I

IDENTIFICATION

Contents

Prints, Finger and Palm

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History of Fingerprints

Finger and palm prints have been of interest to humans for the past 5000 years. This article provides an overview of the development of fingerprinting as a science, followed by a brief introduction to the anatomy that determines print characteristics. The second half of the article discusses forensic aspects of fingerprinting: collection of latent prints, classification of prints, and systems for matching prints. Scientific interest in their properties blossomed in the late nineteenth century. Table 1 summarizes highlights of the use and study of prints.

Composition of Latent Fingerprints – Friction Skin

Fingertips are not the only part of the body that leave identifiable prints. The palms of the hand and the soles of the feet are also printable in the same fashion. These surfaces are covered with friction skin. Friction skin is covered with papillary ridges that assist in the ability to grasp and hold onto objects. The patterns formed in these ridges are very important since they are determined by the fourth month of gestation and remain fixed throughout life. Only severe mutilation or skin disease can cause them to change. The ridges vary in length and width, starting and stopping on occasion, and branching at points. For the most part they flow along with each other, forming individual patterns. Along the crest of the ridges, sweat pore openings are found. These pores number in the thousands per square centimeter.

Friction skin is formed of many layers. As with all skin, the epidermis is the outer layer and the dermis the inner layer. The composition of the epidermis and dermis is slightly different for friction skin than for other parts of the skin. Starting from the outer surface, the epidermis comprises: stratum corneum, stratum lucidum, stratum granulosum, stratum spinosum, and stratum basale. The top three elements are dead and dying cells while the bottom two are the living layers. These two are also known as the Malpighian layer, after Marcello Malpighi. Figure 1 shows the basic structure of friction skin.

The glands attached to the pores in the ridges are eccrine glands. These are one of the two types of sweat glands found in humans. The eccrine gland has a coiled, tubular shape at its genesis in the dermis. Rising up through the epidermis is a duct through which secretions travel prior to emission through the pore. Eccrine glands are primarily responsible for regulating body temperature, although those associated with the friction skin are also linked to nervous reactions. Eccrine sweat contains approximately 99% water and 1% solids. The solids include sodium, potassium lactate, urea, ammonia, serine, ornithine, citrulline, aspartic acid, heavy metals, organic compounds, and proteolytic enzymes. These are the components of sweat that are left behind, forming fingerprints.

Table 1 Highlights of the use and study of prints

3000 BC	Masons 'sign' brickwork with finger impressions in their work on projects meant for kings and pharaohs
500 BC	In China and Babylon clay tablets and records of business transactions are imprinted with the author's fingerprints. It is not known if these societies knew of the uniqueness of fingerprints but there was obviously some attachment of identification to the prints
1684	Nehemiah Grew publishes the first written description of fingerprints in the West. Grew, a plant morphologist, was the first to study ridges and pores on the fingers and hands. In addition to writing he also provides detailed drawings of ridge patterns
1686	Marcello Malpighi, a professor of anatomy at the University of Bologna, Italy, publishes *De Externo Tactus Organo*, in which he describes ridges, spirals, and loops in fingerprints. He makes no mention in this work of their value as a tool for individual identification. The ''Malpighi'' layer of skin is named after him
1823	Joannes Purkinje publishes his thesis *A Commentary on the Physiological Examination of the Organs of Vision and the Cutaneous System*. In this he deals with functions of the ridges, furrows, and pores. He describes and illustrates nine fingerprint patterns. These nine classifications are what Henry will later name arches, tented arches, loops, whorls, and twinned loops
1858	Sir William Herschel, Chief Magistrate in Jungipoor, India, begins using, first, inked palm impressions and later, fingerprints on native contracts as a means of signature. Herschel begins to note that the inked impressions can, indeed, prove or disprove identity. Perhaps Herschel's greater contribution to fingerprint history is in confirming ridge consistency, i.e., friction skin ridge patterns are formed before birth and remain the same throughout life. At times throughout his life, Herschel takes his own fingerprints and notes that no change occurred in them in over 50 years
1870s, 1880	Dr. Henry Faulds, while in Japan, conducts experiments; removing the skin from a patient's fingers after having first fingerprinted them. When the skin grows back he confirms that the pattern is the same. Faulds is credited with identifying fingerprints at crime scenes, which were then compared to suspects who admitted their guilt. Dr. Faulds publishes an article in the scientific journal *Nature,* in which he discusses fingerprints as a means of personal identification, and the use of printer's ink as a method of obtaining such fingerprints. In the article he states: ''When bloody finger marks or impression on clay, glass, etc., exist, they may lead to the scientific identification of criminals.'' His is the first publication to describe fingerprinting as a forensically useful science
1892	Sir Francis Galton, a British anthropologist, publishes *Fingerprints*. The book includes the first classification system for fingerprints. According to his calculations, the odds of two individual fingerprints being the same are 1 in 64 billion. For his classification method, Galton identified the small characteristics by which fingerprints can be identified. These same characteristics (minutiae) are still in use today
1900	Sir Edward Henry develops a classification system that neatly divides 10-print fingerprint cards into 1024 bins. Henry publishes his book *Classification and Uses of Fingerprints.* This system goes on to become the basis for the dominant indexing system in the English-speaking world

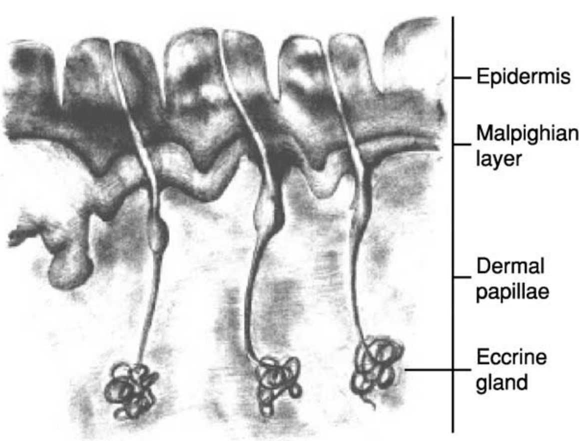

Figure 1 Friction skin: the coiled eccrine glands, located in the dermis, have ducts which rise through the epidermal layers and terminate along the crests of ridge lines. The structure of the dermal papillae gives the fingerprint its characteristic pattern.

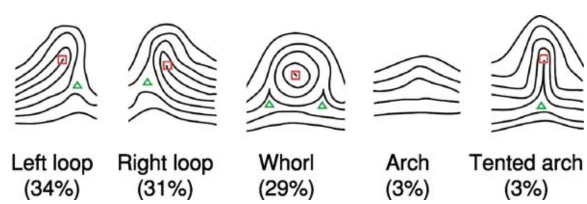

Figure 2 Examples of the most common patterns for ridge lines. The five major classes – left loop, right loop, whorl, arch, and tented arch – are used. The approximate frequency of occurrence for each type is stated in brackets. For each type the position of the core is marked with a red square and the delta is marked with a green triangle.

Patterns of Fingerprints

As Purkinje first published and later Henry codified, there are relatively few primary patterns for fingerprints. They are most commonly referred to as loops, whorls, and arches (Figure 2). Within the Henry system these basic patterns are classified as: loop (ulnar or radial), tented arch, whorl, twinned loop, central pocket loop, lateral pocket loop, composite, and accidental. In order to interpret the rules for classifying a print into these categories it is first necessary to understand the delta formation and the core. As the name suggests, a delta formation is a triangular arrangement of ridge lines, formed where three separate ridge line flows come together. The core formation is the centermost portion of a ridge flow pattern.

Loop – Ulnar or Radial

Loops constitute between 60 and 70% of the patterns encountered. In a loop pattern, one or more of the ridges enters on either side of the impression, recurves, touches, or crosses the line running from the delta to the core, and terminates or tends to terminate on or in the direction of the side where the ridge or ridges entered. There is one delta. By definition, the existence of a core and one delta makes the pattern a loop. There are two kinds of loop, radial and ulnar, named after the radius and ulna, the two bones in the forearm. The radius joins the hand on the same side as the thumb, and the ulna on the same side as the little finger. To determine whether a loop is ulnar or radial you must know from which hand the print comes. If the ridge lines originate on the thumb side, the loop is radial; origination from the side of the little finger indicates ulnar.

Arch

Arches represent only about 5% of the fingerprint patterns encountered. In arch patterns, the ridges run from one side to the other of the pattern, making no backward turn. Arches come in two types – plain or tented. The difference is that tented arches have a significant upthrust in the middle, while the plain arch does not. Plain arches by definition have no deltas. Tented arches may have a delta at the base of the upthrust.

Whorl

Between 25 and 35% of the patterns encountered consist of whorls. In a whorl, some of the ridges make a turn through at least one circuit. Any fingerprint pattern that contains two or more deltas will be a whorl pattern. If a pattern does contain more than two deltas it will always be an accidental whorl. The technical definition of a plain whorl is a whorl that consists of one or more ridges that make or tend to make a complete circuit, with two deltas, between which an imaginary line is drawn and at least one recurving ridge within the inner pattern area is cut or touched.

Accidental

Under this heading are the relatively small numbers of patterns too irregular in outline to be grouped with central pocket loops and double loops. They have two or more deltas and a combination or fusion of two or more types of patterns, not including the plain, radial, or ulnar arch. This category also includes any pattern or formation that does not conform to any conventional type.

Collection Methods

Prior to classification and identification, fingerprints must first be collected. Fingerprints are typically collected from people using tenprint cards. To use these cards the enrollee's fingers are first inked and then the finger is rolled from side to side on the tenprint card, leaving an impression of the fingerprint. In addition to tenprint cards, fingerprint impressions are actively collected using a variety of scanning techniques for applications such as access control. These scanners use a variety of methods ranging from optical to ultrasound and capacitance to determine the pattern of ridges.

Latent Prints

Latent prints are those that are left behind through interaction of hands, palms, and feet with the environment. Preserving and collecting these prints is important in a forensic context. Occasionally these prints are left cleanly so as to be clearly visible to the unaided eye. It is more often the case that the prints are only partially visible or not visible at all without the use of specialized fingerprint-processing methods and equipment. This equipment has been developed to take advantage of properties of the latent print composition in order to enhance and stabilize the prints. The goal is to differentiate the print from the background surface.

A sequence of techniques is used when processing a crime scene for latent fingerprints. This sequence should always begin with nondestructive techniques before proceeding to potentially destructive ones. Lighting, physical processing, and chemical processing are all used in the development of latent prints. Visible examination of the site is the first line of approach, followed by other optical methods, e.g., diffusion, luminescence, ultraviolet absorption, and/or reflection. After these methods have been exhausted, more intrusive physical and chemical approaches can be considered. These methods will vary depending on the type, coloring, and contamination of the surface to be examined and the time and environmental conditions since the prints were thought to be left. The physical and chemical methods use various approaches to enhance prints by interacting with the secretion from the eccrine and sebaceous glands. The choice of enhancement technique is not always as straightforward as it may seem. Some approaches complement each other while others rule out further processing with what may be a promising alternative.

Lighting

Optical detection methods have the advantage of being nondestructive with respect to the latent fingerprint deposit. As a result, these techniques do not preclude the later application of other fingerprint development procedures. Observation of an object under white light may disclose a visible fingerprint that can be photographed without any further treatment or more complex optical detection methods may reveal otherwise invisible prints that may not be developed by other techniques. Photoluminescence, the emission of light by certain chemicals after exposure to light energy of a given wavelength, has proven to be useful in the detection of latent prints on surfaces such as metal, firearms, human skin, and polystyrene foam. A fingerprint is only visible if its luminescence is more intense or at a different wavelength to that emitted by the background. A similar approach can also be taken using ultraviolet spectrum lighting. Episcopic coaxial illumination is another light-based technique. It works well on normally shiny surfaces such as metal. The technique involves the use of a semitransparent mirror to observe the reflection of light perpendicular to the surface. The light is diffused by the fingerprint deposit but specularly reflected by the surface.

Physical

Dusting a surface with a fine powder of contrasting color is one of the oldest, most common, and most readily available methods for the development of latent prints. Fingerprint powder is applied at the crime scene on smooth, nonabsorbent surfaces and, in general, only to objects that cannot be transported back to a laboratory. The powder adheres to the humid, sticky, or greasy substances in the fingerprint deposit. The application of powder is relatively simple and inexpensive. The ideal powder is one of contrasting color, good adherence properties, and sensitivity, possibly incorporating a luminescent material. Fingerprint-lifting tape is the most common method of collecting fingerprint evidence after powdering. The adhesive tape is placed over the dusted print and smoothed down with the finger. Particles of powder adhere to the sticky surface of the tape and transfer a mirror image of the fingerprint pattern.

Small particle reagent (SPR), a suspension of powder in a surfactant solution, is a method of using powdering in wet applications. The reagent is sensitive to the nonwater-soluble compounds of the latent fingerprint and may be used on a wide range of nonabsorbent surfaces. SPR is effective on surfaces that are wet – a condition that excludes the use of conventional powders or reagents sensitive to the water-soluble components of the print.

Chemical

There are numerous chemical reagents at the disposal of a fingerprint collector. Two of the more widely used are described below. Depending on the surface the print is on, other choices may be more appropriate (Table 2).

Ninhydrin The reaction of amines with ninhydrin to form the colored reaction product known as Ruhemann's purple was discovered by Siegfried Ruhemann in 1910. The value of ninhydrin for the development of latent fingerprints was not realized until 1954, when Odén and von Hofsten suggested its use in criminal investigations. Ninhydrin reacts with the amino acid in the fingerprint deposit (eccrine secretion) to give a dark-purple product. Amino acid-specific agents have particular application for the development of fingerprints on paper. The chemical reactions involved are complex and, as a result, the development conditions need to be controlled if optimum results are to be obtained. Prints developed with ninhydrin may be further treated with a metal salt solution ($ZnCl_2$), which produces a color change to orange. The orange product is strongly photoluminescent when cooled with liquid nitrogen and illuminated with light of a wavelength of around 490 nm. There has been significant research into

Table 2 Applicability of selected reagents to a variety of surfaces commonly encountered in forensic fingerprint examination

	Surface type									
Reagent	*Paper*	*Glossy paper*	*Currency*	*Porous*	*Nonporous*	*Glass*	*Plastic*	*Wet*	*Metal*	*Wood*
Basic yellow 40		×				×	×		×	
Cyanoacrylate ester		×			×	×	×		×	
Ninhydrin	×			×						×
Iodine fuming				×						×
Physical developer	×		×							
Silver nitrate	×									×
Small particle reagent		×			×	×	×	×	×	

alternative amino acid-specific reagents. Two of the most successful are 1-8 diazofluorenone and a ninhydrin analog, indandione. These reagents produce a photoluminescent product and significantly improve sensitivity of detection compared to ninhydrin.

Cyanoacrylate fuming Cyanoacrylate esters are colorless, monomeric liquids sold commercially as rapid, high-strength glues, e.g. Superglue®. Cyanoacrylate liquid forms a vapor that reacts with moisture and certain eccrine and sebaceous components in a latent fingerprint. The vapor selectively polymerizes on the fingerprint ridges to form a hard, white polymer known as polycyanoacrylate. Prints with a high sebaceous component appear to be particularly sensitive to cyanoacrylate vapor, although the glue probably also reacts with the moisture and some water-soluble (eccrine) components in the print. The technique is effective on most nonporous surfaces, including metal, glass, and plastic. Originally developed in Japan in the late 1970s, the cyanoacrylate fuming process is now the most widely used fingerprint detection technique for nonporous objects treated in the laboratory.

