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Forensic Hair Comparison: Background Information for Interpretation

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Introduction

Hair evidence is one of the most common types of evidence encountered in criminal investigations. During the course of the normal hair-growth cycle, hairs are readily lost from individuals, and these hairs may be transferred during the course of a criminal activity.

Edmond Locard was the first forensic scientist to formally articulate the foundation for the transfer event (Locard 1930). Now known colloquially as the Locard Exchange Principle, it states that any time there is contact between two surfaces, an exchange of materials will occur. One of the materials that can be readily collected, identified, and compared is hair evidence.

The forensic analysis of hair evidence can be extremely valuable in the examination of physical evidence by (1) demonstrating that there may have been an association between a suspect and a crime scene or a suspect and a victim or (2) demonstrating that no evidence exists for an association between a suspect and a crime scene or a suspect and a victim. Although the science of microscopic hair examination can never result in an identification, that is, conclude that a hair came from one individual to the exclusion of all others, the vast amount of both macroscopic and microscopic information available from hair analysis can provide a strong basis for an association and certainly provides strong exculpatory evidence. The final aim of any forensic examination must be to provide statements based on objective scientific observation that will be of value in a court of law or to any interested party involved in an investigation.

The purpose of this document is to review the bases for microscopic hair analysis and comparison. Hair examinations involve the analysis and comparison of the morphological characteristics present in hair. Based on these morphological characteristics, the first determination that can be made is whether the hair came from a human or an animal (for the purposes of this document, any reference made to animal means nonhuman animal). Within each of these two groups, additional information regarding the potential donor can be obtained using these same microscopic characteristics. Finally, a comparison can be conducted between a hair of unknown origin and a known sample of hairs from an appropriate known sample

Scientific Basis for Microscopic Hair Examinations

All organisms differ widely in many dimensions, including morphological appearance, physiology, and genetic makeup. Some groups of organisms clearly are more similar to some groups than to others. For instance, a monarch butterfly is more similar to a tiger swallowtail butterfly than either is to a ladybird beetle. Biologists seek to identify these differences and use them to organize and classify the world around them. They use these differences to generate classification schemes that can be used for many purposes, from examining how traits evolve to solving crimes.

These classification schemes have their roots in the field of taxonomy. Taxonomy is the practice of classifying biodiversity, and it has a long and venerable history. In 1758, Carl Linnaeus proposed a system that has dominated classification for centuries. He proposed a system of binomial nomenclature to describe living organisms (as cited in Wikipedia 2009). However, the term *taxonomy* is now applied in a wider, more general sense and refers to a classification of things, as well as to the principles underlying such a classification. Almost anything—animate objects, inanimate objects, places, concepts—may be classified according to some scheme.

Evaluation of shared and distinguishing characteristics is essentially the process used in forensic hair examinations. The microscopic characteristics allow for hair to be categorized into smaller groups, such as human or animal, racial group, body area, color, phase of growth, etc. This is considered the identification phase, for example, classifying the hair as being human, exhibiting Caucasian characteristics, coming from

the head, being brown in color, and possessing a telogen root.

The next phase of the examination process is conducting a microscopic comparison. This involves evaluating the microscopic characteristics present in the hair samples, evaluating the points for comparison, and determining whether or not a questioned hair can or cannot be excluded as originating from the source of a known sample.

Hair comparisons are a combination of a pattern-recognition process and a step-by-step analysis of a questioned hair and a known sample. An example of the pattern-recognition process is the manner in which we identify a friend in a crowd of people. It is an instant recognition, based on our experience with that person. It is not conducted in a logical, step-by-step process, evaluating first the height, hair color, skin color, eye color, and other characteristics. It is an almost instantaneous evaluation of all of these characteristics together. The identification of our friend does not carry any less weight based on the mechanism we used to identify him or her.

The same process is used for hairs, but in a more methodical manner. In a microscopic hair comparison, the examiner is determining whether or not similar patterns of microscopic characteristics exist at each point of comparison along the hair shaft. This pattern-recognition process then continues in a step-by-step fashion along the length of the hair.

To be considered an association, the microscopic characteristics of a questioned hair also must be exhibited in the known sample. Forensic hair examination involves the analysis of objective characteristics and a subjective interpretation of the relative weight of these characteristics. The subjective component of hair examination almost dictates that two different examiners will place slightly different weight on individual characteristics or may describe these characteristics using slightly different words.

However, if two examiners have been trained properly, possess adequate experience, and use proper procedures, they should reach the same conclusion. Accordingly, the amount of experience gained by examining a large number of hairs and conducting a large number of hair comparisons is critical.

The scientific method involves generating a hypothesis and testing it to determine if it is false. In order for the hypothesis to be valid, it must be able to be supported repeatedly via reproducible experiments. This process distinguishes science from other professional endeavors. By establishing a reliable, repeatable set of procedures and criteria by which the results are evaluated, an objective scientific methodology can be achieved. This, coupled with a properly trained, qualified examiner operating within a rigorous quality assurance/quality control program, provides credible and reliable results.

Animal Hairs

Hair identification is not employed solely by forensic scientists. Hair identification is an important tool used by wildlife biologists, archeologists, anthropologists, and textile conservators. Many researchers have investigated the morphological characteristics of hair, devised keys, and reviewed the science of animal-hair identification (Appleyard 1960; Day 1966; Mathiak 1938; Mayer 1952; Moore 1974; Oyer 1939; Stains 1958, 1962; Wildman 1954, 1961; Williams 1938). These works have aided in ecological studies, food-habit studies, and law enforcement investigations by providing descriptions, keys, and photographs of the microscopic characteristics of animal hairs.

Brown (1942) attempted to develop a technique for identifying hairs and wools from various types of materials recovered from archeological works. Hausman (1930) used hair examination in his laboratory to perform archeological work, examine stomach remains, identify fur, and conduct legal proceedings.

Animal-hair studies also have been conducted within the field of forensic science. Peabody et al. (1983) determined that the medullary fraction could be used to reliably distinguish between dogs and cats. Hicks (1977) and Deedrick and Koch (2004a) described the microscopic characteristics that can be used to discriminate between animal hairs that are most likely to be encountered in forensic casework.

