Hair Histology as a Tool for Forensic Identification of Various Animals

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ABSTRACT

Hair histology plays a pivotal role in forensic investigations by enabling the identification of various animal species through microscopic examination. Utilizing a compound microscope, forensic analysts can scrutinize specific characteristics of animal hairs—such as cuticle scale patterns, medulla type to distinguish between species. These microscopic features are instrumental in creating reference databases that aid forensic experts in accurately identifying animal hairs found at crime scenes, thereby contributing valuable information to investigations

KEY WORDS: Hair Histology, Forensic Hair Analysis, Animal hair identification, Microscopic hair features, Cuticle patterns, Medullary patterns

1: INTRODUCTION

The Hair histology plays an important role in forensic investigations, especially in the identification of animals involved in criminal cases, wildlife poaching, and ecological studies. It's

Durable biological material that retains its structural characteristics even under extreme environmental condition which makes it a needed tool for analysis.

Every species has unique hair characteristics which includes the medullary patterns, scale structures, pigmentation, and cortex composition. By the examination of these microscopic features, forensic experts can get the difference between different animal species and even determine their geographic origin. Hair is a biological trace evidence commonly seen at crime scenes, which includes wildlife trafficking cases, animal attacks and illegal fur trade cases.

Morphological Features- Cuticle, medulla, cortex, and pigmentation patterns differs among species, allowing forensic differentiation among animals.

Trace evidence plays a vital role in forensic science, helping investigators reconstruct crime scenes and establish links between individuals, objects, and locations. Hair, as a common type of trace evidence, is particularly valuable due to its ability to persist in an environment over time and provide essential forensic insights. Whether of human or animal origin, hair evidence can support criminal investigations by identifying suspects, victims, and crime scene associations.

This paper discusses the significance of hair as trace evidence, highlighting its durability, transferability, morphological characteristics, and forensic applications. While hair analysis does not provide the same level of certainty as DNA testing, it remains an essential tool in forensic investigations, especially when DNA is unavailable or inconclusive.

1.1 PERSISTENCE AND TRANSFERABILITY OF HAIR

Hair is easily transferred through physical contact, making it a crucial piece of trace evidence in forensic investigations. It can attach to clothing, furniture, and various surfaces, linking individuals to crime scenes and victims. Hair can be shed naturally or forcibly removed, leaving behind evidence that forensic experts can analyze.

Unlike biological fluids such as blood and saliva, hair is highly resistant to decomposition, allowing it to remain intact at a crime scene for extended periods. This durability makes it possible to recover hair from older or concealed crime scenes, aiding in long-term investigations. Additionally, the ability of hair to adhere to different materials makes it useful in linking suspects to victims or specific locations.

1.2: DIFFERENTIATING HUMAN AND ANIMAL HAIR

Forensic scientists often analyze hair samples to determine whether they belong to a human or an animal, a distinction that can be critical in many investigations.

Human hair has unique microscopic features, such as an imbricate cuticle pattern and a small or absent medulla. Animal hair, on the other hand, varies significantly in structure and typically has distinct medullary patterns and scale formations that allow forensic experts to identify the species.

In criminal cases, distinguishing between human and animal hair can help investigators determine whether a person was present at a crime scene or if an animal played a role in the investigation. In cases involving pet ownership, forensic experts can use hair analysis to establish connections between individuals and specific animals, providing additional leads in criminal cases.

1.3 MORPHOLOGICAL CHARACTERISTICS USED IN IDENTIFICATION

Hair possesses several microscopic features that forensic experts use for identification. These include:

Cuticle scale pattern: The cuticle, or outer layer of the hair, has different scale structures depending on the species. These patterns help distinguish between human and animal hair and further categorize animal hair types.

Medullary index: The medulla, or central core of the hair, varies between species. In humans, the medullary index (the ratio of the medulla's diameter to the overall hair diameter) is typically less than 0.3, while in most animal species, it is greater than 0.5.