Fingerprint Matching

Henry Classification System

The basic Henry system assigns a numerical value and an index number to each finger. From right thumb to right little finger, the fingers are indexed 1 through 5, while left thumb to left little finger are indexed 6 through 10. Starting with index 1, the right thumb, the first two fingers are valued 16, the next two 8, the next two 4, the next two 2, and the final two 1. To determine a tenprint's Henry classification, only the fingers with whorl prints are considered. The finger values are summed for every whorl-printed finger indexed with an even number. The same is done for the odd-indexed fingers with whorl prints. Each of these numbers is then increased by 1. The result is expressed as a fraction; the even index value in the numerator, and odd index value in the denominator. This fraction is the Henry classification number.

An example is given in Table 3. In practice each of the Henry categories is further refined, in most cases using Galton's details as the next level of indexing.

Automated Fingerprint Identification

The high demand of fingerprint identification services prompted the law enforcement agencies to initiate research into automatic fingerprint identification. The success of fingerprints as a forensic tool for establishing identity led to a much broader use of fingerprints for biometric identification in applications such as access control and passports. These applications require sensors that can quickly and reliably capture an image of a fingerprint. The challenge of automatic fingerprint identification is to transform an art, learnt in time-consuming training, into a precise algorithmic procedure. The following subsections summarize the sensing and enhancement of fingerprints, the representation of digital fingerprints, the classification, and the matching of fingerprints.

Sensing and Enhancement of Fingerprints

Rolled-ink fingerprints, as discussed above, can of course be scanned electronically. However, this acquisition process is slow and requires practice and skill and is therefore both unfeasible and impractical in the operational phase. Fingerprint scanners are used to automate the acquisition process. As opposed to a rolled print, most fingerprint scanners acquire a so-called dab, i.e., the finger is simply pressed on the sensor/paper without rolling it from nail to nail. Obtaining an image of a fingerprint without the intermediate step of getting an impression on paper is termed a live-scan fingerprint. A number of sensing technologies are available to capture live-scan fingerprints: (1) optical frustrated total internal reflection (FTIR); (2) thermal sensing; (3) ultrasonic reflection; (4) differential capacitance; and (5) noncontact two-dimensional and three-dimensional scanning. The FTIR method is one of the most popular concepts.

As opposed to scanning the superficial layers of the surface skin, ultrasound images the internal layers of

Table 3 An example of the Henry classification system. In this example the Henry number is (RR + LM + 1)/(RT + RM + TF + LR + 1). This reduces to (4 + 2 + 1)/(16 + 8 + 2 + 1 + 1) or 7/28 as the Henry index

		RT	***1***	*RF*	*2*	***RM***	***3***	***RR***	***4***	*RP*	*5*
Finger	Finger	***16***		*16*		***8***		**8**		*4*	
Name	Index	@				@		@			
		LT	*6*	***TF***	***7***	***LM***	***8***	***LR***	***9***	*LP*	*10*
Finger value		*4*		**2**		**2**		**1**		1	
Whorl				@		@		@			

the friction skin, focusing on the dermal papillae. This method is believed to be capable of acquiring a very clear fingerprint image, although the finger does not have very clear ridge structures. One disadvantage is that it is a relatively expensive sensing technology. Less accurate than FTIR and cheap enough for mass production is the differential capacitance method. In a capacitive sensor the finger acts as one of the plates of a capacitor. The other plate consists of a silicon plate with sensing circuitry. Each pixel is precharged to a reference voltage and discharged by the reference current. The rate of change of the potential on the capacitor plate is proportional to the capacitance seen by the capacitor plate. This technology is used to build single-touch sensors (15 × 13 mm) as well as cheaper sweep sensors (3.6 × 13.5 mm). To date these sensors are capable of producing an image which has a resolution of more than 500 dpi, which is the resolution the US Federal Bureau of Investigation requires for a digital fingerprint.

If necessary, image enhancement methods can be used to improve the quality of fingerprint scans. The most common issues are a significant number of spurious minutiae, and a large percentage of missing or poorly placed genuine minutiae. Commonly image enhancement methods include noise removal or denoising techniques. Sophisticated pattern recognition techniques can be applied to estimate the underlying structure of an image corrupted by noise. In addition, it needs to be taken into account that 2–5% of the total population have poor-quality fingerprints. Often these are older people in whom there is a natural flattening of the dermal papillae with age, people with finger injuries, people living in dry weather conditions, or people with certain genetic attributes.

Representation

In order to establish reliably whether two prints originate from the same finger, the representation of the prints must be invariant to distortion due to the imaging process and the elasticity of the finger, occlusion of a small part of the finger, and orientation of the finger during the capture of the print. Fingerprint features are generally divided into global and local features. Global features are overall attributes of the finger and typically determined by examining the entire finger. The most important global feature of a fingerprint is its classification.

Current automatic fingerprint identification systems use the same classification system as human examiners, as discussed above (Figure 2). Additional global features include the ridge thickness, ridge separation, and ridge depth. While global features are used to classify a fingerprint, local features are

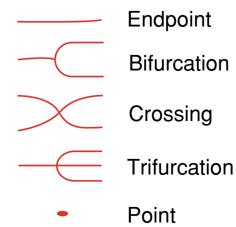

Figure 3 Minutiae types. This figure illustrates the most basic types of minutiae. Human examiners can easily differentiate between 13 different types of minutiae. To date, most automatic fingerprint identification systems do not make use of this information. In practical applications misclassification rates can be very high due to sensor noise and other artifacts.

mainly used for matching. They include ridges, pores on the ridges, and salient features derived from ridges. Typically, standard signal-processing techniques are used to extract the set of ridges. The most frequently used features are the minute details, or minutiae, of the ridges (Figure 3). Most automatic fingerprint identification systems use the pattern of the minutiae as a valid representation of the fingerprint. This representation is very compact, hence good for digital storage, and captures a sufficient amount of information about the individual fingerprint. For reasons of robustness, only the most prominent ridge features, the ridge endings, and ridge bifurcations are extracted. The ANSI-NIST (American National Standards Institute – National Institute of Standards and Technology) standard representation of a fingerprint is mainly based on minutiae and includes one or more global features such as orientation of the finger, locations, and fingerprint class.

Matching

Due to deformations, the elastic nature of the finger, the variation caused by the capture of the print, and for partial latent prints, the unknown location and orientation standard pattern recognition methods are insufficient to determine a match between two different prints. In a first step, a print is typically classified with respect to the Henry system. In addition, the ridge count between the core and the delta of the fingerprint is used for broad classification. Once classified, a number of different methods are used to determine a fingerprint match.

A typical latent print contains about 40 minutiae. The location, orientation, and ridge count between any two minutiae are a natural set of features that are used by the different matching methods. For any given minutia, a signature can be computed by considering its local neighborhood. Figure 4 illustrates two typical choices. It is important to note that any choice of features must be both descriptive

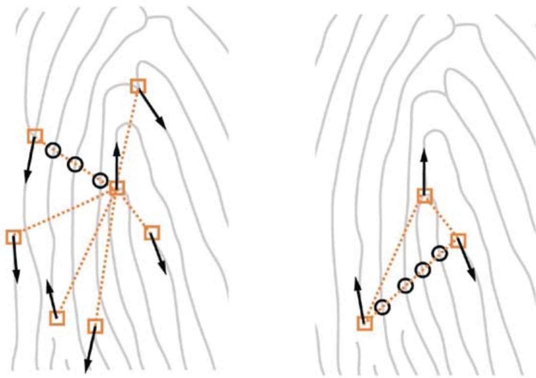

Figure 4 Features for fingerprint matching. A number of different features can be used to characterize minutiae. The graph on the right illustrates how the neighbors of a given minutia can be used. Based on a local coordinate system, the local neighborhood is divided into *N* different sectors. In each of the sectors the minutia closest to the center is used. The resulting signature is composed of the orientation of each minutia, the ridge count (illustrated using black circles) on each edge connecting two minutiae, and relative angles. An alternative to using a local neighborhood system is to use triples of minutiae to form a local signature.

and invariant under transformation. One of the algorithms currently used by the US Federal Bureau of Investigation uses a local signature (Figure 4, left) and employs graph-matching techniques to determine a fingerprint match. A commercial system developed by IBM uses features based on minutiae triples. As opposed to directly comparing a pair of prints, an index is computed for each minutiae triple (Figure 4, right). The search for a match is then based on the set of indices computed for a given latent print. An alternative to these approaches is adaptive elastic string matching, which explicitly tries to address the problem of large nonlinear distortions of fingerprints.

Although automated fingerprint identification systems are very sophisticated, their performance does not match the precision of human examiners. As the science of fingerprint recognition progresses, one can expect a continuous improvement of such systems.

See Also

Identification: Prints, Challenges To Fingerprints; Prints, Ear; Facial

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Prints, Challenges To Fingerprints

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Introduction

For many societies, the reidentification of criminals has been an important aspect of law enforcement. The amputation of a thief's hand marked him for life. The French branded criminals with the fleur de lis. The Romans used tattooing to prevent desertion of mercenary soldiers. Police officers with extraordinary memory were known to identify repeat offenders by sight alone. Photography was used to generate a rogue's gallery.

In addition to having a sound scientific foundation, a biometric identifier needs to survive legal challenges. In 1870, for example, Alphonse Bertillon developed an anthropological system of recorded dimensions such as the length of the femur. These were reduced to a formula that was touted as being unchanging and unique to an individual. However, in 1903 it was determined that a man named Will West was falsely imprisoned after discovering a man named William West with nearly exact Bertillon measurements. Although it has been hypothesized that the two men were identical twins, the Bertillon system never recovered.

Over the last 100 years, fingerprinting has emerged as the biometric of choice for establishing criminal identity. The forensic use of fingerprints goes beyond determining whether or not an individual has a criminal record. Latent prints found at a crime scene have been used both to identify potential suspects and as evidence in the resulting trial.

The credibility of this information has been held in high esteem by the courts. Although convictions have rarely been made on fingerprint evidence alone, it has been a deciding factor in many cases. Today's use of fingerprints is not limited to criminal investigations. The availability of fingerprint readers has made it easy to capture and analyze fingerprints without expert assistance. Hence, they have become a widely accepted biometric for access control and identity authentication.

Fingerprint identification is based on two basic premises: (1) persistence – the basic characteristics of fingerprints do not change with time; and (2) individuality – the fingerprint is unique to an individual. Recently, these assertions have been challenged and the ability to make an identification based on a partial latent print has been questioned.

In this context arguments were raised as to how much information is sufficient to make a decision with certainty. In particular, the 1993 Daubert ruling, which strengthened the requirement for the scientific basis of expert testimony, has resulted in numerous legal challenges to the admissibility of fingerprint evidence. Even though none of these challenges has succeeded, some district attorneys are now for the first time "plea bargaining" when the whole case hinges on a fingerprint, in order to avoid the cost and risk associated with such legal actions.

The study of fingerprints was initially an anatomical inquiry. Their value as a biometric identifier was discovered later. With the emergence of fingerprint analysis as a law enforcement tool, various terms and methods of operation have been defined. After the 1993 Daubert ruling, a number of challenges to the admissibility of fingerprint evidence have been made. Many of these legal arguments revolve around the belief that a scientific basis for fingerprint analysis requires a probabilistic paradigm. However, at a philosophical level, the statistical approach is at odds with the assertion of individuality. This article concludes with an exposition of this conflict.

Naturally, a discussion of these issues cannot avoid controversy. Historical and scientific developments are reviewed so that opposing points of view can be presented in context without passing judgment on the merit or motivation behind them. The author does not claim to speak on behalf of any institution or governing body.

History

In ancient China, thumbprints were found on clay tablets. As early as the third century BC inked fingerprints were used on various official documents. Whether or not these prints were used for identification or just ceremonial purposes is not known.

Grew in 1684 first wrote about the anatomical nature of the surface of the skin. Malpighi in 1686 focused on the substructures of the skin and described fingerprint patterns in terms of ridges, spirals, and loops. Neither recognized the uniqueness of fingerprints. The first to theorize that the arrangement of fingerprint ridges might be unique was Mayer in 1798.

Purkinji published a thesis in 1823 discussing nine fingerprint patterns. These descriptions are the predecessors for the fingerprint pattern classes of arch, tented arch, whorl, and twined loop. Herschel (1856) had local businessmen impress their fingerprints on contracts. Initially this was done on a whim, but as his collection of fingerprints grew, he realized that fingerprints could be used to prove or disprove identity. He observed that his own fingerprints as well as those of various prisoners did not change over the years.

After noticing fingerprints on ancient Japanese pottery, Faulds in 1880 realized their potential use for identification and developed a system of classification. He conjectured that they did not change over time and that they were highly variable. He also observed that "latent" prints, which are prints found at a crime scene, could be used for the scientific identification of criminals. He presented his findings to Charles Darwin who passed them on to his cousin Francis Galton.

Thompson in 1882 used his own fingerprint to prevent forgery. This was the first use of fingerprints in the USA. In 1883 Mark Twain's book *Life on the Mississippi,* a fictional court used fingerprints to solve a murder.

Galton in 1888 published his book *Fingerprints* where he established the concepts of fingerprint individuality and permanence. He presented his own classification system and defined the characteristics known as minutiae or Galton's details which are the main features by which fingerprints are identified today.

In Argentina, Vucetich in 1891 developed a classification system based on Galton pattern types and in 1892 he made the first criminal identification of a woman named Francisca Rojas. She murdered her two sons but accused a neighboring ranch worker of the crime. Her bloody print was found on a doorpost, thus exonerating the worker and implicating Ms. Rojas.

Henry in 1901 established the Henry classification system, which persists today in most English-speaking countries. Such a system provides a method for sorting fingerprints based on type. When a comparison of a reference print against a set of candidate prints is performed, the classification system is used so that the majority of prints can be ruled out without requiring direct comparison.

The first systematic use of fingerprints in the USA was headed by DeForrests in 1902. Locard wrote in 1918 that a correspondence of 12 Galton details between two prints was enough to establish identity.

In 1924 the Federal Bureau of Investigation (FBI) consolidated what are now the FBI fingerprint files. By 1946 the FBI had processed 100 million fingerprint cards, and as of 1971 the collection had grown to 200 million. In 1980 the FBI created a computerized fingerprint file system and by 1989 most fingerprint match requests were performed automatically, although all final individualizations were still reviewed by expert examiners.

In 1993 the Daubert ruling strengthened the requirements for establishing the reliability of experts. The first of many legal challenges to fingerprint admissibility under Daubert was made in 1999.

Definitions

"Classification systems" are methods by which fingerprints are ordered based on fingerprint pattern type.

"Latent" prints are fingerprints found at a crime scene that may not be directly visible to the naked eye. In the UK, they are called "marks."

"Tenprints" are a record of all 10 fingerprints of an individual taken under controlled conditions.

"Identification or individualization" is the conclusion of an expert that two fingerprints show sufficient information in agreement with no principal differences. This leads to the conclusion that the same donor has generated them.

"Level 1 detail" is the overall pattern configuration of a fingerprint. Examples of these pattern types are arches, loops, and whorls.

"Galton level 2 detail" can be described as minutiae and other ridge formations. A minutia is an event that occurs in a regular flow of papillary ridges. The event is a natural disturbance to the normal parallel system of the ridges such as ridge termination and bifurcation.

"Level 3 details" are small shapes on the ridge (edgeoscopy). This includes ridge unit thickness, thinness, and relative pore location (poroscopy). Third-level detail is always used in agreement with second-level detail.

"Points of agreement" are corresponding points between two prints that are deemed to be sufficiently similar.

"AFIS" is an automatic fingerprint identification system that generally relies on level 1 and level 2 features.

Methodology

In this section the various principles for establishing a fingerprint identification are reviewed.

Galton first defined minutiae as the principal features by which two fingerprints are to be compared. Locard established the first rules for the minimum number of minutiae necessary for identification.