It is important to note that although microscopic analysis and comparison of animal hairs can be conducted, the significance ascribed to an animal-hair association often is less than that of a human-hair association. Accordingly, when an animal-hair association is reported, this decreased significance must be highlighted. For example, in a report for a dog-hair association, the FBI Laboratory would use a statement similar to the following:

> It should be noted that dog hairs do not possess enough individual microscopic characteristics to associate a questioned hair to a particular dog to the exclusion of other dogs of a similar breed.

Despite the difference in the significance of animal-hair comparisons to human-hair comparisons, it does not detract from its potential usefulness in a forensic investigation. The presence of a dog hair on an item from the victim that can be microscopically associated with the known hair sample from the suspect's dog may be very important.

Human Hairs

Like the analysis of animal hair, the analysis of human hair is not conducted solely by forensic scientists. Hairs are analyzed by the cosmetics industry in the area of hair-care products and by the medical field in many areas such as nutritional status and toxic-element levels, as well as for certain dermatological diseases. However, the microscopic characterization and comparison of human hairs are largely the domain of forensic scientists.

The first reported use of forensic human-hair comparison was by Rudolf Virchow in 1861 (as cited in Bisbing 1982). He reported the following:

> The greatest majority of the hairs of the victim represent a thorough and complete accord with the hairs found on the defendant that there exists no technical ground opposite to looking at the hairs found on the defendant as being the hairs of the victim. . . . However, the

> hairs found on the defendant do not possess any so pronounced peculiarities or individualities that no one with certainty has the right to assert that they must have originated from the head of the victim (as cited in Bisbing 1982).

Paul Kirk conducted some of the first studies on the potential forensic application of microscopic comparison of hair in the United States (Gamble and Kirk 1941; Greenwell et al. 1941; Kirk 1940). In addition to his publications on the microscopic characteristics of human hairs, he conducted hair-comparison studies using his criminology students. All of the students were required to compare a single hair to 20 known samples, where all of the known samples were of a similar color and from individuals of a similar age. He reported that no student who completed the routine examination failed to report the association correctly (Kirk 1940). He further stated that although this falls short of individualization, the following five factors must be considered:

> (a) that twenty suspects in a single crime is rather an exceptional number; (b) that the eliminative value of a failure to identify the hair as that of any of the suspects is great; (c) that time imposes on students a restriction on the total number of hairs that can be examined, and it is impossible as yet to say whether they could equally well pick, e.g., from 100 standards; (d) that in any random group of suspects there would be greater normal variations than are present in the selected group of similar hairs used for this exercise; and (e) that the students in question have never before examined hairs and are in no sense experts in this examination (Kirk 1940).

Based on his work, Kirk expected that it would be likely to make a determination of individuality using human-hair comparison. Obviously, this has not yet occurred, nor will it likely ever occur. However, his work laid much of the foundation for the methods of microscopic human-hair comparison that remain in use today.

Microscopic CharacteristicsHair Identification

Many characteristics must be considered in microscopic hair identification (Bisbing 1982; Deedrick and Koch 2004b; Hicks 1977; Kirk 1974; Lee and DeForest 1984; Moore 1974; Robertson 1999; Saferstein 1995; Seta 1988). Three distinct anatomical regions are associated with hair: the cuticle, the cortex, and the medulla. Using a wooden pencil as an analogy, we can think of the cuticle as the paint on the outside of the pencil, the cortex as the wooden portion of the pencil, and the medulla as the graphite.

The cuticle is the outermost layer of the hair. It protects the hair from environmental insults. The cuticle is composed of flattened, scale-like cells, which overlap one another much like the scales on a fish or shingles on a roof. These scales slope outward from their attachment point on the cortex, and their free ends point toward the tip of the hair. The free ends interlock with the cells of the inner root sheath and hold the hair in the follicle. In human hairs, the scales form an imbricate pattern, that is, they have no repeating pattern. This characteristic serves to distinguish human hairs from animal hairs; many animal hairs have a very regular, repeating pattern to their scales.

A number of microscopic characteristics associated with the cuticle are used in a hair comparison. The thickness of the cuticle, the variation in the thickness, the presence of pigment, and the color are all useful characteristics. In addition, the nature of the outer cuticular margin may be smooth, looped, ragged, or damaged. When damage or artificial treatment to the hair is extreme, the cuticle may be removed, thereby causing damage to the next innermost region of the hair, the cortex.

The cortex is the main body of the hair and contains many of the characteristics used in the microscopic comparison process. The cortex is composed of elongated and spindle-shaped cells. The cortex contains the structures that primarily give hair its color, the pigment granules. There are two chemical forms of pigment in human hairs: eumelanin and phaeomelanin. The pigment eumelanin manifests in the colors of brown and black, and phaeomelanin in the colors of yellow and red, with each pigment having a slightly different size and shape. From a forensic standpoint, the organization, density, size, and distribution of these pigment granules are the most informative features of the cortex. They vary tremendously between racial groups, between individuals, and, to a much lesser extent, even within an individual.

In addition to pigment granules, small air spaces called cortical fusi are found in the cuticle. These air spaces form during the keratinization process of the hair. They are readily observed with compound microscopy and are typically found near the root end of the hair.

The final structures associated with the cortex are the ovoid bodies. These are large, well-defined, oval-shaped structures that may be found dispersed throughout the hair. According to Robertson (1999), ovoid bodies are well-defined, highly dense clumps of undispersed pigment. Their presence is not rare in human hair, but neither are they commonly seen.

In addition to the cortical structures just discussed, a number of characteristics are associated with the cortical cells themselves. Their texture, size, damage, and shape are all useful characteristics in the comparison process.

Another region of the hair is the innermost layer of cells called the medulla. This layer of cells may be continuous, discontinuous, fragmentary, or absent. In animal hairs, the medullary structure often is used to identify the family and sometimes the species of animal. In comparison to animal hairs, human hairs have no regular structure or pattern. The medullary cells may appear opaque or translucent or may vary even within a single hair. The opaque regions contain trapped air, and the translucent regions are caused by the mounting medium's having displaced the air. The diameter of the medulla is also a useful characteristic in the identification and comparison process.