Pigmentation: The distribution and concentration of pigment granules in the cortex of the hair can offer clues about species, breed, and even individual identification.

Root and tip analysis: Examining the root and tip of a hair strand can provide insight into whether the hair was naturally shed or forcibly removed, which can be significant in violent crime investigations.

These characteristics help forensic experts identify the origin of a hair sample and determine its relevance to a case.

1.4: HAIR AS EVIDENCE FOR LINKING EVIDENCE AND LOCATION

Hair evidence is frequently used to associate individuals with crime scenes or other locations. Hair strands recovered from clothing, bedding, vehicles, or personal belongings can provide crucial investigative leads.

For instance, in assault or homicide cases, the discovery of a suspect's hair at a crime scene or on a victim can serve as strong circumstantial evidence. Likewise, if a victim's hair is found in a suspect's possession, it may support allegations of abduction or assault. Hair evidence can also help establish timelines by indicating how long a person or animal was in a particular location.

Hair evidence is also useful in forensic cases involving burglary, hit-and-run incidents, and missing persons. If a suspect's hair is found at a location where they deny being present, it can serve as significant evidence against them.

1.5: CHEMICAL AND ENVIRONMENTAL ANALYSIS OF HAIR

Beyond morphological examination, forensic scientists can analyze the chemical composition of hair to gain additional insights. Hair absorbs and retains chemical substances from the environment, making it a valuable resource in forensic toxicology and environmental investigations.

Chemical analysis of hair can reveal:

Drug and poison exposure: Hair retains traces of drugs, toxins, and heavy metals, allowing forensic experts to detect past exposure to substances such as narcotics, poisons, or environmental contaminants.

Dietary and environmental information: Elements present in hair can provide clues about an individual's diet, water sources, and environmental surroundings, which can assist in forensic profiling.

By analyzing the chemical composition of hair samples, forensic experts can extract valuable information about an individual's lifestyle, exposure history, and possible involvement in criminal activities.

1.6: HAIR AS AN ALTERNATIVE TO DNA EVIDENCE

Although DNA testing is the most definitive method for forensic identification, hair analysis remains a crucial alternative when DNA material is unavailable. DNA can typically be extracted from hair roots or follicular tissue, but in cases where only the hair shaft is available, microscopic examination becomes essential.

Hair analysis is also cost-effective and non-invasive, making it a useful tool in forensic investigations. While it does not offer the same level of individualization as DNA, hair analysis can provide valuable investigative leads when combined with other forensic evidence.

1.7: MICROSCOPIC HAIR CHARACTERISTICS ACROSS SPECIES

Hair structure varies significantly among species, with unique patterns and formations that serve as distinguishing characteristics. The primary components analyzed in hair histology include:

Cuticle (Outer Layer): The protective outermost layer of the hair, which varies in scale pattern and arrangement.

Cortex (Middle Layer): The thickest part of the hair that contains pigment granules responsible for coloration.

Medulla (Inner Core): The central portion of the hair shaft, which differs in thickness, continuity, and pattern among species.

These features provide valuable information that forensic experts and biologists use to classify hair samples and establish species identity.

1.8: CUTICLE SCALE PATTERNS AND THEIR ROLE IN SPECIES IDENTIFICATION

The cuticle is composed of overlapping scales that differ in pattern and texture across species. These scale arrangements are classified into three main types:

Coronal: These scales appear as stacked crowns and are commonly found in small rodents and bats. This scale pattern provides a rough texture that helps animals navigate through their environment.

Spinous (Petal-like) Scales: This pattern, resembling overlapping petals, is seen in animals such as cats, seals, and mink. Spinous scales provide a smoother texture and are distinct from human hair, making them useful for species differentiation.

Imbricate (Flattened) Scales: The imbricate scale pattern, characterized by flattened and irregularly overlapping scales, is most commonly found in human hair and some animal species like deer. This pattern allows for easy differentiation from species with coronal or spinous scales.