Locard was a student of Bertillon, the founder of the anthropometric system of identification. Locard argued that a fingerprint match must use details such as ridge shape and pore location and not just rely on the correspondence of minutiae. Locard is known as the father of poreoscopy, edgeoscopy, and ridgeology. Locard in 1914 developed the tripartite rule, summarized as follows.

If more than 12 concurring points are present and the fingerprint is sharp, the certainty of identity is beyond debate. If 8–12 concurring points are involved, then the case is borderline and the certainty of identity will depend on the sharpness of the fingerprints; the rarity of its type; the presence of the center of the figure (core) and the triangle (delta) in the exploitable part of the print; the presence of pores (poreoscopy); the perfect and obvious identity regarding the width of the papillary ridges and valleys, the direction of the lines, and the angular value of the bifurcations (ridgeology/edgeoscopy).

Locard also stated the value and the importance of qualified conclusions to the identification process. He said, "if a limited number of characteristic points are present, the fingerprints cannot provide certainty for an identification, but only a presumption proportional to the number of points available and their clarity."

In 1973 the International Association for Identification (IAI) standardization committee stated that: "No valid basis exists at this time for requiring that a pre-determined minimum number of friction ridge characteristics must be present in two impressions in order to establish positive identification." Because of this ruling, countries such as the USA have no minimum threshold for feature correspondence. The remainder of the report dealt with the development of minimum standards with regard to the training and experience needed to testify.

In 1980 the IAI issued what is now referred to as resolution V, establishing the types of conclusion that can be drawn from a fingerprint examination. A direct interpretation of this resolution is that an examiner must state that there is either sufficient information to make an absolute identification or the print is of no value. This implies that no statements regarding the probability of identification should be made. It has been argued that this interpretation can be harmful in that it prohibits the expression of conclusions such as "there is enough information to rule out certain segments of the population but not enough to make an exact identification." Although not conclusive, such information could be useful for investigative purposes. As will be seen, this policy has also been targeted by a number of Daubert challenges.

In 1998, The Interpol European Expert Group on Fingerprint Identification (IEEGFI) explored the feasibility of determining a common European method for fingerprint identification. Two methods were defined: the holistic quality approach and the empirical standard approach.

In the holistic approach, the examiner compares all three levels of fingerprint detail. These details are considered in totality in order to arrive at a conclusion. It is assumed that biological uniqueness exists or does not exist. Uniqueness cannot sometimes be partial and at other times not partial. Any portion of a fingerprint, no matter how large or small, has only one source. However, it is accepted that the content in a given latent print may prove to be insufficient to establish uniqueness.

The empirical standard method advocates a numerical approach to identification. Points of agreement are annotated so that the matching process can be documented and compared. Like the holistic approach, it is assumed that uniqueness either exists or it does not. As a safeguard many European countries set a minimum number of points of agreement needed to ensure uniqueness. This is usually between 12 and 16.

In *United States* v. *Harvard* (2001), an expert witness described the manual comparison of a latent print with an exemplar as a three-stage process. This is described as follows: initially the examiner compares the general level 1 ridge patterns of the two prints. The orientation of the latent print is determined. At this point there is not enough information to individualize but many exemplars can be excluded. Second, the relationship between each ridge and the remaining ridges for both prints is determined. The totality of ridge location, type, direction, and relationships are considered. Some degree of individualization can occur at this point. Finally correspondence of individual ridges between the latent and the exemplar are checked. This is based on level 3 details such as the location of sweat pores. Typically, decisions are confirmed via peer review.

Legal Challenges

In the USA, fingerprint testimony has been generally admitted as evidence based on the concept of "general acceptance" established in *United States* v. *Frye* (1923). However, in 1993 the Daubert ruling (*Daubert* v. *Merrell Dow Pharmaceuticals*) strengthened the requirements for establishing the reliability of expert testimony. The criteria for establishing reliability were defined based on the following factors: (1) whether the particular technique or methodology in question has been subject to statistical hypothesis testing; (2) whether its error rate has been established; (3) whether standards controlling the technique's operations exist and have been maintained; (4) whether it has been peer-reviewed, and published; and (5) whether it has a general widespread acceptance.

The first challenge to fingerprint identification under Daubert was in *United States* v. *Mitchell* (1999) using the argument that the premise for fingerprint identification has not been tested and that the error rates are not known. The motion to exclude fingerprint evidence was denied. Since then there have been numerous challenges under Daubert. The following is a review of significant rulings.

State of Georgia v. *McGee* (2000)

The defense argued that latent print examination is not a science because statistical probabilities are not used to establish a minimum number of points needed to individualize. The court concluded that, despite numerous challenges, fingerprint identification is reliable evidence.

State of California v. *Ake* (2001)

The judge ruled that Daubert is not applicable in California and, since fingerprint analysis is neither new nor novel, expert testimony is admissible.

United States v. *Harvard* (2001)

The defense argued that the government has not established the scientific reliability of fingerprint comparisons so as to render such evidence admissible. The ruling stated that claims of uniqueness and permanence are scientific because those assertions can be falsified and that much of the comparison process is objective. Also, 100 years of adversarial testing make up for any lack of publications.

United States v. *Plaza* (2002)

The court allowed experts to present fingerprints, describe how they were collected, and point out various similarities. However, the experts were not allowed to present their opinion that a given latent print is in fact the print of a particular person. On appeal the decision to prohibit opinion-based testimony was reversed.

United States v. *Crisp* (2003)

Lawyers attempted to dismiss fingerprint testimony on the basis that the premise for fingerprint analysis had not been tested and that operators work without uniform and objective standards. The challenge was defeated with a two to one majority. The following is a summary of the dissenting opinion. It was argued that general acceptance of fingerprint identification does not establish reliability. Persistence of the technique for 100 years under the judicial adversarial system does not imply scientific acceptance, because defendants do not have sufficient access to scientific and financial resources. The judge was not presented with studies that show how likely it is that prints taken from a crime scene will be a match for only one set of fingerprints in the world. He argued that the testing of examiners does not always reflect real-world conditions. He questioned the peer review process for fingerprint publications. He stated that the government had ignored error rates of examiners and referred to tests where examiners are unable to correctly identify matches and eliminate nonmatches. He stated that the subjectivity of the examination process allows the examiner to explain away differences rather than discount the match. He criticized the field for a lack of universal standards and a refusal to hedge testimony in terms of probability. He noted that different examiners come to different conclusions regarding the certainty of identity. Finally, acceptance of the field in the scientific community was questioned. The dissenting judge did not say that fingerprint analysis could not satisfy the Daubert criteria but in his opinion the government has up to now failed to do so.

One of the main issues behind this dissenting decision is the contention that the uniqueness assertion does not necessarily imply reliable matching. The argument is that latent prints are distorted impressions of a fingerprint and skill levels vary from examiner to examiner. It has never been claimed that examiners are infallible and, admittedly, mistakes can be and have been made. That being noted, the FBI performs numerous identifications on a daily basis and to date no challenge has ever overturned an FBI identity decision. Since the quality of both examiners and latent prints varies, these types of challenges may have to be handled on a case-by-case basis.

A more fundamental concern is centered on the fact that many examiners insist on absolute certainty of their identifications and they resist attempts to present fingerprint analysis in a probabilistic framework. In order to understand this issue better, the various probabilistic approaches that have been developed for the purposes of establishing uniqueness of a fingerprint have been reviewed. This will be followed by a discussion of the philosophical issues associated with the statistical paradigm.

Modeling Uniqueness

Over the years scientists have developed a number of statistical models for the purpose of analyzing fingerprints. Initially configuration-based approaches were devised so as to estimate the potential size of the fingerprint population. This was followed by attempts to predict the probability that a given print will have a certain degree of commonality with a print selected at random from the population. Attempts have been made to take into account the variability associated with deformations between multiple impressions of the same fingerprint as well as distortions associated with a latent print.

The first attempts to establish a probabilistic model for uniqueness were to hypothesize that there are a limited number of distinguishable fingerprints. Assuming that all prints are equally probable, the uniqueness of a given print is then proportional to the number of distinguishable prints. To make this estimate, authors such as Galton in 1892 associated a grid with the fingerprint. For a given square in the grid it was argued that there are q possible states or configurations. Based on this logic, the number of possible fingerprints is estimated to be proportional to q^N where N is the number of squares in the grid.

Henry estimated, in 1900, the probability p of observing a minutia at a given location. If a fingerprint has n minutiae, then the probability of observing a fingerprint selected at random from the population with corresponding minutiae would be a function of p^n.

In 1977, Ostenburg took a more refined view of minutia type. He argued that each 1×1 mm region of a fingerprint could be classified by either being empty or having one of 12 different types of minutiae. By computing the probability of each of these states, the probability of two prints matching over a given area can be estimated.

It is argued that probabilistic models must take into account the fact that what takes place in one part of the print is not independent of what takes place in another part of the print. In 1979, Scolve investigated the correlation between neighboring cells of Ostenberg's scheme, which resulted in slightly lower estimates of uniqueness. In 1989, Stoney developed a model of pairwise minutia dependencies.

In the 1999 Daubert trial, attempts were made to assess the intrinsic uniqueness of fingerprints via the results attained from processing 50 000 reference prints using an AFIS system. The scores of the best false matches were compared with the scores associated with the reference print matched against itself. This experiment was criticized because it did not take into account the fact that there is a significant deformation between multiple impressions taken from the same finger. This phenomenon is known as intraclass variation.

Trauring, in 1988, was the first to look at intraclass deviations. He estimated that corresponding features could be displaced by up to 1.5 times the interridge distance between the features. In 2000, Pankanti modeled fingerprint identification as a form of template matching. He used an AFIS system and a model for intraclass variation to compute the probability that two fingerprints with n and m minutiae will have r correspondences.

In 2000, Tu developed a similar template-matching scheme based on a set of Bernoulli trials with the aim of addressing feature correlation. Instead of defining an explicit model for interfeature relationships, measurements based on group statistics were used to compensate for dependencies.

Philosophical Issues

In the statistical frameworks that have been proposed for measuring fingerprint uniqueness, every possible outcome has a distinct nonzero probability of occurring. Even if it is concluded that the probability of observing two identical fingerprints from different individuals is miniscule, the fact that this probability is by definition nonzero flies in the face of the individuality assertion.

At the root of the probabilistic approach is a paradigm based on discrete events. Either a minutia is at a specific location or it is not. A given cell can only be in one of q different states. The criteria in which events are differentiated can be viewed as a type of formulaic thresholding.

Various members of the fingerprint communities would contend that to date no proposed formulaic criteria can match an examiner's ability to determine whether or not two ridges or two points of interest are in correspondence. This is based on the argument that the fingerprint contains a theoretically infinite spectrum of complex detail that cannot be fully characterized in mathematical terms. If this argument is taken to its extreme, an examiner could in theory make an identification based on a single ridge, assuming the mechanisms by which the impressions are captured have sufficient fidelity.

This argument leads to the assertion that the granularity of a probabilistic framework cannot match the fidelity of a human examiner and hence estimates of uniqueness can only be viewed as a lower bound. This is in stark contrast to DNA matching, which is fundamentally discrete in nature and must therefore submit to the conclusions that can be drawn from statistical analysis.

From the point of view of the scientific method, fingerprint individuality represents a hypothesis that has yet to be contradicted. In 1963, Popper had argued that the strength of a hypothesis is proportional to the ease with which it can be falsified. Thus, the individuality hypothesis must be viewed as extremely strong since it could be shown to be invalid with just a single counterexample. To support this argument, in 1990 the Los Angeles fingerprint agency performed 127 732 reference fingerprint searches using a standard AFIS system. This resulted in over 2.5 trillion comparisons. For each search print the top 10 closest false mates were manually compared with the reference print. All were found to be distinguishable from the reference prints.

The debate regarding the justification of the individuality assertion may be academically interesting but fundamentally intractable. An alternative point of view is that all systems benefit from a statistical understanding of their workings. At some point where there is an extremely low degree of probability, in human endeavors that point becomes indistinguishable from certainty. The vast amount of daily fingerprint identification is generally accepted to fall into this category. Most of the current activity is engaged in setting the borders for extreme cases where the information content is much harder to use.

Clearly the courts demand answers to these complicated issues. Whether or not a satisfactory resolution can be achieved will depend on the wisdom and understanding of the judiciary, the defense bar, scientists, law enforcement officials, and practitioners of fingerprint identification. The importance of this outcome cannot be overstated since both lives and society's right to receive justice are at stake.

See Also

Identification: Prints, Finger and Palm; Prints, Ear; Facial

Further Reading

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Prints, Footprints

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Introduction

Forensic podiatry is an emergent discipline, defined in 1999 by Vernon and McCourt as “the application of sound and researched podiatric knowledge in the context of forensic and mass disaster investigations.” From this definition forensic podiatry may concern issues related to human identification, linking a suspect with a crime scene or resolving legal issues concerned with the function of the foot. It may be used to associate or eliminate a suspect from a crime scene by direct comparison of a footmark left at the scene with a suspects’ feet. The field encompasses footprints and barefoot impressions but excludes footwear analysis. Thus, within the topic of forensic podiatry are impressions made by bare feet that retain skin ridge patterns (footprints); impressions made by bare feet devoid of skin ridge patterns; and impressions made by sock-clad feet. In many cases, excellent morphological features are deposited and retained on a variety of substrates or media. This could include impressions made into soil, sand, or snow, blood-stained impressions on to hard surfaces, or residue impressions. On a two-dimensional surface the bare human foot is known to leave relatively consistent foot impressions with little effect due to slippage or distortion, although these latter problems are encountered in foot impressions made into three-dimensional substrates such as sand. The importance of such evidence should not be overlooked, although such impressions may occur less frequently in western countries compared to other areas of the world, for example in India, where footwear is less frequently worn. The purpose of this article is to provide the reader with an overview of the methods employed in the field of forensic podiatry and to consider other areas that may be of value, such as dermatoglyphic or chiropody studies.

Historical Review

The analysis of footprint evidence and its use in criminal procedures is not new to forensic science or popular crime fiction. Records of the use of plantar footprint identification in criminal trials date back to the Le Dru case of 1888, with gait analysis of footmark evidence left at scenes, for example used to follow criminals to hideouts, dating to the 1920s, although this specific area had been published in 1887 within the Sherlock Holmes novel entitled *A Study in Scarlet*. The Falkirk burglar case demonstrated how offender identification from footmarks left inside shoes could be achieved. In 1935 the Ruxton case, where Dr. Ruxton killed and dismembered his wife and housemaid, illustrated the use of foot casts to assist in the identification of the mutilated body parts. When the feet of the victims were discovered, casts were made of them which were subsequently shown to fit the missing women’s shoes. In 1938, the Supreme Judicial Court of Massachusetts in the case of *Commonwealth* v. *Bartolini* upheld a blood-stained footprint comparison. Within the UK, three cases in the 1950s made use of plantar print evidence left at scenes of crime, although since then the use of forensic podiatry remains infrequent. It is therefore not surprising that, from a forensic viewpoint, there are few published data regarding the uniqueness of barefoot impressions. The main area of research has been within shoe mark analysis, within the industry, army, and forensic world with few small studies into footmark analysis. The growing belief is that feet are unique and the evidence used to support this claim is central to the validity of such evidence.

The Individuality of Human Feet

As with other features of the human body, for example, fingerprints, ears, or facial details, feet are assumed to be highly individualized in shape, size, and form, and it is these features that the forensic podiatrist uses to identify an indizvidual. The nature of each foot is influenced by congenital and acquired influences which may be genetic, racial, ethnic, environmental, physiological, biomechanical, or pathological, be it naturally acquired disease of any component of the foot or as the result of an injury to the foot, leg, or pelvis. It is these influences that lead to a person's individuality. Other factors that will affect the print are the substrate on to which the foot is pressed and the method of locomotion, i.e., standing, walking, running, or jumping.