In addition to the three anatomical regions of the hair, many other characteristics are useful in the microscopic comparison process. These characteristics relate to the growth stage, environmental influences, and disease influences on the hair.

The nature of the root may contribute information regarding the species of origin of the hair, and in addition, the growth stage of the hair when it was separated from the body. In animal hairs, the root morphology may assist in the identification of the group of animals from which the hair came. For example, the hairs of dogs,

cattle, horses, and members of the deer family have very distinct root morphologies from one another and from humans. In human hairs, the nature of the root depends on the growth stage of the hair. Many authors have offered classification schemes for the description of hair roots (Bisbing 1982; Harding and Rogers 1984; Lee and DeForest 1984; McCrone 1982; Shaffer 1982; Strauss 1983).

Hair grows from the dermal papillae, which lie in the base of the hair follicle. As new material is added to the hair, the "older" portion of the hair is slowly pushed out of the follicle until the hair naturally sheds from the body. At any given time, between 80 and 95 percent of the hairs on the human body are in an actively growing, or *anagen*, phase (Orentreich 1969; Pinkus 1981; Zviak and Dawber 1986).

The presence of an anagen root implies that some amount of force was required to remove the hair from the body (Ludwig 1969). The hair is still actively growing and is therefore still attached to the follicle. No statement can typically be made as to how much force was required; however, one would not expect to see this stage of root on hairs that fell from the body as a normal part of daily activities.

The second growth phase of hair is a transitional stage, called the *catagen stage*. During this short phase, the bulbous root of the hair begins to develop. At any given time, approximately 2 percent of hairs are in this growth phase (Pinkus 1981). No consensus exists with regard to the microscopic characteristics that are specific to this growth phase.

The third and final growth phase of hair is the dormant stage, called the *telogen stage*. These hairs are characterized by decreased pigment near the root, lack of medullation near the root, and increased cortical fusi near the root (Petraco 1988). In telogen hairs, the bulbous root is fully formed and is no longer attached to the dermal papillae. The hair is anchored in the follicle because of the interlocking cuticular scales of the hair and the inner root sheath of the hair follicle. Approximately 10 to 20 percent of the hairs are in this growth phase (Orentreich 1969; Pinkus 1981; Zviak and Dawber 1986).

In addition to the characteristics resulting from the growth phase of the hair, other characteristics are associated with the root. At times, when hairs are forcibly removed, follicular material may be attached. This material may be suitable for nuclear DNA analysis, if warranted. In forensic cases, hairs from dead bodies are sometimes examined. The decomposition process can impart specific characteristics on hairs (Linch and Prahlow 2001; Petraco et al. 1988), which can be used in the comparison process.

Hair color depends on the pigment granules present in the hair and on the other physical properties that affect how light is transmitted through the hair. Hair color is a useful feature in the hair-comparison process. Within an individual, hair color will show a degree of variation. In fact, variation may be observed within a single hair because of differences in exposure to the environment. However, the degree of variation within an individual is less than the variation among individuals (Robertson 1999).

Many authors have offered classification schemes for hair color (Bisbing 1982; Gaudette and Keeping 1974; Harding and Rogers 1984; Lee and DeForest 1984; McCrone 1982; Robertson 1982; Strauss 1983; Trotter 1939). Regardless of the classification scheme used, the hue (color shade), the value (light versus dark), and the intensity (saturation) must be considered during the comparison process (Hicks 1977).

The tip, or the distal end, of the hair also can vary greatly in morphology. The tip of a newly formed hair will taper naturally to a point. As the hair is subjected to grooming, abrasion, cutting, and possibly artificial treatment, microscopic characteristics are imparted to the tip of the hair. As they have with hair roots and hair color, numerous authors have offered classification schemes for the nature of hair tips (Bisbing 1982; Gaudette 1976; Gaudette and Keeping 1974; Harding and Rogers 1984; Lee and DeForest 1984; Robertson and Aitken 1986; Shaffer 1982). Regardless of the classification scheme used, the nature of the tip must be considered during the comparison process.

The length of the hair should be considered, keeping in mind that hairs may have been cut in the time between the deposition of the hair at the crime scene and the collection of the known sample. Conversely, the known hair sample may have grown if a significant length of time has elapsed between the deposition of the hair and the collection of the known sample. These additional factors must be considered during the comparison process.

The diameter of the hair is another feature that can be used in the comparison process. The overall shaft diameter may range from very fine (40–50 micrometers) to very coarse (110–120 micrometers). The diameter of the hair plays a significant role in the classification of racial group and determination of the body area from which the hair may have arisen.

The presence of artificial treatment may give the hair a characteristic color. Bleaching will remove pigment from the hair and give a Caucasian hair a characteristic yellow color. Dyes will add color to the hair and often result in a hair color that is outside the normal range of color expected in human hairs. Repeated artificial treatments will result in distinct regions of varying color.

When an artificial treatment is applied to the hair, it often results in a line of demarcation, that is, a notable change in color along the length of the hair. This is due to the treatment's interaction with the hair shaft down to the skin layer. As the hair continues to grow, the newly formed hair is not subjected to the same treatment and retains its natural color, resulting in the line of demarcation between the treated and untreated areas. Artificial treatment may also result in changes to the color of the cuticle, either within the cells of the cuticle or on the exterior of the cuticle.

Any damage present in the hair also should be noted. Cutting a hair with scissors typically results in a sheared or squared-cut appearance. This can be contrasted with hairs that are cut with a razor, which typically have an angular-cut appearance. Hairs that have been crushed, broken, burned, or chewed by insects all have very distinctive characteristics. These characteristics provide value to the comparison process, such as finding crushed or damaged hairs on a tool used to strike the head of the victim.

Diseases and other hair abnormalities may be informative to the hair-comparison process. A number of diseases may cause specific microscopic characteristics to appear in the hair. Seta et al. (1988) summarized the diseases and abnormalities that can result in these characteristics. Because these disease conditions are very rare, considerable weight is given to the presence of these characteristics.

