunk. Consequently, it supported the assumption that Casey Anthony possessed knowledge of the child's death beyond what she had disclosed in her statements[30].

One of the high-profile cases in which hair played a key role occurred in August 1991, when Robert C., a contractor supervising the renovation of a chemical laboratory at Wilkes University, began experiencing severe symptoms such as persistent vomiting and rapid hair loss. Clinical diagnostics revealed significantly elevated levels of thallium (a toxic heavy metal previously used in rodent poisons, banned in 1984 due to its high toxicity). Initially, accidental exposure in the laboratory environment was suspected, but further investigation showed no similar symptoms among others in the same building. The turning point in the investigation was the analysis of Robert C.'s hair samples, which indicated chronic, systematic exposure to thallium even before his employment at the university. Postmortem hair samples taken during exhumation enabled the reconstruction of the exposure timeline over nine months, with a marked increase in thallium concentration shortly before his death. The collected data pointed to deliberate poisoning. Suspicion fell on Robert's wife, Joann C., who frequently visited him in the hospital and brought homemade meals. During the investigation, it was established that she systematically administered thallium to her husband with the intent to eliminate him, motivated by the desire to collect a $300,000 life insurance payout. To divert suspicion, she also poisoned herself and her daughters, attempting to support the theory of accidental exposure. Joann C. was charged with her husband's murder. She pled guilty in exchange for avoiding trial and a possible death sentence. After her husband's death, she received insurance benefits totaling $1.2 million. This case exemplifies how chemical hair analysis not only enabled the detection of a crime but also helped reconstruct the perpetrator's modus operandi[31].

In 2014, Elżbieta G. lost consciousness after consuming alcohol. She regained consciousness only several hours later, away from her place of residence. Additionally, numerous injuries were observed on her body, which could indicate physical abuse. Due to the circumstances, the woman went to the Department of Forensic Medicine to undergo a medical examination. She suspected her spouse, with whom she was in conflict during divorce proceedings, believing he had

30 B. Hołyst, op. cit., p. 451.

31 Ibid., p. 450.

administered her a psychoactive substance classified as a so-called "date rape drug." In March 2015, the woman reported to the Institute of Forensic Expertise Analityks in Poznań, where a hair sample was collected and a screening analysis was performed. The analysis results confirmed the presence of gamma-hydroxybutyric acid (GHB), indicating exposure to this substance during the period declared by the patient — September 2014[32].

In December 2014, the grandmother of four-year-old Weronika p. submitted a hair sample of the child for testing. The conducted physicochemical analysis revealed the presence of, among other substances, amphetamine and GHB (a substance typical of the so-called "date rape drug"). It was determined that the child had been exposed to these substances approximately six months earlier. In January 2015, to confirm the results, an expert personally collected a new hair sample from the occipital region of the child and conducted a repeated analysis, which confirmed the initial findings. The obtained results formed the basis for initiating proceedings by the prosecutor's office and the family court[33].

Conclusions

Hair as forensic evidence in criminalistics represents an exceptionally rich source of information with high evidentiary value, stemming from its complex structure and resistance to environmental factors. Thanks to its unique physical, chemical, and genetic properties, hair allows for multidimensional analysis, encompassing both the identification of individuals and the reconstruction of event circumstances. Modern forensic science treats hair as a bridge between molecular biology, analytical chemistry, forensic genetics, and advanced instrumental technology.

The application of advanced analytical techniques, such as scanning electron microscopy (SEM), ion mobility spectrometry (IMS), and fluorescence in situ hybridization (FISH), significantly broadens the analytical scope of hair analysis. SEM enables precise examination of the hair shaft's microstructure, allowing assessment of damage mechanisms (e.g., pulling, cutting, thermal or chemical damage), which can aid in reconstructing events. IMS provides highly sensitive detection of trace amounts of toxic, explosive, or narcotic materials, even from secondary transfer, making it useful in investigations related to violent acts or terrorism. The FISH method allows identification of specific DNA sequences in chromosomes, including determination of biological sex from a single hair containing the hair follicle. One of the most important aspects of hair analysis is the ability to utilize the genetic material it contains, both nuclear (from the follicle) and mitochondrial (also present in the hair shaft). Through the PCR technique (polymerase chain reaction), it is possible to precisely reconstruct a genetic profile even from a small amount of biological

32 https://kwartalnik.csp.edu.pl/kp/archiwum-1/2015/nr-22015/2682%2CWlosy-jako-material-analityczny-w-badaniach-kryminalistycznych-Zastosowanie-bada.html [08.05.2025].

33 Ibid.

material, which in many cases is decisive for individual identification. Isotopic and elemental analyses provide information related to lifestyle, diet, health status, and long-term exposure to heavy metals and toxic substances.

Additionally, hair is characterized by exceptional stability; its keratin structure provides resistance to microbiological and chemical degradation, making it particularly valuable as forensic evidence in cases where other biological samples have been destroyed. Even under extreme conditions (high temperature, humidity, exposure to light), hair can retain its structural and informational integrity.

In summary, hair is not only a passive biological trace but an active carrier of data with enormous informational potential. Its analysis, supported by modern scientific techniques, plays a key role in investigative and judicial processes. In the future, the development of research methods may further strengthen the role of hair as critical forensic material, expanding the boundaries of knowledge and increasing investigative effectiveness.

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