Forensic Podiatry

The actual forensic examination compares the shape, size, and relationship of individual parts of the foot, such as the toes (singularly or together), ball, arch, and heel to each other. This provides the ability to discriminate an individual from larger populations, but assumes an inherent degree of variability within barefoot impressions. To this can be added the presence and site of natural diseases such as corns and verrucas, and the examination of plantar ridge detail. At present there are only a few forensic studies that provide quantitative evidence toward the uniqueness of barefoot morphology. Although the individuality of human feet is acknowledged, the methods lack the necessary degree of objectivity to be compatible with a forensic approach. Forensic studies have used a range of methods to investigate "uniqueness," although to date there is no standardized system to analyze barefoot impressions. However, the methods can be summarized into three main categories: (1) quantitative methods; (2) dermatoglyphics; and (3) chiropody.

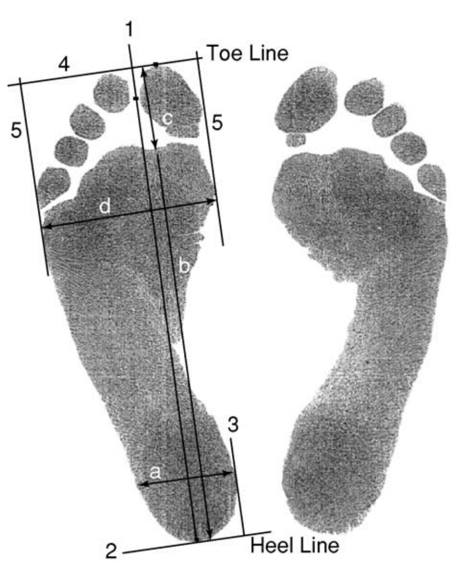
Quantitative Methods of Footmark Analysis

To date there are three published quantitative manual methods for footmark analysis, which can be used on their own or in combination: (1) linear axis method; (2) linear measurement method; and (3) optical center method.

Linear Axis Method

The linear axis method of footmark analysis was first published by Robbins in 1976. He described both a quantitative and qualitative method of footmark analysis. Taking a footmark, he divided the foot into 10 sections which comprised morphological features such as the toes, ball, arch, and heel, as well as shape contours. He then placed a centimeter grid over the print such that the zero point was positioned at the medial posterior point of the heel and the zero line parallel to the longitudinal axis of the foot. The grid was then used to identify points on the toes where the curvature occurred as well as how much curvature was present. Standard linear measurements were also taken, such as width of the big toe, ball, arch, and heel.

Barker and Scheuer later provided a quantitative method of plantar footprint analysis for the purpose of individual forensic identification building upon the method of Robbins. Measurements were obtained from the walking and standing footprints of 105 adult volunteers. Standard construction lines were made on each print according to a series of predetermined rules (Figure 1). The construction lines were secondary to a central "linear axis" that passed through the footprint between the first and second



1. Linear axis: From the apex of the heel through arch and ball regions, passing through a point equidistant between the first and second toes.
2. Heel line: Drawn perpendicular to the linear axis, to pass through a tangent of the heel print.
3. A perpendicular construction line is drawn from the heel line through a tangent of the medial aspect of the heel print. "Heel width" can then be measured perpendicularly from the intercept to the lateral border of the print (a).
4. Toe line: Drawn perpendicular to the linear axis, to pass through a tangent to the most distal point of the footprint.
   Print length is measured along the linear axis from the heel line to the toe line (b). "Big toe length" is the distance from the toe line to the ball intersection with the ballprint (c).
5. Perpendicular construction lines are dropped from the toe line to pass through tangents to the ball print both medially and laterally. The "ball width" (d) is measured between these perpendiculars along the toe line.

Figure 1 Linear axis method of footmark analysis.

toes. In theory, therefore, this method ensures reproducible measurements from barefoot impressions. The measurements obtained were not used to highlight the individuality of barefoot impressions, but instead were used to establish the predictive value of associating a footprint with specific subpopulations. For example, the footprints showed a normal distribution in both sexes but, not surprisingly, male footprint length was found to be greater than female footprint length for any given height.

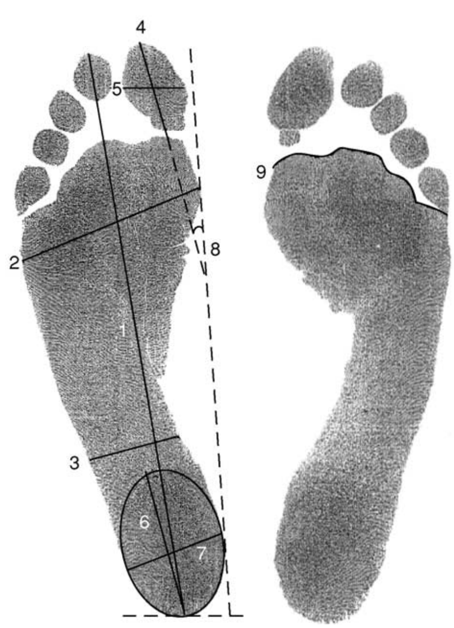
Linear Measurement Method

The next advancement in methodology for footmark analysis was made by Qamra *et al.*, who published a method for footmark analysis in 1980 that utilized linear measurements from predefined landmarks of the plantar footprint (Figure 2). This method was applied to two-dimensional ink-stained prints taken from the feet of 725 healthy subjects. The dimensions of the toes, ball, arch, and heel of the footprint were converted into length–width indices to minimize the effect of intrapersonal and intraobserver errors. This can occur when the same person elicits different footprints due to the foot becoming fatigued or when different substrates are used during registration of the print, for example in dust, wet mud, paint, or cement. Using these interdependent indices a range of probabilities for a positive chance match were identified. Qamra also identified the potential value of "humps" (protruding curvatures in the ball line) to distinguish footprints. Although these data were only treated empirically, one, two, or three humps were found to be more common than no humps or four or five humps (the maximum number identified). Qamra noted that the number of humps on each foot of an individual may not be the same, although this particular feature of footmarks may be difficult to confirm or may be absent under scene-of-crime conditions. Finally, he also made reference to foot creases which tend to occur on the inner margin of the instep, radiating toward the toes or outer margin of the foot. Creases were found to be more prevalent in females than males and in flat feet rather than normal feet, although no further observations were made in relation to the potential use for identification purposes by the authors.

This method was later expanded upon in 1988 by Laskowski and Kyle, who not only used a linear measurement method with index nomenclature but also introduced additional measurements to the system measurements, such as the angle between the great toe and the medial site of the foot. They investigated the use of a "well index" as well as the "well impression," revisited the notion of the analysis of "humps" (up to seven in their series) and proposed the consideration of both racial and cultural aspects of foot morphology, although ultimately agreed with the findings and methods of Robbins and Qamra.

The Optical Center Method

Since 1989 a database of approximately 4000 footprints has been compiled by the Royal Canadian Mounted Police to study the uniqueness of barefoot



1. Foot length
   Base of heel – tip of the longest toe.
2. Maximum foot width
   Width at the ball of the foot across the 1st–5th metatarsal heads.
3. Minimum foot width
   Minimum width measured across arch of the foot.
4. Toe length
   Maximum length of big toe: tip prominence–ball line.
5. Toe width
   Maximum width of the big toe.
6. Heel length
   Maximum length of the heel portion.
7. Heel width
   Maximum width of the heel measured across encircled area.
8. Great toe angle
   Measured from the intersecting vertices passing through the center if the great toe and along the medial site of the foot.
9. Metatarsal humps
   Number of protuberances, i.e., peaks and dips projecting from the ball line.

Figure 2 Linear measurement method for footmark analysis.

morphology. Inked two-dimensional impressions were taken from volunteers and 38 measurements were entered into a computerized database along with a tracing of each barefoot impression. The optical center of the toes and heel were introduced as landmarks to obtain a greater range of barefoot dimensions.

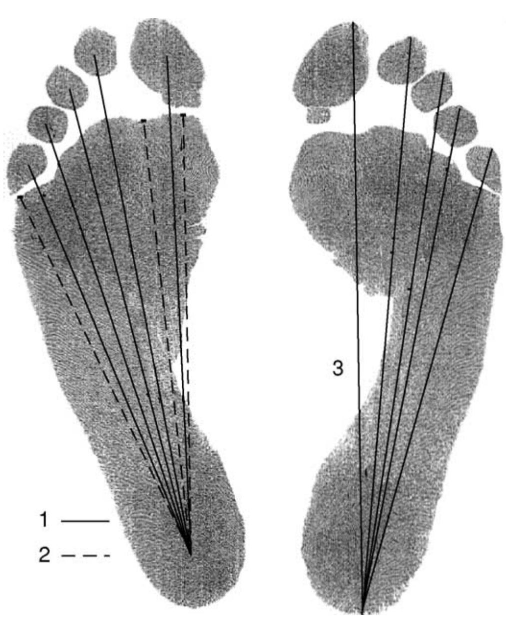
The method published by Kennedy illustrated the use of the optical center of the heel to ensure reproducibility for foot measurements. He used a simple concentric circle template to identify the optical center of the heel and then took measurements to the optical center of the toes as well as to points on the metatarsal ridge and finally, as with other methods, peripheral point measurements (Figure 3). A computer database was used to store and compare the measurements from each barefoot impression. As each new set of impressions was obtained the data were entered into the system and compared with the features of previously entered impressions. The results obtained from this study have shown that a significant degree of individuality can be established for barefoot impressions. To date, there are no two impressions that share the same characteristics. Kennedy also found that only three to five input measurements were required to eliminate all other impressions from the search. To increase the chances of a positive chance match, a ± 5 mm error range was arbitrarily given to each measurement. Even with this variance, all the other impressions were eliminated using no more than 15 input measurements. Blind searches were also used where the inked impression may or may not have been present in the database. In each case, the impression was correctly identified or eliminated from the database search.

Combined Methods

Studies by the Federal Bureau of Investigation have combined a linear axis method similar to that described by Robbins, but instead the metric grid is aligned using a longitudinal axis that passes through the optical center of the heel and the second toe. The grid is used to fix the most medial and lateral points of the metatarsal areas and the impression is entered into a computer. Software is used for the comparison of numerous attributes or measurements on each of the left and right feet. The results were similar to those found by Kennedy in that, of a limited database of 500 footprints, only three to five of the most general characteristics were required either to identify or discriminate these footprints from all others in the study.

Plantar Dermatoglyphics

Dermatoglyphics is the study of ridge patterns in the skin. To date, in the case of fingerprints, these ridge patterns are unique and so confer individual identification regardless of the size of the population database. Fingerprints are often used to make formal identifications and are still a primary source of evidence in linking a suspect to a particular crime



Foot length
Base of heel–tip of the longest toe.

Maximum foot width
Width at the ball of the foot across the 1st–5th metatarsal head.

Minimum foot width
Minimum width measured across arch of the foot.

1 Optical center of heel to optical center of toes. (illustrated on left footprint)

2 Metatarsal measurements
Optical center of heel to three predefined metatarsal ridge points
(illustrated on left footprint)

3 Edge of heel to edge of toes
Apex of heel to the most distal point on each toe.
(illustrated on right footprint)

Figure 3 Optical center method for footmark analysis.

scene, although nowadays the role of DNA is rapidly overtaking traditional policing methods. Despite the value of fingerprints in forensic investigations, relatively little study has been carried out into plantar dermatoglyphics.

Historically, the earliest research into plantar dermatoglyphics was undertaken by Wilder in 1902, when he compared the sole prints of humans with quadripedal mammals. Over the next 23 years he made many observations in relation to sole pattern, including both interracial observations and analysis of the patterns of twins. Although interest in this area continued intermittently throughout the twentieth century, fingerprints became the main subject of interest with little work continuing in Caucasians on the sole, especially the toes.

This lack of research into plantar dermatoglyphics in part is due to the difficulty in taking sole and toe print impressions. Recovered barefoot impressions rarely show ridge detail because either the substrate smudges the print or the individual is wearing socks. There have, however, been instances in the UK where the use of plantar dermatoglyphic evidence has been crucial in resolving forensic investigations. Footprint identification via papillary ridge detail is regarded as being no less valuable, where available, than identification by fingerprints: it is equally infallible and admissible. If plantar friction ridge detail is observed, then a positive identification can be made in exactly the same way as fingerprint identification.

Fox and Plato undertook a study of American Caucasian plantar dermatoglyphics. They considered both the toes and the soles in their study and found that epidermal ridge detail produces specific patterns of arches, loops, and whorls that are found on both the distal toe pads and the plantar surfaces (which have eight dermatoglyphic areas) of the feet. They concluded that areas of the toes and sole containing important details are difficult to print and thus these details may be lost. They also found that plantar dermatoglyphics differ from palmar dermatoglyphics and that toe patterns differ from fingerprints in distribution, location, and pattern type. There appeared to be no interpopulation polymorphism in toe pattern frequencies and no racial differences that were attributed to the later embryological development of the foot compared to the hand. However, further work remains to be undertaken within this area.

Chiropody

The last area of potential interest to the forensic podiatrist is the much underutilized area of forensic chiropody. Originally described by Doney and Harris in 1984, this field makes use of acquired diseases of the foot which may necessitate the visit of the individual to a chiropodist. The subsequent records made at the clinical consultation can be used for comparative identification of deceased

CHIROPODY ANALYSIS RECORD.

Mr.
Mrs.
Miss...Address.................. ....Date.................. Tel.

Age {Young / Medium / Elderly} Weight {Slight / Average / Heavy} Occupation ....Exercise No......................

General Constitution................................Appliances worn...Shoe................

Medical Supervision...Advised...

Doctor...Address...

External Appearance...

Fundamental Weakness...

Treatment and
Chemicals used..Prescription...

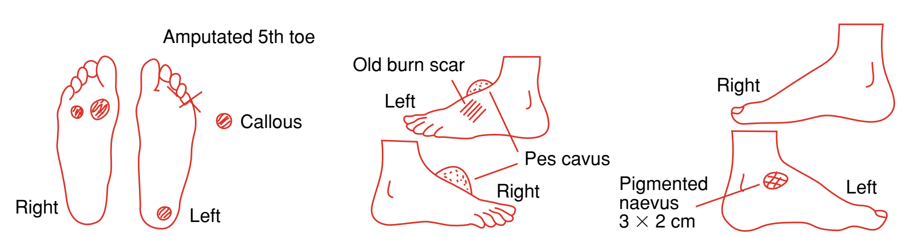


Figure 4 An example of a chiropody analysis sheet with a fictitious patient.

individuals, for example in a mass-disaster arena (Figure 4). Such charting of the feet is undertaken, for example, of American naval crews as often, in cases of death due to fire, the thick boots worn by the crew protect the feet resulting in the feet being the last body part to be destroyed and thus potentially the only part available for use for identification purposes. Later work by Vernon has shown that the use of chiropody notes may lead to a positive identification of an individual in up to 86% of cases.

See Also

Identification: Prints, Finger and Palm; Prints, Challenges To Fingerprints; Prints, Ear

Further Reading

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Prints, Ear

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History

The ear has always been considered as one of the most important organs of man. In the days of Aristotle for instance, the length of the earlobe was considered to be a sign of precision of memory. Also, in some Southeast Asian regions, long earlobes were considered to be a sign of great wisdom. During the Renaissance, when the doctrine of physiognomy was introduced, which stated that the face is a reflection of all qualities of intelligence in a human being, much attention was paid to the shape of the ear.