Hairs are remarkably robust, retaining their comparable microscopic characteristics for a very long time, making them very suitable for forensic analysis. Hairs recovered from Ice Age sites, between 10,000 and 18,000 years old, were still able to be identified as human hairs. In fact, one hair still had its follicle attached (Bonnichsen and Schneider 1995). In its reference collection, the FBI Laboratory has hair samples collected from mummies identified to be more than 2000 years old (Olen unpublished data).

Transfer and Persistence of Hairs

The primary mechanism for the transfer of trace evidence is described by the Locard Exchange Principle (Locard 1930). Although there will always be a transfer of trace evidence, in some instances, the material exchanged may be too small to detect or may be rapidly lost. Numerous authors have addressed the transfer and persistence of fibers in forensic cases, including Kidd and Robertson 1982; Pounds and Smalldon 1975a, 1975b, 1975c; and Robertson et al. 1982.

These authors investigated the mechanisms involved in the transfer of textile fibers and the persistence of the fibers after the transfer occurred. Although these studies primarily involved textile fibers, wool fibers were used in these studies; therefore, the results of these studies also apply to human hair. These authors found that the number of fibers transferred depended on the amount of pressure involved in the contact and the duration of the contact.

With regard to persistence, these authors found that the nature of the recipient garment, the size of the transferred fiber, and the movement of the recipient garment had a dramatic effect. If the garment containing transferred fibers was worn, most fibers were lost rather quickly (within a few hours). If the garment containing transferred fibers was held in a fume hood, the rate at which fibers were lost was much lower.

Gaudette and Tessaroto (1987) stated that many of the variables affecting fiber transfer and persistence were also important in hair transfer and persistence. In order to document some of these variables, they conducted several experiments on hair transfer. They identified two mechanisms of hair transfer: primary and secondary transfer.

Primary transfer can be either direct (from person A's scalp to another location) or indirect (from person A's scalp to person A's environment and then to another location). Secondary transfer is an indirect transfer (from person A's environment to person B's environment to person C's environment). The authors demonstrated that secondary transfer of human scalp hair can and does occur in casework situations and that persistence of the transferred hair is similar to that previously found for fibers by Pounds and Smalldon (1975a, 1975b, 1975c). Robertson and Somerset (1987) conducted a similar study on persistence and found comparable results; that is, most transferred hairs are lost with normal wear after about three hours.

Quill (1985) recovered 81 hairs from his clothing over a 31-day period. Of the hairs that were suitable for microscopic comparison, all had been transferred from family members. Quill concluded that for a foreign hair to be present on clothing, close personal contact is required. Simons (1986) found that although most hairs are removed from clothing during the laundering process, some hairs do remain on clothing and hair transfers can occur as a result of the laundering process.

Peabody et al. (1985) investigated the shedding of hairs into various types of headgear. They found that the number of hairs shed varies with the type of headgear worn and with the individual. They also noted the importance of collecting head-hair combings, because the nature of the hairs shed in their study were more similar to the naturally shed hairs encountered in combings than to the hairs encountered in plucked, known head-hair samples.

Based on these studies, it can be concluded that it is reasonable to find hair evidence in forensic cases. Hair is ubiquitous in the environment and, therefore, may be transferred during a crime. However, it is imperative for proper and timely collection of evidentiary materials, including known hair samples, to occur if hair examinations are going to be valid, reliable, and meaningful.

Hair-Collection Process

In order for hair evidence to be meaningful, the hair must not only be transferred, it must persist and be recovered as evidence. There are two distinct locations where evidence recovery typically occurs: at the crime scene and at the laboratory. Because of the potential loss of hair evidence, it is crucial that evidentiary items be collected as soon as possible; properly packaged to prevent loss, contamination, or deleterious change; and transported to the laboratory expeditiously. Any additional handling or wear increases the likelihood that the evidence will be lost.

Once the evidentiary item is transported to the laboratory, it must be handled in much the same manner. If the evidentiary item is going to be subjected to a variety of forensic disciplines, it is imperative that the trace evidence (including the hairs) be recovered before these other disciplines analyze the evidence, to protect against loss, contamination, or deleterious change. A number of techniques may be employed to collect and preserve the debris from the evidentiary item, including but not limited to taping, scraping, picking, and vacuuming.

Once the debris has been collected and preserved, the next step involves low-magnification microscopic analysis of the debris. Using a stereomicroscope, the debris is examined, and hairs are removed from the debris and mounted on glass microscope slides. This allows the hairs to be examined using a high-magnification compound microscope. Depending upon the number of hairs encountered in the debris sample, all of the hairs can be mounted on glass microscope slides, or a representative sample can be mounted.

Two methods may be used in determining which hairs are mounted when a representative sample is employed. In the first method, a sample of each of the distinct types of hairs observed with the stereomicroscope can be mounted, that is, some of each color, length, diameter, and texture.

The second method involves using a targeted search. This may be used in cases where known hair samples are submitted along with the evidentiary items. The known samples may be examined and mounted first. Once proper precautions have been taken to prevent contamination (cleaning the work area, cleaning the

tools, changing gloves), the debris from the evidentiary items is then examined. Hairs macroscopically similar to those in the previously mounted known hair samples can be identified and preserved on glass microscope slides.

After the hairs have been preserved on glass microscope slides, they can then be examined with a high-magnification compound microscope. Using magnification ranges from 50x to 400x, the microscopic characteristics can be observed. Based on the analysis of these microscopic characteristics, a number of possible determinations can be made.

Race and Body-Area Identification

A human hair can be classified into one of three racial groups: Caucasian, Negroid, or Mongoloid. A classification of Caucasian typically means of European descent. Negroid typically means of Sub-Saharan African descent. Mongoloid typically means of Asian or Native American descent. It must be understood that designation of these racial groups is based upon an evaluation of the microscopic characteristics present in the hair. The microscopic designation of racial group may or may not coincide with how a person self-identifies his or her racial group.

If a hair or a hair sample cannot be easily associated with a particular racial designation, these hairs may be described as either exhibiting mixed racial characteristics or as not classifiable to one of the three groups. Even if a hair or a hair sample cannot be classified as to race, it still may be of value for meaningful microscopic comparison purposes. The inability to classify a hair into only one of these three groups serves as an additional characteristic that can be used in the comparison process.