By examining these scale types under a compound microscope, forensic analysts can determine whether a hair sample is of human or animal origin and further classify it into specific species.

1.9: MEDULLARY INDEX AND THEIR IMPORTANCE IN SPECIES IDENTIFICATION

The medulla, located at the core of the hair shaft, varies in size, structure, and composition among species. The medullary index, which is the ratio of the medulla's diameter to the overall hair diameter, is a key feature in differentiating between human and animal hair.

Humans**:** Typically have a medullary index of less than 0.3, meaning the medulla is either absent or very thin compared to the overall hair diameter.

Animals: Often have a medullary index greater than 0.5, meaning the medulla occupies a significant portion of the hair shaft. This makes it a defining characteristic in identifying non-human hair.

In addition to the medullary index, the continuity of the medulla also varies among species:

Fragmented or Absent Medulla: Common in human hair, where the medulla appears in broken segments or is completely absent.

Interrupted Medulla: Seen in some species where the medulla appears in irregularly spaced sections.

Continuous Medulla: Found in many animal species, where the medulla runs uninterrupted throughout the hair shaft.

Lattice or multiserial medulla: Characteristic of some species like rabbits and rodents, where the medulla forms complex, multi-rowed structures.

These distinctions make the medulla an important feature in forensic and zoological hair analysis.

1.10: DETAILED STRUCTURE OF ANIMAL HAIR

* CUTICLE (OUTER LAYER)

Have overlapping scales that protect the hair shaft .The Scale patterns differs among species (coronal, spinous, imbricate) also its very useful for species identification using scanning electron microscopy.

Size and distance – The spacing and size of the scales differs across species and can be used for species identification .Hair Colour and Structure – The cuticle, is combined with the underlying cortex which helps to reflect and preserve the colour and structural integrity of the hair, helping in identification .In forensic identification, light microscopy or scanning electron microscopy (SEM) is typically used to examine the cuticle, because it allows detailed observation of its morphological features. Comparing these features with known species characteristics, forensic experts can determine the origin of the hair, helping in criminal cases and other forensic analysis.

*CORTEX (MIDDLE LAYER)

It Contains granules of pigments which is responsible for hair colour. The variation in pigment distribution it can be continuous, interrupted, fragmented, or it can absent .Pigmentation and colour Pattern – The cortex houses melanin granules that determine the hair's colour . Different species have distinct pigmentation patterns that can aid in species identification. The distribution and type of pigment granules can vary, for example, Eumelanin (black or brown pigment) is found in most mammal. Pheomelanin (yellow to red pigment) is more common in certain species like dogs and foxes.

Cortex Structure and Density – The arrangement of keratin Fibre in the cortex contributes to the strength and rigidity of the hair. This structure can vary between species, aiding in distinguishing animal hairs .The cortex can retain information about the animal's environment (e.g., exposure to pollutants or toxins) and health (e.g., stress markers). This makes it useful for toxicological analysis or ecological research. In forensic applications, light microscopy and scanning electron microscopy (SEM) are used to examine the cortex's pigment distribution, fibre structure, and chemical composition. These analyses help forensic experts to accurately identify species and possibly even trace hair back to a specific individual animal when combined with DNA analysis.

*MEDULLA (INNER LAYER)

It is the central core of the hair shaft, but have differences in its size and continuity.

Medullary Pattern – The structure of the medulla can vary, and it is a key feature used to distinguish animal hairs. Common medullary patterns include continuous which is solid line running through the centre of the hair which is common in cows, horses, and deer. It is can be Interrupted or fragmented which is broken or interrupted patterns that are found in dogs, cats, and some primates and it can be lattice-like or cellular which is a network of interconnected cells found in rabbits and other small mammals . It can be absent in some areas.