Darwin attracted scientific attention to the ear, during his studies on primates, by defining the ear as one of the elementary organs. He regarded the bulge in the middle of the helix (auricular tubercle) as the proof for this assumption, pointing out that this could be nothing other than a corner of the primitive ear reducing. Scientifically, this reducing of the corner has been recognized, and this part of the ear has been assigned the name "tubercle of Darwin." Schwalbe was one of the first scientists to invent a method for measuring the external ear and was able to prove Darwin's theory. He was also the first to describe the racial peculiarities of ear structure.

The Belgian statistician Quételet (1796–1874) initiated the first scientific steps for positive identification of individuals, by theorizing that no two members of the population were exactly alike. The French statistician Bertillon continued work in this area and formulated in 1882, his results, which came to be known as the Bertillon system.

Many research projects were carried out by various medical scientists to study whether the ear could be utilized to establish identity. A survey by Imhofer states that the ear can indeed be very important in establishing identity: a comparison of 500 pictures of ears established that a combination of any three features of ear appears only in two cases; a combination of four features is enough to establish the identity.

In 1959 Iannarelli described an identification method on the basis of ear structure based on a survey carried out over the previous 14 years. No attention was paid to earprints in this article. However, a reprinted and revised edition of *The Iannarelli System* *of Ear Identification* in 1989 introduced methods of recovery and comparison of latent earprints.

Research on development of the ear of newborns, where pictures of infants were taken over a period of time, showed that the ear remained constant whilst other features of the face changed. A study was conducted to include a series of photographs of the right and left ears from a group of infants, taken daily from the day of birth to the day of discharge from the hospital. These photographs were taken to document the minute changes that took place in the growing ear during each 24-h period and to document the gross morphological changes during the period between birth and the day of departure from the hospital. It was concluded that the described photographic procedure has thus met all of the requirements of a reliable and standardized identification technique: individuality, continuity, and immutability.

In connection with a 1965 burglary case in Bienne (Switzerland) earprints were reported to have been found. A comparison of these prints was carried out by studying individual characteristics, as well as using an overlay technique. The earprints of left and right ears could be identified. The study reported work done regarding the position where the earprint was found and the height of the perpetrator.

In a report from the 61st Annual Meeting of the German Society of Forensic Medicine, a paragraph is dedicated to the use of earprints as a means of identification. In this report, Händel quotes Trube-Becker, who pointed out that there are no absolutely identical ears, but only similar ears. Even two ears of an individual are not identical. This is also true for identical twins. Händel warns that the properties of ears can change, for example, as they are pressed against a wall or a door.

Another early report dealt with earprints found after a series of burglaries at Freiburg (Germany). Two girls were seen close to the scene of the burglaries and were suspected of having listened at the door. The girls were arrested for identification purposes. During the investigation, prints of their left ears were taken. Three girls in Stuttgart were arrested for the same type of burglary. Investigations showed very quickly that the girls from Stuttgart – according to the left earprints – could not be excluded from being suspects in the burglaries in Freiburg. A fingerprint expert in Baden–Württemberg identified one of the girls. Hammer and Neubert have also stressed that earprints can be a useful tool in identification.

The first Dutch case in which an earprint led to a conviction by a Dutch District Court of Law was published in 1988. During the investigation, a forensic odontologist and an ear, nose, and throat specialist were consulted. The District Court accepted the earprint as evidence and convicted the suspect. The Court of Appeals subsequently accepted the earprint only as supporting evidence and based its conviction on other evidence in the case.

The Concerns of US and UK Courts with Ear Print Evidence

Earprint evidence has been used in courts in various countries around the world. Earprints have been used as evidence or supporting evidence in various cases and have contributed in the conviction of perpetrators of crimes. Nevertheless, concerns about the reliability of earprints have been expressed. It must be stated that earprints have not been fully accepted by the relevant scientific community. Apart from the fact that an earprint itself is hardly ever directly connected to the crime (it only indicates the fact that a person has been on or near the crime scene at a certain time) the "science" of earprints is still in its infancy.

In the US a District Court admitted this type of evidence during a Frye hearing, with the restriction that a positive conclusion for that reason could not be accepted. The Court of Appeal allowed the use of an earprint in the same case, but limited the conclusion once again. The experts were to limit their opinion in stating that a person could either be included or excluded as being the donor of the print. The case ended in a mistrial, and the suspect was not prosecuted again on the assumption that evidence connecting the suspect to the crime "beyond reasonable doubt" could not be provided.

More or less the same applied to a case in the UK. In a *voir dire* the judge admitted the evidence, but contrary to the US case, did not limit the experts' opinion. The Court of Appeal in this case accepted the earprint evidence and allowed its use in a retrial. During the preparations for the trial, the prosecution decided to drop the charges against the suspect because of the fact that evidence "beyond reasonable doubt" could not be provided.

Morphology of the Ear

The external ears (auricles and pinna) are found on both sides of the skull. The opening in the middle of the ear leads to the auditory canal, at the end of which is the eardrum. The function of the external ear is to receive incoming sound, amplify it, and direct it to the middle ear (Figure 1A).

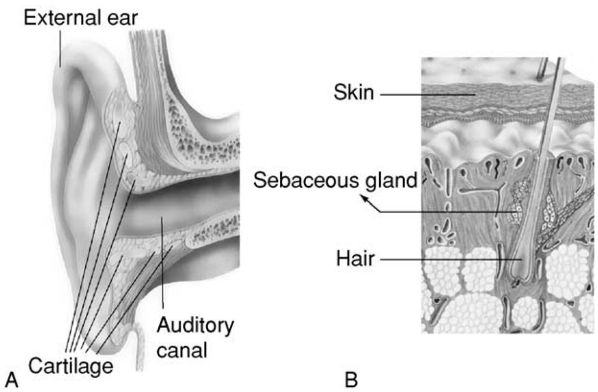

Figure 1 Morphology of ear: (A) external ear and (B) subcutaneous tissue.

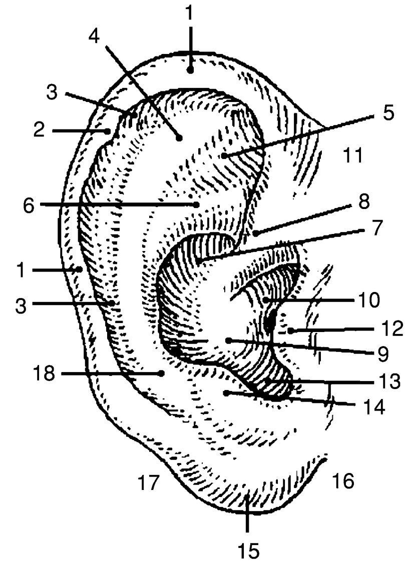

Figure 2 Drawing of the anatomical features of a human ear (right). 1 crux of the helix, 2 helix, 3 auricular tubercle (knob of Darwin), 4 anterior notch, 5 anterior knob, 6 tragus, 7 intertragic notch, 8 antitragus, 9 posterior auricular furrow, 10 anthelix, 11 lower crux of the anthelix, 12 upper crux of the anthelix, 13 lobule, 14 triangular fossa, 15 scaphoid fossa, and 16 concha.

The skeleton of the ear (pinna) consists of cartilage. The cartilage is elastic and makes the ear flexible but prevents it from adopting a different shape permanently. The cartilage is covered with skin and contains hairs, sebaceous glands, and earwax-producing glands (Figure 1B).

The development of a human form starts soon after conception. At first, it can hardly be seen, but by the 38th day, various parts of the ear can be recognized, among them the helix and the lobe. In this early stage, the ear is not yet in its right place. The ear acquires its 'normal' place on about the 56th day after conception. At that point, features of the ear, such as the helix, anthelix or antihelix, concha, and earlobe, are clearly discernible. After the 70th day, the growth of the human ear speeds up, without major changes in the configuration taking place.

In some cases, the ear growth is disturbed because of the fetus's position or movements, and this will affect the unattached anatomical form of the ear. After birth, however, the ear can proceed with its free and natural configuration without disturbance.

The proportions of the skull bones of children differ from those of adults. For instance, the inner ear (auris interna), consisting of the hearing (cochlea) and the balance organ (labyrinth), and the ossicles of the middle ear (auris media), the hammer (malleus), the anvil (incus) and the stirrup (stapes), already have their final size at birth. The surrounding bones develop into their final size much later in life, and in addition their proportions change.

At birth, the pinna has a length of about 30 mm. However, it does not yet have its final shape. Shortly after birth, the auricle grows rapidly, about 4 mm, thereby reaching its finite and unique shape; this occurs after approximately 1 month. At the end of the first year, it is of about 45–50 mm in length. During the next 2 years, it grows evenly, reaching a length of 53 mm at age 3. At 10 years of age, the ear is 55 mm, and at 15 its final length is reached, which is slightly less than 70 mm (50–82 mm) in the normal West European male. The female ear is about 3.5 mm smaller.

The human ear has various anatomical features. These features are shown in Figure 2.

Ears can be categorized into four basic shapes: oval, round, rectangular, and triangular (Figure 3). Ears of all shapes and sizes occur in every race, but the distribution of different shapes within races differ. The difference between shapes of ears is only a class characteristic. The same applies for sizes of ears and differences between male and female ears. Ear shape and size do not identify an individual's race.

Anatomical Ear Features and their Appearance

In addition to their own anatomical names, each of the ear features also has its own appearance when an ear is pressed against a surface and leaves an impression. These appearances will be briefly discussed.

The crux of the helix (Figure 4) is the starting point of the rolled up edge of the helix and originates from the upper part of the concha. For identification purposes, this point is referred to as an area. The crux

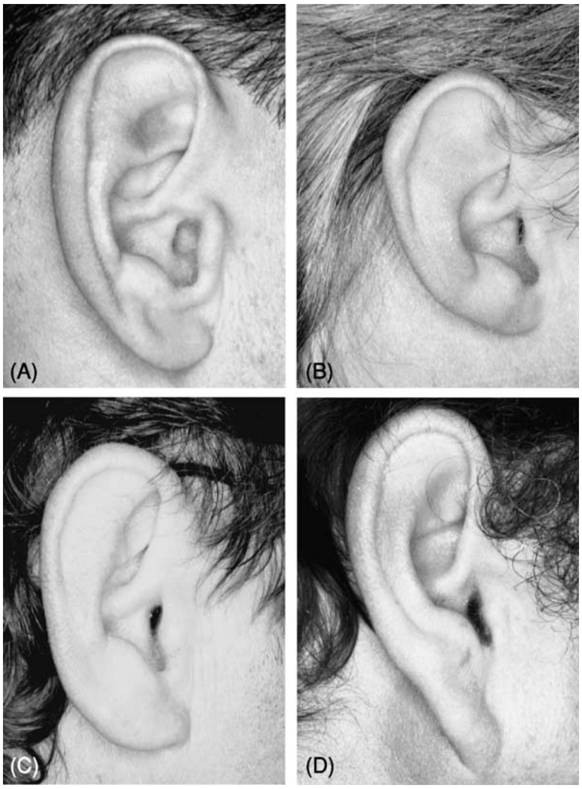

Figure 3 Photograph of an oval ear (A), round ear (B), rectangular ear (C), and triangular ear (D).

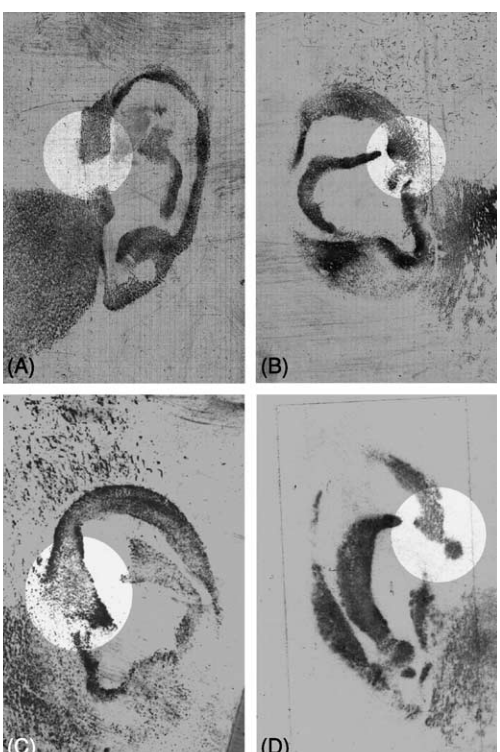

Figure 4 Different prints from the shape of the area of the crux of the helix. The white circle indicates this area.

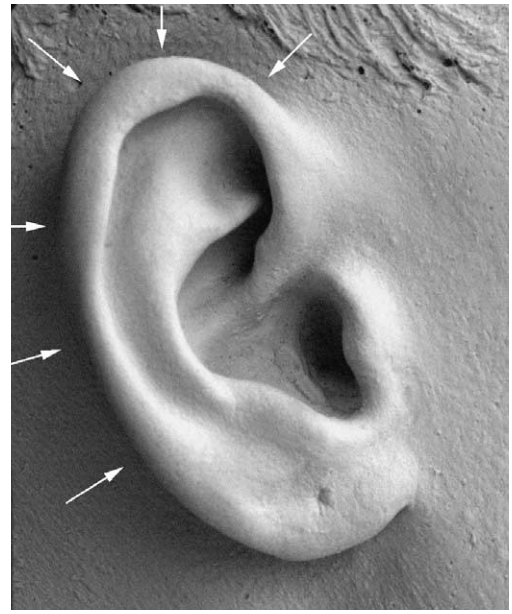

Figure 5 The helix; the whole rim – from the start near the crux of the helix to the lobule section – is pointed out by arrows.

of the helix is a folded type of rim and the cartilage is rather thick at this point, which is why this crux of the helix area often leaves prints when an ear is pressed against a surface. It leaves prints in many different shapes, some of which are shown here.

The helix (Figure 5) is the outer rim or frame of the ear. The whole rim consists of cartilage with covered skin and basically defines the shape of the ear. The helix starts at the crux of the helix and ends near the lobule (earlobe). The helix is a rolled-up edge near the crux of the helix and "unrolls" on its way to the lobule. This folded or rolled helix rim has many variations. The extent to which the helix is folded or rolled is different in each ear. Even the ears of one individual can show different helix rims, with differences in positions where the unrolling starts and ends.

In addition to the characteristics of folding of the helix, we also have to deal with the inside line of the helix (the inside edge) when it leaves prints. This edge can be very typical. It often shows different pressure points and can even be "double," which means that the helix prints its inside and outside edge but not the skin in between. This type of helix has great identification value. In prints, the top part of the helix will usually be visible. Depending on the shape and elevation of the helix and the anthelix, more parts will be visible.

The next feature of a human ear that can be found is the auricular tubercle (Figure 6) or "knob of Darwin."

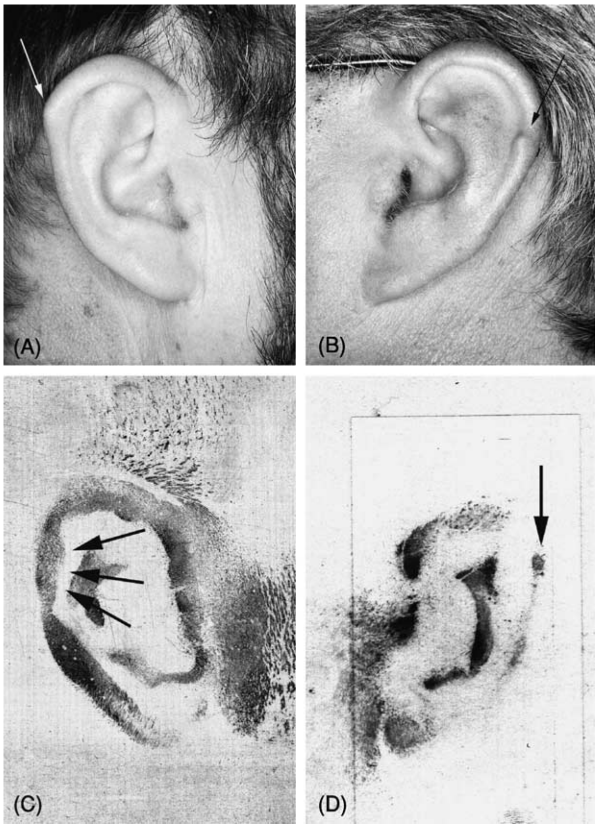

Figure 6 Different types of the auricular tubercle (see arrows).