A human hair also can be classified as to the region of the body from which it came. Using the same features listed previously, this designation can be made with considerable accuracy. Typically, the body-area determinations that can be made are head hairs (from the scalp), pubic hairs, facial hairs (beard and mustache), limb hairs (arm/leg), chest hairs, axillary hairs (armpit), and eyebrow/eyelash hairs. However, hairs may be encountered that cannot be categorized into one of these groups. These may consist of "transitional" hairs, that is, those hairs growing between two body regions, hair fragments that are not large enough to be identified, or hairs from other body areas.

Procedure for Microscopic Hair Comparisons

Once the race and body-area determinations have been made, the suitability for comparison is determined. Hairs that have been characterized as head hairs or pubic hairs are generally considered suitable for comparison with a known head-hair or pubic-hair sample. Hairs from other body areas generally are not considered suitable for comparison because these other body-area hairs generally do not contain sufficient variation in their microscopic characteristics to reliably distinguish between hairs from different individuals. In limited circumstances and with limited significance ascribed to an association, a microscopic comparison may be conducted between these other body-area hairs and an appropriate known sample. However, the limitations of these comparisons must be understood by the hair examiner and conveyed in a report.

Once a hair has been determined to be suitable for microscopic comparison, it is compared with an appropriate known hair sample. Head hairs must be compared with known head-hair samples, and pubic hairs must be compared to known pubic-hair samples.

The comparison process involves the side-by-side analysis of a questioned hair and known hair samples using a comparison microscope. This allows for a direct comparison of the microscopic characteristics of the questioned hair within the same relative area of the known sample, at the same time and in the same field of view. This comparison must occur over the entire length of the hair.

In 1982, an ad-hoc Committee on Forensic Hair Comparisons was formed with Barry Gaudette as the chairman. This committee represented 10 U.S. states, Canada, and Great Britain laboratories and included representatives from law enforcement laboratories, private laboratories, academic institutions, and the National Bureau of Standards. This group of highly qualified hair examiners met to advance forensic hair comparison as a science (as cited in Federal Bureau of Investigation [FBI] 1985).

After two meetings, the committee published its recommendations in the following seven areas:

1. Terminology definition and standardization.
1. Establishment of a protocol for microscopical human-hair comparison.
1. Investigation and standardization of macroscopic and microscopic hair comparison characteristics.
1. Conclusion, report writing, and court testimony in forensic hair comparison.
1. Training of hair examiners.
1. Quality assurance in forensic hair comparison.
1. Nonmicroscopical methods of forensic hair comparison. (as cited in FBI 1985)

These meetings were followed in 1985 by an International Symposium on Forensic Hair Comparisons.

The Committee on Forensic Hair Comparison recommended using a comparison microscope, stating that the hair examiner must use a high-quality comparison microscope at different magnifications to conduct a thorough and careful examination of both the gross and microscopic characteristics exhibited by properly prepared hairs (as cited in FBI 1985). Robertson (1999) also expressed the opinion that the microscopic comparison of hairs cannot be conducted without a comparison microscope.

The Scientific Working Group on Materials Analysis (SWGMAT), which evolved from the original Committee on Forensic Hair Comparison, has one of its subgroups dedicated to forensic hair comparisons. SWGMAT states that the use of a high-quality transmitted light microscope is necessary to examine and identify the microscopic characteristics of hairs (SWGMAT 2005).

A number of authors have published examination procedures for the forensic examination of hair, including the Committee on Forensic Hair Comparison (as cited in FBI 1985), Robertson (1999), Shaffer (1982), Strauss (1983), and SWGMAT (2005). According to the SWGMAT guidelines (2005), in order to conclude that a questioned hair and a known sample are consistent with sharing a common origin (association), it must be determined that there are no significant differences between the two. In other words, for a

conclusion of an association to be made, it must be determined that the characteristics exhibited by the questioned sample are represented in the known sample.

The starting point in a forensic hair examination must be an attempt to look for differences, not similarities, between a questioned hair and a known sample (Robertson 1999). Even within an individual, the expectation must be that a known sample will exhibit a range of microscopic characteristics. Because hairs are a biological product and there are both genotypic and phenotypic influences on the arrangement of their microscopic characteristics, no two hairs, even from the same person, can look exactly alike. Therefore, even when an association is made, it does not mean that the questioned hair and a single hair from the known sample will be identical in all features along the entire length of the hairs.

The assessment of what is or is not a meaningful or significant difference lies at the core of the training and experience of the forensic hair examiner. These examinations should be conducted only by a properly trained hair examiner employing a side-by-side comparison of a questioned hair and a known sample.

Three general conclusions can be reached as a result of microscopic hair analysis: exclusion, no conclusion, or association. Within the categories of exclusion and association, there are two subcategories (see Gaudette 1985). When a questioned hair (a hair of unknown origin) is compared with a known hair sample (a sample of hairs removed from a particular body area of a person) and differences in the observed microscopic characteristics are found, the hair examiner can conclude that the questioned hair is not consistent with originating from the source or donor of the known hair sample.

Is it possible to definitively exclude an evidence sample as originating from a particular donor based on microscopic hair comparisons? Stating categorically that a questioned hair definitely did not come from the donor of a known sample implies that the probability of an incorrect exclusion is zero (or so small to be effectively zero). Some possible causes of an incorrect exclusion are examiner error, too few reference hairs comprising the known sample, the known sample is not representative of the body region, incomplete hairs in the known sample, a large amount of time between the deposition of the questioned hair and the collection of the known sample, and the possibility that the questioned sample is an atypical hair. If an examiner is properly trained and follows appropriate procedures, then the probability of an incorrect exclusion based on these possible scenarios is minimal.

Regardless, a hair examiner is limited when providing an interpretation that the hair definitely did not come from a particular person (as an examiner would be if he or she were to state that the hair definitely came from a particular person—an almost impossible conclusion given the limitations of the evidence and/or technology). Although a false exclusion is not as serious as a false inclusion, there are still consequences associated with a false exclusion.

For example, an examiner can state that the questioned hair (a short, colorless [gray] hair) is not consistent with originating from the suspect, but the number of gray hairs on the suspect's scalp was so few that they were not represented in the known sample. A categorical exclusion in this case might direct an investigation in an improper course.