MEDULLARY INDEX OF VARIOUS SPECIES

Medullary index of human hair <0.33

Medullary index of animal hair: >0.50

Medullary index of common animal hairs:

Medullary index of dog: 0.50 to 0.75

Medullary index of cat: 0.60 to 0.80

Medullary index of deer: 0.75 to 1.00

Medullary index of rabbit: 0.60 to 0.80

1.11: HAIR GROWTH CYCLE IN ANIMALS

The hair growth cycle in animals consists of three main phases, anagen (growth phase), catagen (transition phase), and telogen (resting phase), with some classifications also including an exogen (shedding) phase. The duration of each phase varies depending on species, breed, age, and environmental factors such as temperature and daylight. During the anagen phase, the hair follicle is actively producing new hair, with rapid cell division pushing older hair upward. The length of this phase determines the overall hair length, which is why long-haired animals, such as Poodles, have a prolonged anagen phase. Following this, the catagen phase marks a short transitional period where the follicle shrinks, and hair growth slows down. The hair detaches from its blood supply but remains in place, preparing for eventual shedding. Seasonal shedders, like Huskies, enter this phase before shedding their undercoat. Next, the telogen phase is the resting stage, where the hair is fully formed but no longer growing. It remains anchored in the follicle until a new hair begins to grow. Some animals, such as deer, experience synchronized telogen phases, leading to seasonal shedding. Finally, in the exogen phase, old hairs are shed to make way for new growth, with shedding patterns varying across species, breeds, and seasonal conditions. Several factors influence the hair growth cycle, including genetics, which determines hair length and shedding tendencies, as well as seasonal changes that cause fluctuations in hair density. For example, animals like horses and dogs shed more heavily in certain seasons to adapt to temperature variations. Additionally, stress and health conditions can disrupt the cycle, leading to abnormal shedding patterns, such as telogen effluvium, where stress-induced hair loss occurs in cats and dogs. Understanding the hair growth cycle is crucial in forensic investigations, veterinary science, and animal care, as it helps in identifying species, diagnosing health issues, and managing shedding patterns effectively.

1.12: PIGMENTATION AND COLOUR DISTRIBUTION IN ANIMAL HAIR

The colour of animal hair is determined by the type, amount, and distribution of pigments within the hair shaft. These pigments, primarily eumelanin (black or brown) and pheomelanin (yellow, red, or orange), are produced by melanocytes in the hair follicle. The interaction between genetic factors, environmental influences, and hormonal regulation affects pigmentation patterns and coat colour variations among species.

Pigment distribution within the hair shaft varies, leading to different coat patterns. Some animals exhibit uniform pigmentation, where the hair is throughout, as seen in black horses or golden retrievers. Others display banded hair (agouti pattern), where alternating bands of eumelanin and pheomelanin create a natural camouflage effect, commonly observed in wolves and rabbits. Tipped hair is another variation, where the hair base is darker while the tip is lighter, such as in Siamese cats, whose temperature-sensitive pigmentation leads to distinct points. Some animals, like Dutch Shepherds and tabby cats, have a grizzled or brindle pattern, where dark and light pigments mix irregularly along the hair shaft. Additionally, genetic mutations can lead to albinism (complete lack of melanin) or laicism (partial pigment loss), resulting in white or pale-coloured coats.

Several factors influence hair pigmentation. Genetics plays a major role in determining pigment type and distribution, while environmental factors, such as sun exposure, can cause hair to lighten. Cold temperatures can also intensify pigmentation, as seen in Himalayan cats. Age-related changes lead to greying due to reduced melanin production. Hormonal imbalances, such as thyroid or adrenal disorders, can also alter pigmentation.

Understanding hair pigmentation and colour distribution is essential in forensic investigations, as it aids in species identification, tracking animal movements, and linking hair evidence to crime scenes. Additionally, this knowledge is valuable in veterinary science, breeding programs, and wildlife conservation effort

Pigmentation and colour distribution in animal hair are essential aspects of forensic identification, species differentiation, and biological adaptation. The coloration of hair is determined by the type, amount, and distribution of melanin pigments within the hair shaft, influenced by genetics, environmental factors, and hormonal regulation. This variation in hair colour plays a vital role in camouflage, communication, and thermoregulation in different animal species.