This feature is not present in all ears. In one individual it may be present in one ear and absent in the other; or it may be very prominent in one ear and hardly recognizable in the other. The auricular tubercle comes in various shapes. It is located on the helix rim around the 2-o'clock site, or the 10-o'clock site, depending on whether it is the left or the right ear. The auricular tubercle can be located on the inside of the helix rim, but also on the outside. But the auricular tubercle may be hardly recognizable as well and may not be visible instantly when it is located on the rim itself. There may even be two knobs on the inside or outside, or on both sides.

The fourth characteristic anatomical feature is the anterior notch, which is located – if visible – between the crux of the helix and the tragus or the anterior knob. In a way, the shape of the anterior notch is affected by the presence of an anterior knob. The anterior knob is located above the tragus and is sometimes very hard to discern on a picture of the ear. Viewing it from a different angle however, the knob may suddenly be very well recognizable. If the knob is present and there is a protruding tragus, it will certainly print and leave a distinct characteristic.

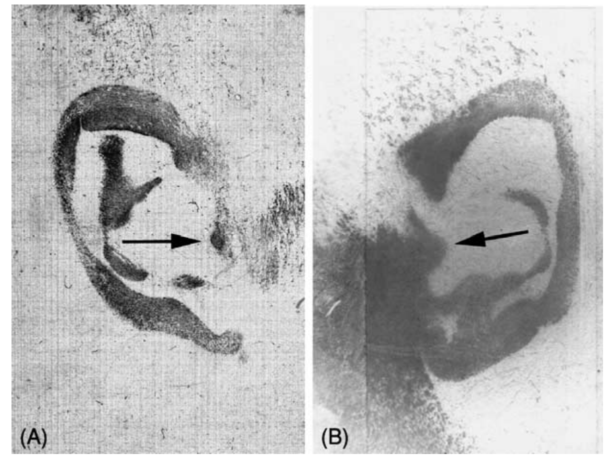

Figure 7 Prints of different types of the tragus (arrow).

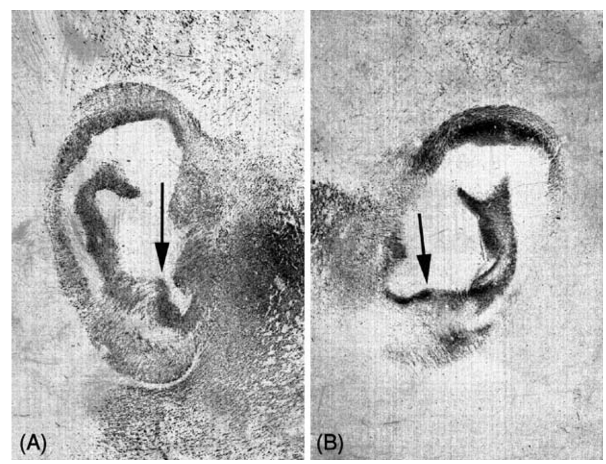

Figure 8 Prints of antitragus: (A) dominant (arrow), (B) hardly visible (arrow).

The tragus (Figure 7) is a built-in protective device for the auditory canal; if something hits the head on the side, the tragus covers the canal. The tragus consists of rather thick cartilage and is usually protruding and, therefore, almost always visible in prints. Because the tragus point is so close to the head, it hardly moves, even when pressed hard, and so it is one of the most important features that can be used for comparison. Also, the tragus comes in different shapes. Because it is usually protruding, it is visible in impressions as a dominant feature. The shape of the tragus is affected by the presence or absence of the anterior knob. Examples of the various different shapes are given in Figure 7. Opposite the tragus is the antitragus (Figure 8). It can be very dominant or hardly visible.

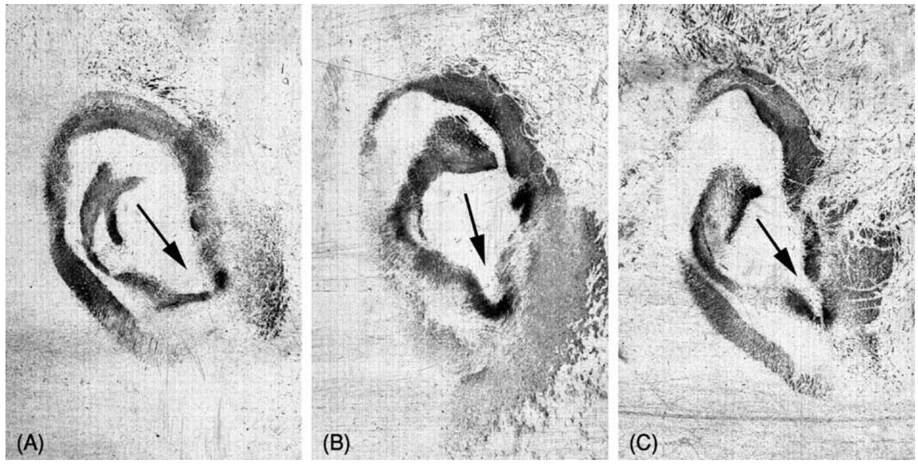

Figure 9 Three types of an intertragic notch: round (A); horseshoe-shaped (B); V-shaped (C). See arrows.

Between the antitragus and the tragus is the intertragic notch. Depending on the shapes of the tragus and antitragus, this notch can have three different types of appearances (Figure 9).

The next and very important feature of the ear is the anthelix. This Y-shaped ridge can either form a straight vertical line (anthelix superior) or bend in the direction of the face (anthelix anterior). The upper parts of this Y-shaped anthelix are the lower crux of the anthelix (crux inferior) and the upper crux of the anthelix (crux superior). In rare cases there is a third crux, usually pointing backwards (to the rear side of the head; crux posterior). The lower crux of the anthelix usually points in the direction of the face (anterior). The upper crux of the anthelix can either point in the same direction, point upwards (superior) or, in rare cases, backwards (posterior). In most ears, the anthelix leaves prints when the ear is pressed against a surface. There are ears, however, that have an anthelix situated much deeper than the helix. In these cases, the anthelix and often the lower crux of the anthelix will not leave a print.

Between the antitragus and the anthelix, sometimes another feature appears: the posterior auricular furrow. This feature is not present in every ear and, if it is, it may be hardly recognizable. When present, the furrow can be very superficial and not visible in prints left by hard pressure. Deep furrows usually leave a characteristic print. The furrow will point to the back of the head (posterior) in most cases. The lowest part of the ear is called the lobule or earlobe. Earlobes can have various shapes, which can be categorized into four groups: round, triangular, square, or lobed. All features of the ear that – under normal circumstances – can leave a mark when an ear is pressed against a surface have been covered. Nevertheless, there are some features left with clear anatomical names but that will not leave a mark. Those features usually are located in a deeper area of the ear. Sometimes, however, when surrounding features leave a clear print, the shape or contours of these features can become visible and add very characteristic information to the impression.

The first of these features is the triangular fossa. The shape of the triangular fossa will be visible when the helix, including a part of the crux of the helix, and the lower and upper cruxes of the anthelix leave their mark on the surface. The shape of the fossa is usually triangular, as its name suggests. In most cases, the shape of the triangular fossa is not clear or visible at all, because one of the surrounding features – most often the upper crux of the anthelix – does not leave a print.

The second feature that can only be found if other parts leave prints, is the scaphoid fossa. If the helix and anthelix leave a clear mark, the shape of the scaphoid fossa is clearly recognizable. This shape can be very characteristic, and often shows great detail. The last, but not the least, important feature that can be recognized is the concha. The concha is the deep inner part of the auricle, leading to the auditory canal. The full shape of the concha can only be found in an earprint when many other parts leave their characteristic marks.

Peculiarities of the Ear

As discussed before, apart from the natural features of ears, there may be some peculiar ones as well.

These features are not present in all ears. Some of them are "natural" in the way that they exist throughout life, others can develop at different times in life. They can be categorized, for instance, into:

- birthmarks – important because of an elevation of the skin and possible different skin texture;
- knobs – on the auricle itself or more often in the pre-auricular area;
- scars – usually caused by accidents involving the ear;
- ear "defects" – ear defects or injuries often originate from specific kinds of sports, like boxing, judo, and rugby. The ears are usually referred to as cauliflower ears;
- missing parts of the ear – this may be caused by an accident. The newly arisen shape will be very characteristic and, without treatment, will stay the same for the rest of its existence.

Medical Treatment, Ear Surgery, and Plastic Surgery

There are many reasons for ears to become the object of medical treatment or plastic surgery; it would take too long to discuss all the possibilities. If for any reason the auricle is missing and an artificial ear is made that has great resemblance to the other ear (if still present), the artificial ear does not contain sebaceous glands and therefore hardly ever leaves a mark. In cases of defects on ears, because of a disease or accident, reconstruction of the ear is often carried out. These methods all aim to give the auricle a shape that is very much like the original or like the other ear.

With respect to our goal to identify people from the print of their ear, it is important to realize that the intended medical treatment does change the ear characteristics. Depending on the scope of the reconstruction, this impact will be substantial or only minor, affecting a small part of the ear. If the texture of the skin is used for identification, one must realize that in certain types of reconstruction a different skin is used to repair the defect, and will, therefore, leave different prints. In addition, in cases of reconstruction of the ear because of missing parts – perhaps even since birth – the size and shape of the ear can change.

Hereditary Factor Effect on Ear Configuration

These are divided opinions about whether hereditary factors affect ear configuration.

Ever since World War I, much research has been done, especially in Germany, that shows that some elements in the human ear could have been inherited from parents: at least they justified a strong suspicion or belief. Some new studies, however, using modern DNA techniques, show that these conclusions have not always been right.

To the author's knowledge, there has been no scientific research in this respect with regards to earprints. It will however be obvious that the ear prints of related people will differ because their ears do. It would be hard to believe that the same two-dimensional print could originate from two different three-dimensional objects.

Ears of Twins and Triplets, etc.

Like fingerprints and like the right and left ears of one individual, ears of identical twins differ. In fingerprints one can often observe similar features like whorls, loops, etc, occurring in the same finger of two individuals. In ears, a similar effect can be observed. The overall shapes of the ears, as well as some features of the ears, often look the same. By close observation, one can find the differences, e.g., in size, but differences can also be found in specific features, like the helix rim, the tragus and antitragus, and the shape of the anthelix. Sometimes, these differences are hard to observe, and require special skill and equipment. If prints of both ears are available, offering the opportunity to overlay one with a transparency of another, the differences will show instantly.

The Area around the Ear

Finally, useful information can be obtained not from the ear itself, but from the area around the ear. Often a part of the cheek, called the preauricular area, located immediately in front of the ear, leaves a print. The print will show the texture of the skin and often contains creases. These can be of great help because, in almost all prints of the same person, they should be more or less the same. Of course, the amount of pressure applied will influence the appearance, but in most cases a person listens with more or less the same pressure. Other areas that could often be present in earprints are the areas above and behind the ear. Usually, there is hair, and one might be able to observe the hair texture. Although a visit to the hairdresser may change this, prints of these areas can be very useful when, for example, the hair texture is obviously that of

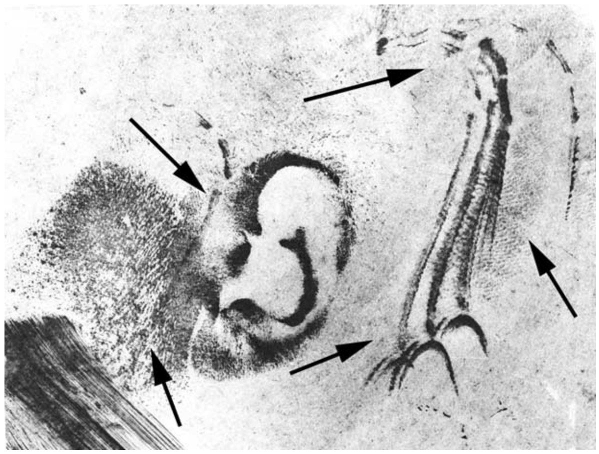

Figure 10 Print of an ear, found at a crime scene, with clearly visible dreadlocks (arrows).

dreadlocks (see Figure 10), which is often very simple to recognize.

Distortion of Earprints by Pressure and Rotation

Because of the variation in pressure, earprints recovered from a crime scene are never identical, in all aspects, to standard ones taken from a suspect. This is due to the fact that the exact pressure exerted at the crime scene is unknown and, therefore, cannot be reproduced. Likewise, the direction from which the pressure was applied cannot be duplicated exactly. The amount of pressure applied by a person is very much dependent on the configuration of the ear. In general, an ear creates a kind of vacuum, a closed area in the concha region; one tries to eliminate other sounds by closing off the concha area. Too little pressure will not only result in a bad earprint, but the person listening will not hear much or anything at all. Because the ear is a flexible, three-dimensional object, with features in different shapes which protrude to some degree, the pressure that each individual will need to apply differs. Experienced listeners usually have found the right pressure to apply; they are "experienced" in that respect, and the print of their ear is almost always exactly the same.

Research on Pressure Distortion

Several papers have been published on the effects of pressure upon the ear. It is generally agreed, that no two ears are completely similar in this respect. In addition to pressure, the effect of rotation has to be considered. In the act of listening, most individuals adopt a comfortable stance, with the head slightly bent forward from its normal upright position. This type of distortion has an influence on the type of print obtained. Depending on the angle with the surface, increased pressure might be applied to the top of the helix rim, to the back part of the helix, or to the lobule or lower parts of the auricle. It might even be the case that a comparison with standards taken from a suspect in a normal upright position is very difficult to make. At first sight, the prints may look different, but certain key features lead the investigator in the right direction.

When and Where to Find Earprints

In numerous cases (e.g., burglaries and homicides), perpetrators listen at doors and windows before entering the premises. However, it may not be at the door or window where entry was gained. Perpetrators may have listened at several premises along a street, or several windows in one house. In the Netherlands, the majority of earprints are found on doors in blocks of apartments with porticos. They are found at different heights, depending on the perpetrator's habits or the local circumstances. In most cases, earprints are found at a normal standing height, usually between 130 and 180 cm from the floor. Commonly, they are found in the middle of the door or window. Most people listen by pulling back one shoulder and placing the side of the head against the surface. By doing so, one usually bends forward slightly. The area to be searched for earprints will be from the middle of the door (vertically) to the top. There is also a group of people who bend over, when listening. Their earprints will be found approximately at the same height as the doorknob. The tragus point of the ear will be visible on the bottom of the print, whereas the helix rim will be on the top. Earprints can sometimes be located at a height of ~30 cm from the floor. These prints occur on doors of houses with porticos, next to a staircase.

Recovery and Lifting of Earprints

There are a variety of methods for the enhancement and subsequent recovery of earprints left at a crime scene. The method to be employed will depend on the availability of products and the nature of the surface on which the earprint is found. Commonly, the same techniques will be applied as for fingerprints. In most cases, a fingerprint powder is used in combination with photography or lifting of the marks found.

An additional tool, useful in relation to earprints, is the calculation of a person's stature from the height where the earprint is found. Based on a study by Hirschi, the author noted that a formula could be found for calculating the average distance that people bent forward while listening, combined with the average distance between the top of the skull and the middle of the auditory canal and added to the height of an earprint above the floor. This height needs to be measured from the tragus point in the earprint.