There are few circumstances in which an absolute exclusion can be rendered, such as when the questioned hair and the known hair samples exhibit different racial characteristics. In this scenario, the examiner may be able to conclude that "the questioned hair is microscopically dissimilar to hairs in the known hair sample and therefore could not have come from the donor of the known hair sample."

The scenario of the gray-hair exclusion cited above, however, would not meet any of these potential exclusion circumstances. The examiner would have to conclude that "the questioned hair is microscopically dissimilar to the hairs in the known hair sample, and the questioned hair is not consistent with originating from the source of the known sample." Although the characteristics of the questioned hair may not encompass the range of characteristics exhibited by the known hair sample, a low percentage of gray hairs may not be seen simply because of sampling error. The great majority of microscopic hair exclusions have similar limitations.

When a significant difference is observed between a questioned hair and a known hair sample, then it must be concluded that the questioned hair and the known hair sample are not consistent with sharing a common origin. More precisely, the hair is not consistent with originating from the donor of the known sample as represented by the hairs present in the known sample.

Another category of conclusion that can be reached by a microscopic-hair examiner is that "no conclusion" can be reached as to whether or not the questioned hair is consistent with originating from the donor of the known sample. This conclusion is reserved for circumstances when the questioned hair exhibits similarities to the hairs in the known sample but also exhibits some slight microscopic differences; however, these differences are not sufficient to conclude that the hair is not consistent with originating from the donor of the known sample. Some possible causes for these slight differences are (1) a significant amount of time has occurred between the deposition of the questioned hair and the collection of the known sample (typically more than one year); (2) the questioned hair is significantly longer (or shorter) than the hairs in the known head-hair sample (for example, the donor of the known sample may have cut his or her hair after deposition of the questioned hair); (3) the questioned hair has not been artificially treated, but the known sample has been; (4) the questioned hair is not a full-length hair; that is, a portion(s) of the hair is/are missing; (5) the known sample contains too few hairs for an adequate comparison; and (6) the questioned hair comes from a different donor.

The typical wording for a "no conclusion" is: "The questioned hair exhibits similarities and slight microscopic differences, and therefore, no conclusion can be reached as to whether or not the questioned hair is consistent with originating from the donor of the known hair sample." When this conclusion is reached, these hairs may be submitted for mitochondrial DNA (mtDNA) analysis.

The final category of conclusion that can be reached in a microscopic hair comparison is that of an association. In contrast to the two subcategories of an exclusion result, there is only one conclusion for association, that the questioned hair exhibits the same microscopic characteristics as the hairs in the known hair sample and therefore cannot be excluded from originating from the source of the known sample. It is

possible to contrive a scenario where one might logically report a strong positive association, that is, state that the questioned hair originated from the donor of the known hair sample.

For example, if one knew that the person with the longest hair in the world had hair that was 26 feet long and if a 26-foot-long hair was recovered from a crime scene that exhibited all of the same microscopic characteristics as the hairs in the known hair sample, it would be possible to state that the hair definitely came from that person. However, the likelihood of such an event occurring is so rare that it is not meaningful.

When an association is made, the conclusion would be stated as follows: "The questioned hair exhibits the same microscopic characteristics as the hairs in the known hair sample, and accordingly, the questioned hair is consistent with originating from the same source as the known sample." This means that all of the microscopic characteristics expressed by the questioned hair are represented within the range of characteristics exhibited by the known hair sample. In other words, no significant differences can be found.

The final step of a hair examination should be a verification or confirmation procedure. This step involves having a second qualified examiner conduct an independent microscopic comparison of the hair that has been associated (SWGMAT 2005). The second examiner must conduct a thorough, complete analysis and must be free to reach his or her own conclusion on each hair. Only upon the second examiner's reaching agreement should a microscopic hair association be reported. In accordance with FBI Laboratory standard operating procedures, when this conclusion is reached, these hairs are submitted for mtDNA analysis.

Not all conclusions of a hair association can be weighted equally. Consider the following two examples. First, a questioned hair is recovered from a hat that was found on the side of the road and believed to be used in a bank robbery. Microscopic examination reveals that the hair is a blond, Caucasian head hair. Comparison with known hair samples from suspects in a bank robbery results in the questioned hair's being associated with one of the suspects and excluded from the other two suspects.

Second, a questioned hair is recovered from the backseat of a vehicle used to transport the victim of a kidnapping. Microscopic examination reveals that the hair is a long, dark brown, Caucasian head hair that exhibits characteristics of being artificially treated three separate times over the length of the hair. Comparison with known hair samples from the victim and persons that were known or suspected to be in the car results in the questioned hair's being associated with the victim and excluded from the persons known or suspected to have been in the car.

In these two scenarios, more relative weight can be ascribed to the hair association in the second scenario, because additional characteristics are present for comparison, namely the artificial treatment (dark brown color) and the length of the hair. Because there is no known mechanism for a hair examiner to quantitatively assess the additional weight of these special characteristics, it is incumbent upon the hair examiner to explain this to the trier of fact. Fact finders, from their own experiences, can assess the significance of the results conveyed by the hair examiner.

Most important, when conducting hair examinations, properly trained and qualified examiners would not and should not opine that a hair could be attributed to an individual to the exclusion of all others. This basic tenet of the science has been espoused since the inception of the discipline (as first described by Rudolf Virchow in 1861; cited in Bisbing 1982). The hair examiner must convey, both in the written report and in courtroom testimony, the limitations of the science and, especially, an interpretation of an association.

In order to ensure that proper weight is put on the results and interpretation of a microscopic hair comparison, FBI Laboratory reports for the past 40 years have stated that hair comparisons are not a means of individualization in reports of examination containing microscopic hair comparisons. In addition, FBI hair examiners are trained to include, at a minimum, the same information during their testimony on cases involving a hair association.

Not only must fact finders be aware of the conclusion reached by the examiner, they also must be aware of the limitations of the science so they can properly appreciate the significance of a result. Providing an explanation of the results will best overcome possible confusion from similar but differently phrased conclusions such as "is consistent with" or "could have come from." Regardless of the phraseology used, the fact finder must be given supporting information beyond the statement of an association.