Animal hair colour is primarily determined by two types of melanin pigments synthesized by melanocytes in the hair follicle. Eumelanin produces black and brown shades, with higher concentrations resulting in darker hair, as seen in black horses, panthers, and German shepherd dogs. Pheomelanin, on the other hand, produces yellow, red, orange, and golden shades, commonly found in red foxes, golden retrievers, and lions. Some animals exhibit mixed pigmentation, where eumelanin and pheomelanin combine to create intermediate colours like tan, sable, or brindle coats, seen in calico cats, brindle-coated dogs, and agouti-patterned rodents. The pigmentation process occurs within the, specialized organelles inside melanocytes responsible for melanin production melanosomes. These melanocytes transfer melanin granules to keratinocytes, which form the hair shaft. The distribution of melanin granules in the cortex of the hair determines its shade and pattern, with dense eumelanin creating solid black coats and mixed melanin distribution producing lighter or banded coats. Genetic mutations can alter melanin production, leading to unique pigmentation patterns.

Colour distribution in animal hair varies across species and breeds, forming different patterns based on genetic and adaptive significance. Uniform pigmentation results in evenly coloured hair, producing solid-coloured coats like those of black horses, golden retrievers, and albino rabbits. In contrast, banded hair (agouti pattern) displays alternating light and dark bands due to variations in melanin deposition, as seen in wolves, wild rodents, and tabby cats, where the agouti pattern provides natural camouflage. Tipped hair, where the base of the hair is dark while the tips are lighter, is common in Siamese cats, Himalayan rabbits, and Arctic foxes. Temperature-sensitive pigmentation in these animals results in darker fur on colder body areas due to enzyme activity in melanin production. Grizzled or brindle patterns, where dark and light pigments mix irregularly along the hair shaft, appear in brindle-coated dogs (Dutch Shepherds, Boxers), wild boars, and some tabby cats. Genetic mutations can lead to leucism, which results in white patches or pale-coloured coats, while albinism causes a complete absence of melanin, producing white hair, pink skin, and red eyes, seen in albino rabbits and lab rats.

Several factors influence pigmentation and coloured distribution in animal hair. Genetics is the primary determinant of coat coloured with genes such as MC1R (Melanocortin-1 receptor) and ASIP (Agouti Signalling Protein) controlling melanin synthesis and colour patterns. Environmental factors such as sunlight exposure can degrade melanin, causing coats to fade over time, while temperature effects in some species influence pigment expression, as seen in Siamese cats and Himalayan rabbits. Diet and nutrition also play a role, as deficiencies in essential nutrients like copper or tyrosine can cause fading or loss of pigmentation. Age-related changes can result in greying hair due to reduced melanocyte activity, while hormonal imbalances such as hypothyroidism or adrenal disorders can disrupt melanin production, altering coat colour.

Pigmentation and colour distribution in animal hair are crucial in forensic investigations, species identification, and crime scene analysis. The microscopic examination of pigment granules, banding patterns, and hair shaft structure allows forensic experts to distinguish between wild and domestic species and link animal hair to suspects in criminal cases. Hair found at crime scenes can connect individuals to locations, confirm pet ownership, or provide evidence in wildlife crimes such as illegal fur trade and poaching. Pigment analysis also plays a role in the food and textile industry, where it helps detect foreign hair contamination in food products and fabrics.

In conclusion, pigmentation and colour distribution in animal hair are determined by a complex interaction of genetics, environmental conditions, and physiological factors. Eumelanin and pheomelanin contribute to a wide range of coat colours and patterns, while genetic mutations produce unique variations such as albinism, brindle, and agouti banding. These variations are critical in forensic investigations, allowing for species identification, crime scene analysis, and wildlife conservation efforts. Through microscopic examination, pigment analysis, and forensic hair comparison, experts can use pigmentation studies to differentiate species, track animal movements, and provide valuable evidence in forensic case

2: RESEARCH METHODOLOGY

2.1: RESEARCH APPROACH

This study follows a mixed-method approach, incorporating both qualitative techniques for a comprehensive forensic analysis of animal hair.