Preparing a Comparison

For an actual comparison of earprints, several methods are in use:

1. *Measurement*. The different features of the ear are measured from the print. Data on overall sizes of the parts and distances between them are obtained. Often, arrows are used to indicate special shapes of various parts. A problem with this method can be caused by differences in pressure or rotation of the ear. Measuring outlines, either on the inside or outside of a feature, is very difficult, as is trying to find the middle of a feature. Therefore, this method is not advisable.
2. *Overlay technique*. One of the available earprints (either the known or the unknown one) is copied onto a transparent sheet. The other print will usually be copied on a nontransparent sheet and put one on top of the other and fixed on one side. The transparency can now be lifted, in order to make the prints visible separately.
3. *Quartering technique*. In this technique, the prints are divided into four separate parts and put together, two by two (known and unknown), to get a full print again.

In order to copy the earprints, one needs to photograph or digitize them. For earprints on a gelatine foil or lifter, a flatbed scanner is very suitable. The advantage of using a scanner is the fact that the result will always be a 1:1 image of the original, unless different settings are used. The scanning resolution should be at least 600 dpi. A three-color scan (RGB) has proven to give better detail and possibilities for optimum quality. To economize the storage requirement, the color information can be removed.

Obtaining Earprints from Suspects

Legal methods for obtaining earprints from suspects differ between countries around the world. This will not be discussed here. Most documented methods for obtaining standards include photographing the ear, in addition to any other technique employed. The most useful method to get earprints is to ask the suspect to listen several times at a glass pane or at a very flat (and clean) surface. Usually, three prints per ear are sufficient. The first print should be a "functional" pressure print. The suspect needs to listen to a sound and if possible memorize what he has heard. After obtaining the first print in this way, a second one with gentle, obviously less pressure, and a third print, should be taken with considerably more pressure (see Figure 11). The prints must be recovered and lifted in the same way as for fingerprints.

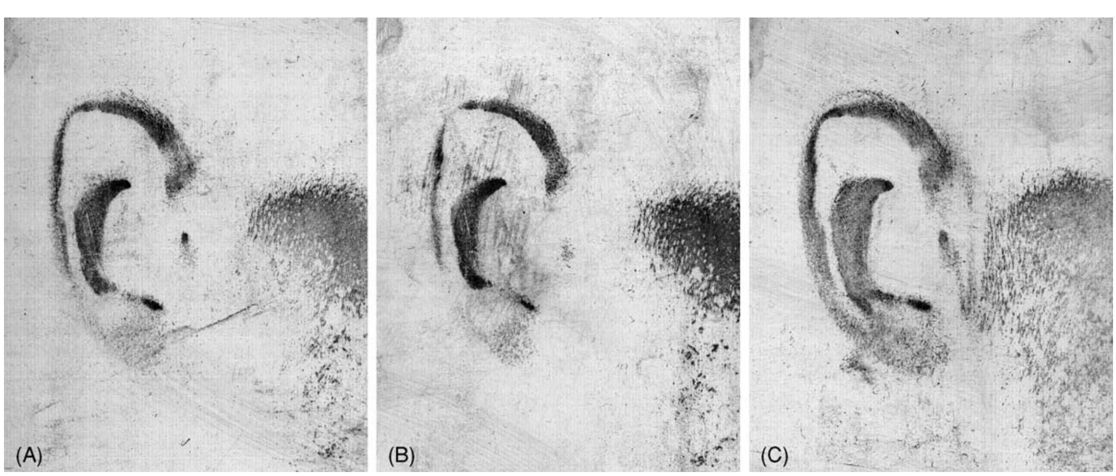

Figure 11 Earprint taken with functional (A), gentle (B), and hard pressure (C).

In all cases, a photograph of the right and the left ear should be taken, with the camera at an angle of 90°, corresponding to the head. From noncooperative suspects and those who offer passive resistance, five prints per ear should be taken, placing a glass or a synthetic plate with varying pressure on each ear, preventing one part of the ear (upper, lower, front, or back side) from being pressed more firmly than another.

It is often preferable to attempt to recreate the crime scene conditions so that height, rotation, and pressure can be accounted for.

The Process of Comparison

After collecting the traces as well as the reference prints from suspects and/or witnesses, the earprint traces need to be individualized. This is achieved by finding agreement of corresponding individual characteristics of such number and significance as to preclude the possibility (or probability) of their having occurred by mere coincidence, and establishing that there are no differences that cannot be accounted for. "Agreement of corresponding individual characteristics" means that the characteristics used for comparison must be found to agree in shape or appearance and in position and orientation. These corresponding characteristics must be of "such number and significance as to preclude the possibility (or probability) of their having occurred by mere coincidence." It does not say how many need to be found, because there is no fixed number! Particularly in earprint comparisons, the required number depends on the assessment of the significance of each characteristic. It is important to establish that there are no differences that cannot be accounted for. Since earprints can differ because of pressure and rotation, at least three prints, made with different pressures, are needed to be able to see how the (flexible) ear reacts when put against a surface. Further procedure is divided in three major steps: analysis, comparison, and evaluation (ACE).

Analysis

The process of analysis consists of two steps. First the unknown earprint must be examined carefully. It is important to start with the unknown print, before getting into the details of the known earprint of a suspect. The general and specific information about the print needs to be precisely documented including the morphology and anatomy of the earprint. Often a small drawing will help. After observing the earprint in full detail, it is possible to answer a very important question: is the information sufficient for comparison with a known print? The characteristics that can be used to individualize an impression fall into two categories:

1. Class characteristics, i.e., "characteristics which are common to several objects." The examples are size, general shape, or even the presence or absence of a feature. This type of characteristic has no value in the process of individualization: it can, however, be used as a preliminary screening technique.
2. Individual characteristics, i.e., "characteristics that are unique." A general appreciation of the origin of individual characteristics is useful in their recognition. They are basically attributable to natural variation.

The second step is to describe the known prints (the standards taken from a suspect) along the lines of the same procedure as followed for the sample collected.

Comparison

In this step, a comparison is made between the characteristics found on the unknown earprint and the characteristics of the known earprint. All the similarities and dissimilarities of the characteristics observed must be documented. To show the similarities and dissimilarities, the overlay and quartering techniques can be used.

Evaluation

Evaluation which is the critical step where one must decide the terms of the opinion to be offered. The scope of the opinion can vary: positive (certainty), highly probable (strong belief), probable possible (consistent with; may be), or no basis for comparison.

Positive opinion A positive opinion can be given when the examiner is certain beyond a reasonable doubt that the trace matches with the reference standards. Enough information on class and individual characteristics are present to lead to his/her unique conclusion. There is no possibility of the similarities having occurred by coincidence on two different objects and there are no differences, except those that can be accounted for.

Probable opinion Highly probable and "probable" are both probabilitistic opinions. Their judgment on the match between the traces and the standards lies somewhere between impossible and certain. Most often it is very difficult to decide which opinion to offer, probable or highly probable.

Possible opinion The use of the word "possible" in this perspective would mean that there are some class characteristics available but do not have any significant individual characteristic.

No basis for comparison This category of conclusions is very close to the category "possible." In fact, quite a number of features are missing, which means that a positive identification will not be possible. However, this print, though worthless for individualization might be suitable for exclusion.

Negative opinion All conclusions explained here can also be used in the negative. The strongest in this category, of course, is an exclusion. On the basis of the earprint found at the scene and the standards taken from the suspect, especially if many features are present, one can conclude in the negative. "This earprint, found on the outside of the front door was not made by this suspect."

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Facial

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Introduction

The identification of human remains is a major issue for forensic systems. A number of people disappear every year; others are buried anonymously. Furthermore, mass murders are committed worldwide. Identification may be very difficult, either because the body is in a poor condition, or because of a lack of identification records (dental charts, X-rays, or DNA databases). Therefore, the identification strategy depends on the available evidence, the thoroughness of the police investigation, and the presence (or absence) of antemortem records. Sometimes the only possible form of identification is through facial reconstruction. There are several means of facial reconstruction: (1) video or photographic comparison (comparison of a video image or photo with the actual face, video, or photo of a suspect); (2) superimposition (overlaying a facial image, i.e., a portrait, a photo, or video footage, on a skull); (3) facial restoration, or craniofacial restoration (when sufficient soft tissues persist on the head: the aim is to restore the head to its original appearance); (4) facial reconstruction or craniofacial reconstruction (when no tissue remains on the skull); and (5) aging the face of a missing child or adult.

These methods are very sophisticated, and are used in current forensic cases, with a certain amount of success, even if the techniques have not been scientifically validated. They are based on the relationship between the bony frame (the bony face and skull), and the corresponding soft-tissue points.

Superimposition

Superimposition compares the skull with a photo of the missing person. This technique is complex, either directly superimposing questioned skull photos with a photo of the missing person, or comparing the skull and the photo using video or a computer-assisted process. The distance, magnification, orientation, distortion, and depth of field must be carefully checked. It is important to establish the number and quality of criteria necessary to determine if the identity can be ascertained (probably very difficult), excluded, or simply included.

Video or Photographic Comparisons

In this process an image of the suspect (video image or photo) is compared with the actual face of the suspect, or with a video or photo of him/her. This is an increasingly popular method, due to the widespread use of video in public places, and in sensitive locations such as banks, airports, and stores. These comparisons are both qualitative and quantitative. Quantification is based on horizontal, vertical, or oblique measurements; however, the distance, orientation, and magnification of the images must be thoroughly checked, avoiding any distortion.

Facial Reconstruction

Facial reconstruction is an important tool in the identification of unknown remains. It is based on the relationship between anthropological (bony) points and the soft-tissue points to which they are connected. Average soft-tissue thicknesses are known in relation to some bony points. Unfortunately, the skull does not provide all the clues to enable a perfect reconstruction to be made. As a result, facial reconstruction can be only an approximation that helps to stimulate the eyes or brain of the next of kin, and it is followed by other comparative methods. There are many types of facial reconstruction: two- or three-dimensional, manual, and computer-assisted.

Two-dimensional methods include the lateral craniographic George's method, which creates a profile of the subject by connecting points drawn in relation to radiographic points; and a sketch of the face, drawn by a forensic artist, directed by a forensic anthropologist or scientist.

The most popular three-dimensional method is probably the manual (or plastic, or sculptural) three-dimensional one. This is carried out by a forensic pathologist, anthropologist, odontologist, scientist, or artist. It starts with a thorough osteological examination, assessing skull morphology, taking anthropological measurements, and paying particular attention to classical anthropological items (age, sex, race, stature), as well as the size and shape of the skull and face, and its own particular features. The study is completed by a cephalometric (radiographic) analysis, which allows detailed study of skeletal abnormalities, such as skeletal balance and dental occlusion. Then, average soft-tissue thickness is translated into clay or clay-like material and placed on specific anthropological landmarks. The space between these points is filled in, and gradually the face is reconstructed. Areas such as the ears, eyes, nose, mouth, lips, and chin are difficult to place correctly and to check, despite comprehensive studies published in the literature. Scientific validation of the method is scarce, and includes only isolated forensic cases and controlled blind reconstruction in small series. Computerized methods are very sophisticated, rendering the results in either two or three dimensions. The advantages of computerized methods are speed and the possibility of editing several versions of the reconstruction.

Aging a face on a photo is a complex process that can be performed by an artist and, rarely, using a computer-assisted method. The size, shape, and features of the faces of both parents are usually taken into account, and used as predictors of possible changes in the facial features of the missing child. However, these methods are not scientifically validated.

Facial Restoration

Facial restoration deals with a face that is altered by decomposition, fire, or trauma. The idea of restoring the body comes from the common use of this technique in the forensic context to obtain fingerprints. Water or a saline solution is injected under the pulp of the fingers, in order to swell the tip of the decomposed finger. This permits the forensic pathologist to take the fingerprints, which may identify the deceased, even before the autopsy is completed. Furthermore, the face and hands of the deceased are commonly improved, or even restored, by morticians, before the decedent is presented to the next of kin.

The aim of facial restoration is to improve recognition of the face, in order to generate leads to identification. Nevertheless, in a forensic context, facial restoration is rarely reported in the literature. Dérobert has described individuals with faces that were badly altered by trauma whose facial restoration permitted a spectacular improvement, allowing their photograph to be published or shown to the family for identification. Spitz and Fisher have presented the photograph of a decomposed face, which was restored, sketched, and then broadcast. Ubelaker has shown sketches from decomposed faces, which were released for identification purpose. Pötsch and colleagues worked on mutilated faces, restored them, and issued the results in the media, as sketches or photographs, depending on the quality of the results.

There are three steps to the process: (1) restoration; (2) restitution; and (3) appropriation. Restoration is achieved by surgery or with the embalming process. Surgical techniques are used whenever the face is badly altered by trauma; the stitching can be perfect stitches, and skin losses are covered by various surgical techniques, such as grafts or rotation flaps. These techniques may lead to a high-quality restoration, even if the face is severely damaged and is missing some parts.

The embalming process is commonly performed by morticians. Formaldehyde solutions are injected into the body, and the facial outlook can be improved by the injection of specific products under the skin. This process is primarily used for decomposed bodies and faces. The embalming products make it possible to sustain the soft tissues, remodel emaciated parts of the face, and give some tonicity to the eyeballs. These techniques must be used after autopsy, and after samples have been taken for toxicology, histopathology, and DNA analysis.

Presentation of the result is the second step, and this can be achieved with various methods. The simplest is to take a photograph of the restored face: this has the advantages of speed, ease, and cost-effectiveness. However, there are some obvious drawbacks; the most significant is the ethical issue, because the result is not always suitable for viewing by the media or the next of kin.

The second process is sketching the restored face. The advantage is that the sketch can always be viewed by the family, and can be shown to the media. The drawback is that it must be performed by a forensic artist (raising the cost), and the possible subjectivity, since the artist is asked to humanize the result of a crude restoration. In one way, this last point may be an advantage, because a more human aspect of the face would stimulate the cognitive processes of the next of kin.

The third method is to cast the restored face. Quatrehomme and coworkers discussed two cases where the face was severely damaged, one by decomposition and one by trauma. In both cases, publishing the photograph of the face either before or after restoration was inconceivable.

In the first case (decomposition), the gases were released at the time of autopsy by making incisions along the frontal area and the mandibular arch. Then the face looked dehydrated and badly emaciated. Subcutaneous injections were used, filling out the sunken temples and eyes, plumping up the nose tip, the lips, and the forehead. A second product was used to remodel the facial contours. This material looks like wax, but is soft enough to be injected, molded, and handled. The interest of this restoration is multiple. First, it aims to give the face a human appearance; second, it is excellent preparation for use before the casting step, bearing in mind that this material (used by any mortician) is able to hold the tissues firm in any position, and stick to them, even if they are wet.

The casting process is quite easy, once one has some experience in this field. It requires polyurethane elastomer, which ensures flexibility and faithful reproduction. The elastomer is spread on to the face, and several hours later a plaster cover is laid on top. The cast is removed 24 h later, and consolidated by subsequent layers of plaster. Eventually, the cast is done, representing a "negative" of the face. The positive printing is achieved with either a polyester resin or a plain plaster. The interest of this technique is to give a three-dimensional representation of the head of the missing person that can be given to the judge, and photographed in any orientation. In the specific case described by Quatrehomme and colleagues, the individual was immediately recognized from a television program.

In the second case (trauma), the state of the head was worse, because the individual committed suicide by standing between the rails of a train track, waiting for the collision. Flesh and bone fragments were found up to 100 m away from the scene. The face was extremely damaged, and most of the bones of the skull were absent; only small fragments of the occipital bone and a few teeth were still present. The process of restoration was very difficult, but gradually the face was rebuilt, using surgical techniques. Then a cast was made and a three-dimensional representation of the head was created. In this case, the results were unsatisfactory because the face was too thick. From the autopsy results we knew that the subject was very thin. This "overthickness" was explained by the fact that the weight of the cast on the face of the cadaver was excessive, and had a gravitational effect, spreading the face badly. Furthermore restoration of the nose was almost impossible, due to the absence of the nasal bones.