Some critics emphasize the fact that microscopic-hair examiners are unable to statistically quantify the significance of an association (see, for example, Robertson 1999). The development of a statistical model would involve frequency data across the entire population for all microscopic characteristics present in hair. Although this is an attractive idea, the difficulties associated with generating such a database have been, to date, practically insurmountable. In order to generate frequency data for hair characteristics, microscopic-hair examiners might be required to use a "checklist" or "archetype" approach rather than the pattern-recognition process normally used.

However, two hairs that may be "alike" based on a checklist may very well be microscopically different (see Gaudette and Keeping 1974; Strauss 1983). In addition, different examiners are likely to describe hairs in different ways (see Gaudette and Keeping 1974; Podolak and Blythe 1985). Finally, the same examiner may vary his or her description of the same hair on different days (see Wickenheiser and Hepworth 1990).

These examples do not reflect a flaw in the science of microscopic hair comparisons or an error by a microscopic-hair examiner; rather, they serve to highlight the limitations of generating a useful database. The database approach confines the examiner to documenting the status of single characteristics at a specific location in a single focal plane as opposed to a holistic approach. That characteristic may change slightly at a different focal plane even at the exact same location and may change dramatically at a different location in the hair. In a single hair, there are hundreds or even thousands of possible different fields of view.

It has been pointed out previously (see Wickenheiser and Hepworth 1990) that this classification method would force the examiner to choose, subjectively, from the myriad possible fields of view, the one that best represents that characteristic. This subjective choice then must be repeated for all of the remaining microscopic characteristics present in hair. Because of the inherent variation in the microscopic

characteristics of hair, the use of such an approach likely would result in a situation where two hairs that "match" according to the checklist in reality look nothing alike.

Given that useful statistical data are not generated regarding the relative frequency of an evidentiary hair, one must accept that the answer to the question, what proportion of the population would have characteristics that are the same as the evidentiary hair? is we do not know. Similarly, the answer to the question, what is the probability of a coincidental match between the questioned hair and the known sample? is we do not know. Rather, the fundamental question that can be addressed is, what is the value of the evidence in establishing the association? (see Gaudette 1986). Numerous empirical studies exist detailing the ability of microscopic hair comparisons to reach the correct conclusion; these empirical studies can provide some guidance on the significance of an association.

Studies Supporting Microscopic Hair Comparison

Numerous studies have been conducted that support the science of microscopic hair comparisons. Strauss (1983) conducted a study using 100 individuals comprising 54 Caucasian, 19 Negroid, and 27 Mongoloid. From each of the 100 individuals, 7 hairs were chosen to represent the widest variation possible. These were mounted on glass microscope slides and were designated as the known samples. One hair was also chosen from each of the 100 samples, mounted on glass microscope slides, and designated as questioned hair samples. All 800 hairs (700 known hairs and 100 questioned hairs) were individually characterized using a checklist and punch cards.

A series of seven experiments was conducted. A neutral party selected a total of 10 single questioned hairs to be compared with 10 known samples. Comparison microscopy resulted in 100 percent accuracy in associating the correct questioned hair with its known source, showing that they could reliably associate a questioned hair with a known sample. In addition, the study showed that the examiners correctly identified each of the 100 individuals in the questioned hair pool to the correct known hair group, that is, 54 Caucasian, 19 Negroid, and 27 Mongoloid.

Gaudette and Keeping (1974) obtained head-hair samples from 100 individuals. Within the group, 92 were Caucasian, 6 were Mongoloid, and 2 were Negroid hairs. From each of these samples, 6 to 11 macroscopically dissimilar hairs were selected to represent the range of microscopic characteristics present in the known sample. These hairs were then mounted individually on glass microscope slides. The hairs were characterized, and the microscopic characteristics were categorized using punch cards. Each hole in the punch card was associated with a specific microscopic characteristic. The cards from each individual were combined with all of the others and were sorted based on similar holes in the punch cards. The hairs for each of these similar cards were then compared microscopically. Using this system, a total of 861 hairs from 100 different individuals were examined and compared, for a total of 370,230 comparisons. From all of these comparisons, only 9 pairs of hairs were found to be indistinguishable.

In a similar study, Gaudette (1976) obtained 30 pulled pubic hairs from 60 different individuals. All of these were Caucasian hairs. From these, 6 to 11 dissimilar hairs were selected randomly to represent the range of characteristics present in the 30 hairs. As in the previous study, the characteristics were coded on punch cards, and the cards were combined and sorted. With the 454 hairs, the total number of comparisons made was 102,831. A total of 16 pairs of hairs were found to be indistinguishable.

From each of these studies, the authors attempted to obtain probability estimates for head-hair and pubic-hair comparisons. The probability estimates proposed by Gaudette and Keeping (1974) and Gaudette (1976) for the frequency of head and pubic hairs cannot apply to the population at large. The probabilities they derived refer to the process of distinguishing between two hairs that the examiner knew originated from different people. In addition, the authors found that different examiners obtained different results in the single-hair comparison study. This would mean that even if the data were correct, the probability estimate would have to be generated by each new person using the technique. This is not comparable to the normal casework scenario for a microscopic-hair examiner, where a questioned hair is compared to known hair samples (Barnett and Ogle 1982). In a later paper, Gaudette (1978) stated that "the significance of this research is not in the actual probability numbers found but in experimental proof of the proposition that macroscopic and microscopic hair comparison is a useful technique and that hair evidence is good evidence" (Gaudette 1978).

In the same study (1978), Gaudette provided each of three examiner trainees with one separate known head-hair sample, consisting of 80 scalp hairs. Each of the trainees was then given 100 questioned hairs from different individuals, one of which was the one represented by the known standard. Without being told how many individuals the unknowns were from or how many, if any, of the hairs were supposed to be similar to the standard, the trainees were instructed to compare the questioned hairs with the known standards and report their results. Two of the trainees correctly identified one and only one hair with the known standard.

The third trainee initially concluded that there were four hairs similar to the standard. However, upon further examination and consultation with other examiners, he was able to eliminate one of the four. However, he still concluded that the three remaining hairs could not be eliminated: the correct one and two others. All of the hairs that remained were of the common, featureless type.