2.2: SAMPLE COLLECTION

A) SOURCES

- Animal hair samples are collected from different areas which includes farms , domestic shelter , pet shop etc
- Horse hair collected from horse riding club
- Hairs samples of Cat , guinea pig , rabbit collected from pet shop
- Hair samples of cow taken from domestic shelter
- Hair samples of Dog collected from my home itself

B) SPECIES SELECTION

- Domestic animals (e.g., dogs, cats, cows, horses)
- Small mammals (guinea pig, rabbits).

2.3: SAMPLE PREPARATION

- Contaminants are removed using ethanol or distilled water.
- Hair samples are mounted on glass with nail polish

2.4: MICROSCOPIC EXAMINATION

- Medullary pattern , cuticle and cortex are analysed using compound Microscope

2.5: DATA COLLECTION AND ANALYSIS

Morphological Features are recorded

- Cuticle: scale pattern (coronal , spinous or imbricate)
- Medulla : Continuous, fragmented or absent

2.6: VALIDATION AND RELIABILITY MEASURES

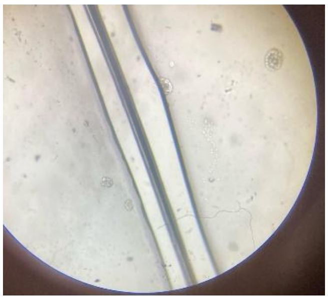
- Re examination is done by Cross checking the results
- Compare findings with known reference samples to verify accuracy.

3: RESULT

MICROSCOPIC HAIR ANALYSIS RESULTS

Hair histology involves the microscopic examination of hair structure to determine its origin. The microscopic characteristics of hair provide essential forensic clues, allowing for species identification. The analysis of hair from different animal species revealed distinct variations in the medulla and cuticle which are key components in forensic identification.

3.1: CAT

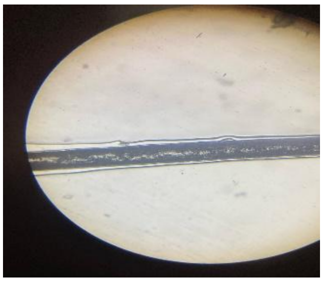


(Fig 1) Microscopic view of cat hair

***Examination of medulla and cuticle**

- Medulla: The dark central core is well-defined and continuous, which is typical of cat hairs.
- Cuticle: The outermost layer appears smooth. It have an imbricate scale pattern, and the cuticle edges are spinal in pattern

3.2: RABBIT

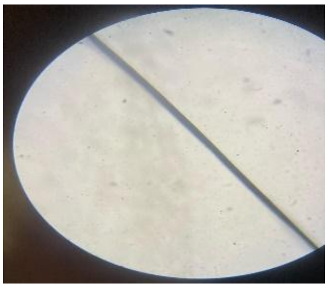


(Fig 2)Microscopic view of rabbit hair

***Examination of medulla and cuticle**

- Medulla: The central dark area is prominent or fragmented which is common in rabbit hairs. The medullary patterns in rabbits in rabbits appears as discontinuous
- Cuticle: Rabbit hair typically has a coronal cuticle pattern, which is different from the imbricate patterns seen in cats.

- **3.3: GUINEA PIG**

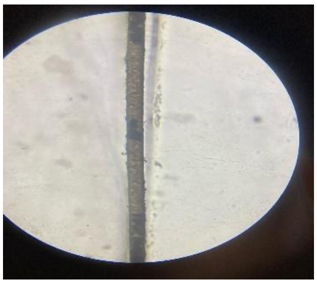


(Fig 3) Microscopic view of guinea pig hair

***Examination of medulla and cuticle**

- Medulla: The medulla seems very thin or absent which is common in some rodent species.
- Cuticle: Imbricate