The advantages of casting a face are numerous. The result of the work is very objective, and three-dimensional, so more realistic. The elastomer is able to retain the slightest facial details, such as wrinkles, and the proportions of the face are globally accurate, which is key to recognition by the family.

The main advantage is that the casting can always be communicated to the media, and shown to the next of kin, even when the restoration could not have been. The drawbacks are the complexity of this time-consuming method.

To conclude, in the future it will be interesting to carry out computer sketching or computer modification from the restored (or unrestored) face.

Recognition and Identification

The last step is recognition of the face by the family or friends. In the end, as in facial reconstruction, it is probably impossible to achieve a perfect copy of the missing person's face. At least, facial restoration aims at making identification possible, if the family can see a resemblance to the missing relative. Comparative methods of identification should then be used, in order to prove positive identification beyond reasonable doubt.

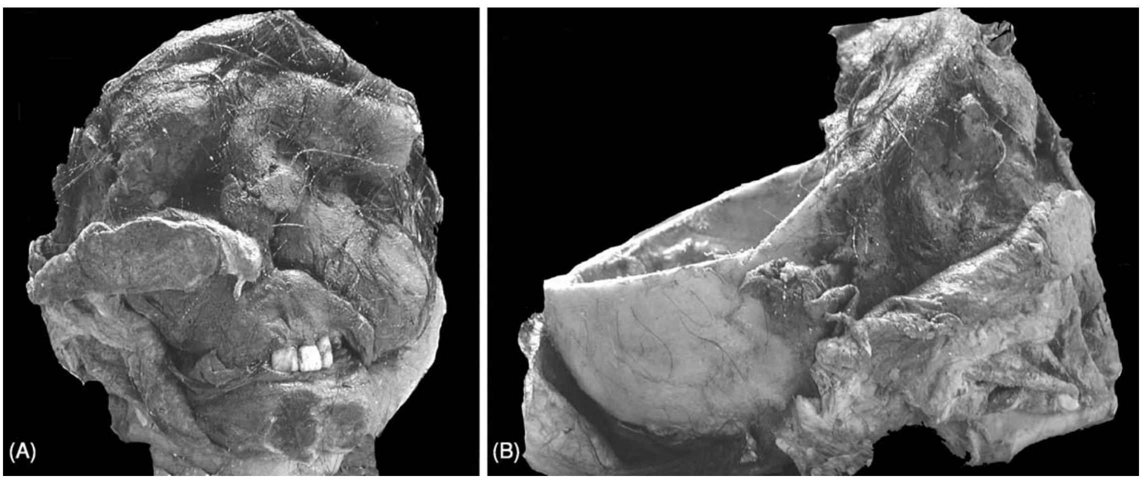

Figure 1 Initial status: the badly decomposed and damaged head ((A) and (B)). (Courtesy of Professor Didier Gosset.)

Figure 2 Restoration process ((A) and (B)).

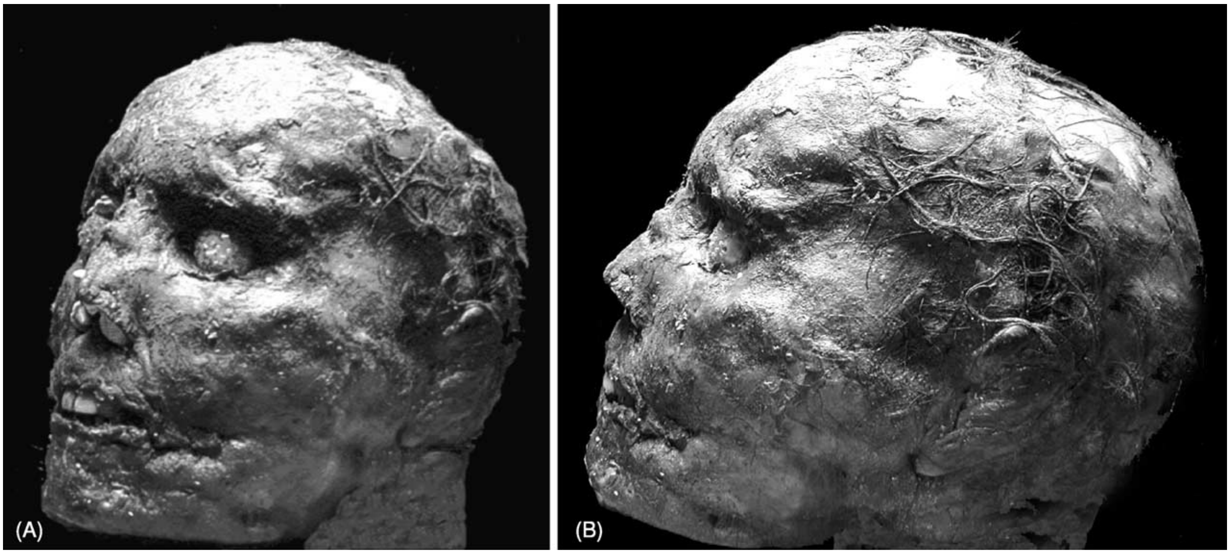

Figure 3 Results of the restoration of the face ((A) and (B)).

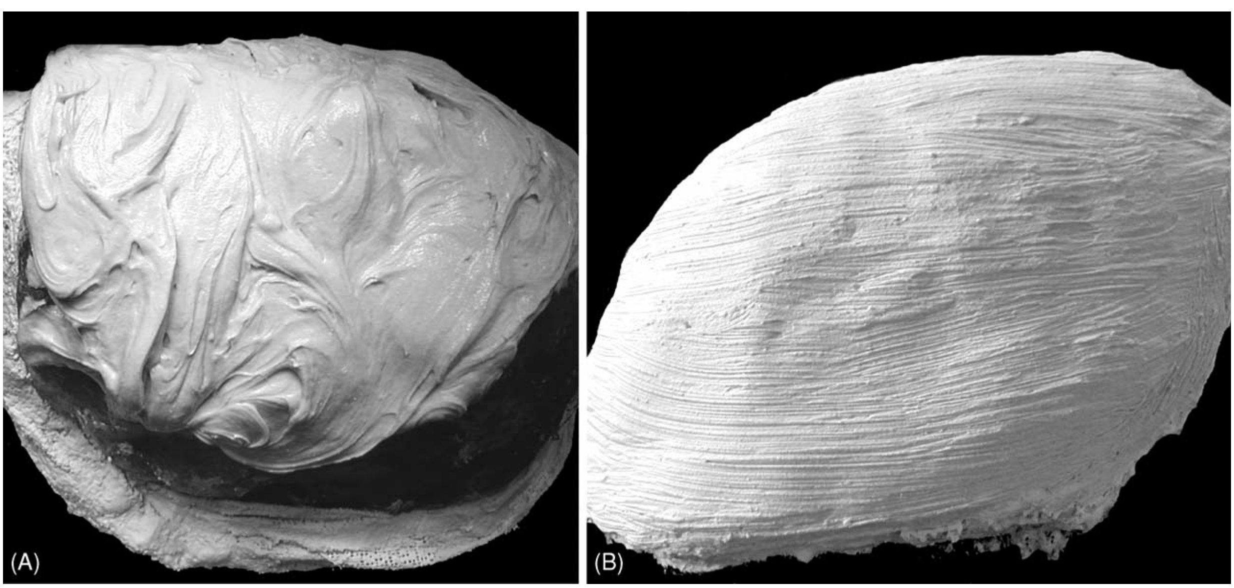

Figure 4 Casting process ((A) and (B)).

Figure 1 shows an example of restoration in a case of advanced decomposition, where the head was autopsied. It was badly decomposed and damaged, but some soft tissue remained, so we decided to attempt a restoration process (Figure 2). This restoration was extremely complex and time-consuming. The result of the restoration is shown in Figure 3. Despite lengthy restoration, the result could not be made public. Therefore, we tried two solutions: casting and drawing. The casting process is partly shown in Figure 4. The result of the three-dimensional casting is demonstrated in Figure 5 (full profile), and Figure 6 (oblique views). These pictures show that the cast can always be shown to the next of kin, and then released to the media. Nevertheless, the problem of casting is that the result often gives quite a "ghostly appearance" (Figures 5 and 6). This is why only the sketches of the results are presented. Figure 7 shows sketches of the restored head, and Figure 8 shows a sketch of the casting of the restored head. The artist is able to draw versions with closed or open eyes, or with closed or half-open mouth (Figure 7). Usually, it is easier to draw from the three-dimensional casting (Figure 8) than from photographs of the restored face (even with full-face, profile, and oblique views), because the three-dimensional casting allows the artist to get an excellent perception of the volumes and proportions. Obviously, in the case presented here, the sketch gives a more "human" appearance to the result, and, in our opinion, will probably be of more assistance to the family.

Figure 5 Result of the casting process: full profile.

The indications for restoration are numerous. In our department, we use it in cases ranging from decomposition and drowning to burning; wherever sufficient soft tissues remain on the skull, even if the quality of these soft tissues is poor. The results, in terms of possibility of recognition by the next of kin, are good, and often very fast. This rapidity of recognition was underlined by Pötsch and coworkers. The explanation is that the general shape of the face persists, despite the dramatic alteration of the soft tissues, and that the proportion between various parts of the face persists (especially what we call the "noble parts" of the face, including eyes, nose, lips, chin, and ears). In the case we have presented above, the soft tissues were dramatically altered, but the whole shape and proportions of the face were preserved; the only important issue in this case was that part of the nose tip was absent, due to animal activity. However one side of the nose tip was sufficiently preserved to reconstruct the other side, and give a correct result.

In conclusion, this method is of interest in difficult forensic identification cases. Once the autopsy has been carried out and samples have been taken, restoring the face is a good technique to stimulate the cognitive functions of the family or friends, in order

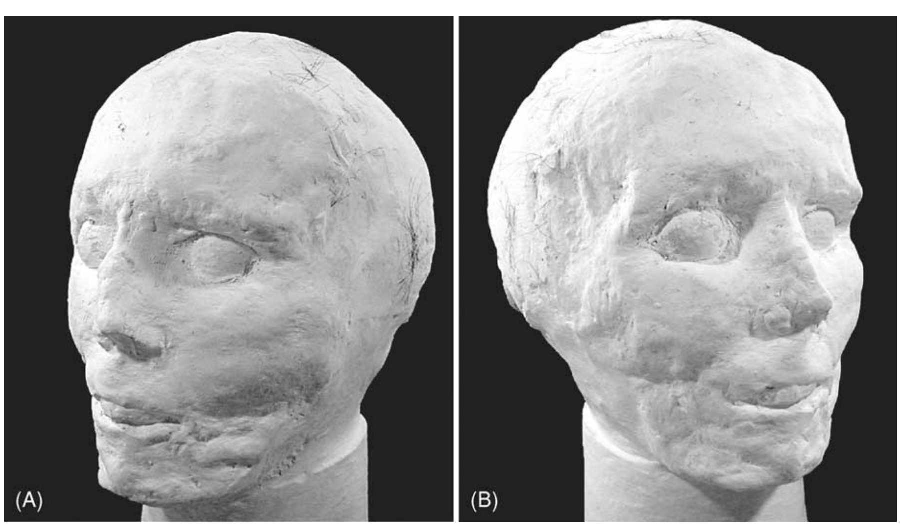

Figure 6 Result of the casting process: oblique views ((A) and (B)).

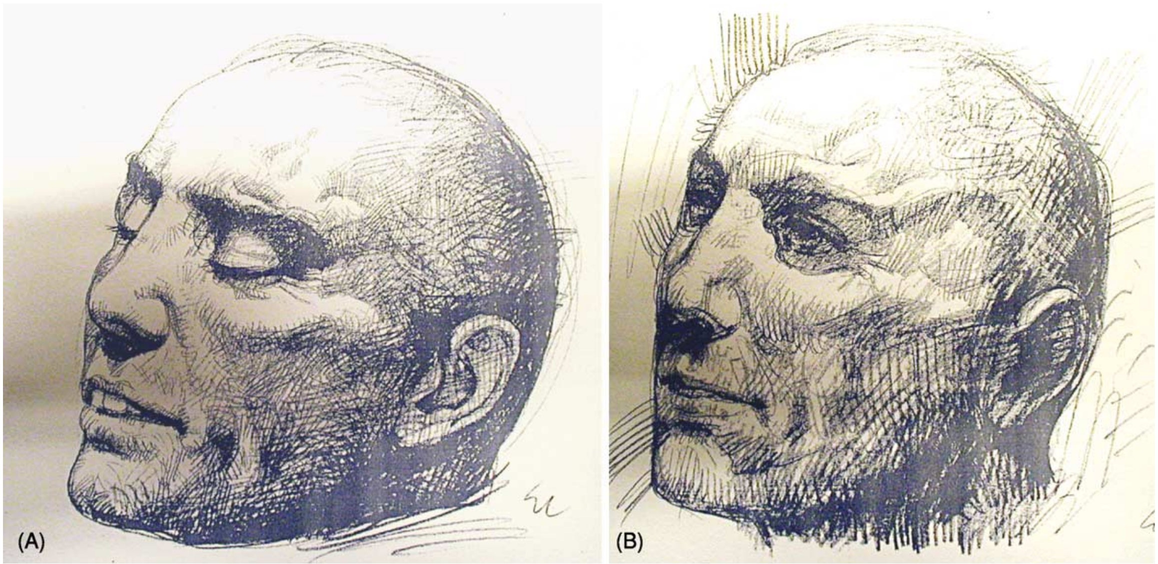

Figure 7 Sketches of the restored head ((A) and (B)). (Courtesy of Giovanni Civardi.)

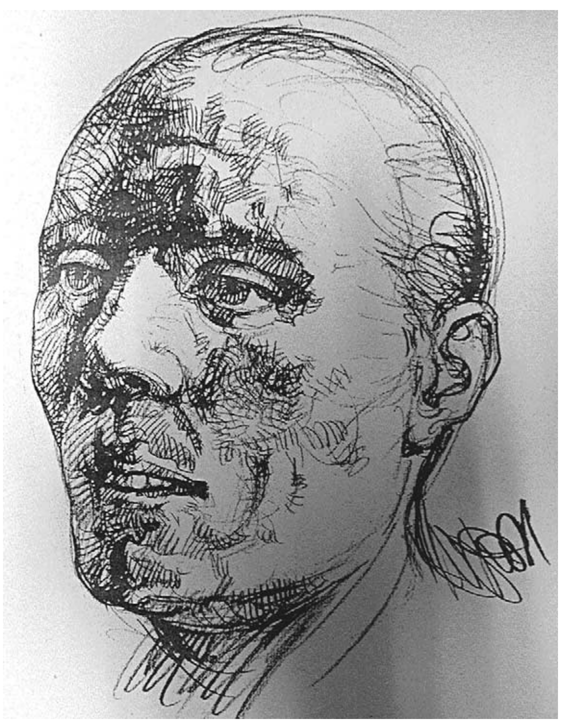

Figure 8 Sketch of the casting of the restored head. (Courtesy of Giovanni Civardi.)

to get a lead toward a positive identification. This method is preferred to facial reconstruction, whenever possible, because facial reconstruction is far more difficult (in terms of a resemblance) than facial restoration. Furthermore, facial reconstruction can always be done, even after an attempt at facial restoration, since facial reconstruction works on the skulls when no soft tissue is left.

See Also

Anthropology: Overview; Stature Estimation from the Skeleton

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