Another experienced examiner evaluated the three remaining hairs and concluded that the correct hair could not be eliminated and, in addition, that one of the two others could not be eliminated. Yet another examiner looked at the remaining three hairs and agreed that the correct hair could not be eliminated and, in addition, that the other of the remaining two could not be eliminated.

Another experiment was conducted, again using 100 representative scalp hairs from 100 individuals. From these, one sample was selected. From this sample, a single hair was then selected at random. Thus, there was one questioned hair that was compared with 100 known standards. This experiment was then repeated. On both occasions, it was found that the unknown hair could be associated with one and only one standard—the correct one.

In a third experiment, the unknown hair was chosen specifically to be a common, featureless hair. This hair was found to be similar to two standards: the correct one and one additional one.

Based on these series of experiments, Gaudette found that when an experienced hair examiner conducts a hair comparison using all of the available microscopic characteristics, these comparisons were reliable and repeatable. He also offered that special training in hair comparison of at least a year in length is required to enable a person to develop the required level of discrimination.

Wickenheiser and Hepworth (1990) obtained head-hair samples from 97 different individuals, including a number of closely related individuals from several generations. Between 5 and 13 dissimilar hairs from each sample were chosen to represent the range of characteristics in the known sample. These were numbered randomly by an independent party. In addition, 53 additional hairs randomly chosen from the original 97 known samples were also numbered randomly. In total, 930 hairs were selected and placed on glass microscope slides. All of these hairs were examined to determine how many matching pairs were present. Each hair was compared to all of the other 929 hairs, for a total of 431,985 hair comparisons.

Two different examiners developed comparison checklists and used a computer program to sort the hairs based on these checklists. As a result of the computer sorting based on gross macroscopic and microscopic characteristics, the first examiner conducted 749 one-to-one microscopic comparisons, and the second examiner conducted 2006 comparisons. The first examiner found seven pairs of hairs that were microscopically indistinguishable, and the second examiner found six pairs. In every case where a one-to-one association was found, the hairs were truly from the same source. No incorrect associations were made by either examiner. Based on their findings, the authors determined that if a one-to-one match is the requirement in a microscopic hair comparison, then the incidence for an error is very low.

Bisbing and Wolner (1984) conducted a series of studies using known head-hair samples recovered from 17 sets of twins and 1 set of identical triplets. Of the twins included in the study, 9 were fraternal twins, 6 were identical twins, and 2 were of unknown zygosity. All of the twins were Caucasian, and 11 of the 18 sets were blond. In addition, all of the samples were cut. The authors commented that the predominance of blond hair and the absence of hair roots made these comparisons unusually difficult. In fact, many of the samples were considered by the authors to be common, featureless hairs.

From each of the individuals in the study, two known hair samples were mounted on glass microscope slides and were assigned a random number. This resulted in a total of 74 known samples. The authors then conducted comparisons of each twin sample with all other samples. By visual and microscopic examination, both authors were able to correctly distinguish all of the known samples and were able to accurately associate the duplicate samples with each other. The specimens were never incorrectly associated, even with the known hair sample of the twin.

In order to more closely resemble true forensic casework, a second study was conducted. This study involved removing 2 or 3 hairs from 7 randomly selected unmounted samples, which were then mounted on glass microscope slides. For each of these 7 "questioned" samples, between 5 and 10 known samples were randomly selected from the 74 mounted known samples for microscopic comparison. There were 52 comparisons made by each of the two examiners, for a total of 104 comparisons. Because of the random sampling, none of the true known samples for the questioned hairs was present in any of the comparison scenarios. The two examiners correctly excluded 96 of the known samples as being possible donors of the questioned hairs. Eight of the questioned hair samples were incorrectly associated to the known samples (5 by one examiner and 3 by the second examiner). In one of these cases, a sample of the fraternal twin's hair was present in the known pool and was correctly eliminated. In the other simulated cases, the questioned hairs were incorrectly associated with control samples that were neither the true source nor the twin of the true source.

It is interesting to note that 7 of the 8 incorrectly associated hairs were classified by the authors as being blond, common, featureless hairs. These results serve to reinforce that human hair cannot be associated with one person to the exclusion of all others. In addition, this study served to show that caution is necessary when comparing common, featureless hairs. Finally, the authors stated that the verification process might measurably reduce the possibility of Type II errors.

Suzanski (1988) conducted a blind study involving comparison of 15 questioned hairs with known hair samples obtained from 25 purebred German shepherd dogs. He made no false inclusions and correctly assigned 6 of the 15 questioned hairs to their known sample of origin. In a later study (1989), Suzanski compared 25 questioned hair samples of approximately 10 hairs each with known samples from 100 mixed-breed and purebred dogs. He was able to assign all 25 of the questioned hair samples to the known samples, with no incorrect associations.

From these studies, we can conclude that microscopic hair comparisons are reliable and are indeed a valid scientific method. If a properly trained hair examiner uses a valid procedure, the examiner can achieve the correct result. It is important to note that hairs are not a means of personal identification, and this information must be conveyed both in a written report and during testimony. It is acknowledged that the microscopic characteristics exhibited by a questioned hair can be encompassed by the range of characteristics exhibited by more than one person. However, if an examiner associates a questioned hair with a known sample that is known to be from a different person, it does not imply an error or a mistake on the part of the microscopic-hair examiner. Rather, it highlights the limitations of the science.

For the past 100 years, microscopic hair comparisons have been the only method available to determine if an association exists between two people or between a person and an object based on hairs recovered from evidentiary items. These comparisons have been routinely conducted in forensic laboratories and accepted both in the scientific community and in the legal community for the past 75 years. Because of the limits of the science of microscopic hair comparison, the strongest conclusion that a microscopic-hair examiner can ever make is that a hair "is consistent with" or "could have come from" the donor of the known sample. However, the studies cited above do show that the method is reliable and repeatable. In addition, these studies demonstrate both the exclusionary and a degree of inclusionary power of microscopic hair comparison.

A wealth of information can be gained from the microscopic analysis and comparison of hairs—information that may be crucial to a case, such as the ability to exclude persons who are not the source of an evidence hair. Fortunately, another tool is available to augment microscopic hair analysis. With the advent of DNA