3.4: DOG

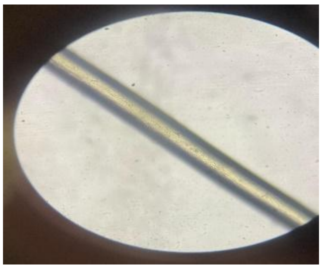


(Fig 4) Microscopic view of Dog hair

***Examination of medulla and cuticle**

- Medulla: The medulla of dog hair seems to be like wide and fragmented
- Cuticle: the cuticle of dog hair appears to be imbricate pattern

3.5: HORSE

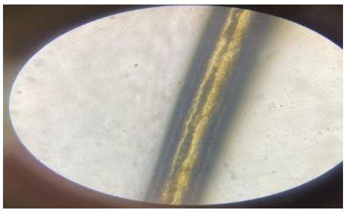


(Fig 5)Microscopic view of Horse hair

***Examination of medulla and cuticle**

- Medulla: the medulla seems to be very thin and absent which is common in horse hairs
- Cuticle: The cuticle found on horse hair appears to be smooth and imbricate

3.6: COW



(Fig 6) Microscopic view of cow hair

***Examination of medulla and cuticle**

- Medulla: The medulla found on cow hair is wide and fragmented
- Cuticle: The cuticle seems to be fragmented

4: DISCUSSION

The analysis of animal hair using histological techniques and a comparison microscope is a valuable tool in forensic science. By examining the morphological characteristics of hair samples, forensic investigators can determine the species origin, which can be crucial in cases involving animal attacks, poaching, or illegal wildlife trade.

4.1: SIGNIFICANCE OF HAIR HISTOLOGY IN FORENSICS

Hair is often found at crime scenes and can serve as trace evidence. Unlike DNA analysis, which requires expensive equipment and expertise, hair histology offers a relatively simple and cost-effective approach for preliminary forensic investigations. The cuticle pattern, medullary index of hair provide species-specific identifiers, making it a useful tool for forensic comparison.

4.2: ROLE OF COMPOUND MICROSCOPE

A compound microscope consists of multiple optical lenses that provide high magnification, making it possible to study minute structural details in hair samples. This microscope enables forensic scientists to observe cuticle patterns, medullary structures, and pigmentation distribution, all of which are critical for distinguishing between species. The ability to analyze samples at different magnifications enhances accuracy in hair identification.

ADVANTAGES

The use of a compound microscope in forensic hair analysis offers several benefits:

Enhanced Precision**:** High magnification allows detailed visualization of microscopic structures, reducing misidentifications.

Efficient Analysis: Microscopic examination enables quick assessment of hair characteristics, expediting forensic investigations.

Image Documentation: Many modern compound microscopes are equipped with imaging systems, allowing forensic analysts to capture detailed images for records and court proceedings.

Legal Significance: Hair analysis using microscopy provides critical forensic evidence in wildlife crime cases, poaching investigations, and legal disputes involving animals

4.3: MORPHOLOGICAL FEATURES OF DIFFRENTIATION

Several microscopic characteristics are considered in hair histology for forensic identification:

CUTICLE STRUCTURE: The outer layer of the hair shaft varies in scale patterns among different species, such as coronal, spinous, and imbricate.

MEDULLARY PATTERNS: Continuous, fragmented, or absent medullae are key identifiers for different species.

Characteristics like scale patterns, medullary index, and pigmentation serve as important markers in cases related to wildlife crimes, illegal trade, or animal involvement in forensic cases. Although hair analysis does not provide individual identification like DNA testing, it remains a cost-effective, non-destructive, and reliable method for forensic applications. Advancements in

5: CONCLUSION

Hair histology is a valuable forensic tool for identifying different animal species, particularly through the use of a compound microscope. By analysing distinct hair structures such as the cuticle, cortex and medulla, forensic experts can differentiate between species and trace animal origins in forensic investigations.

microscopic imaging and digital analysis may further improve the precision and effectiveness of forensic hair examination in the future.

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