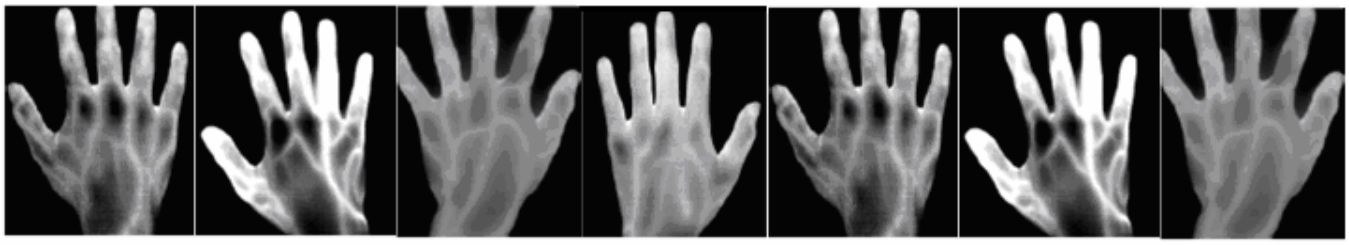
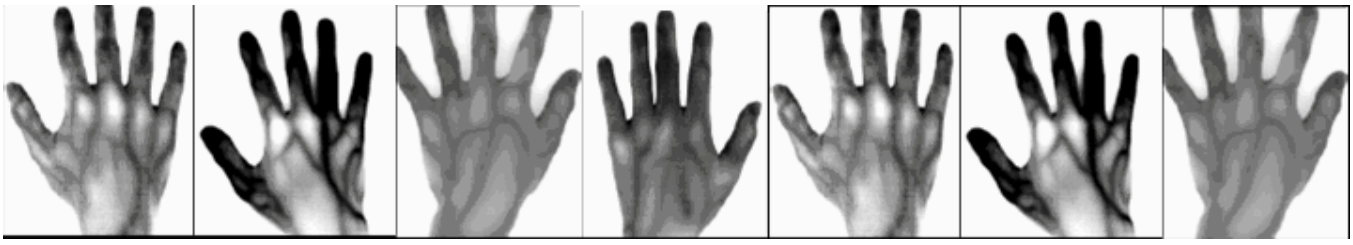


The Hand Vein Pattern Used as a Biometric Feature

Master Literature Thesis
by

Annemarie Nadort

Amsterdam - May 2007



Justitie Nederlands Forensisch Instituut

vrije Universiteit amsterdam

The Hand Vein Pattern Used as a Biometric Feature

Author: Annemarie Nadort

Context: Literature thesis for Master of Science programme Physics of Life, research master of study Medical Natural Sciences at the Free University, Amsterdam

Supervisor: dr. ing. Zeno J.M.H. Geradts
Forensic scientist Image Analysis and Biometrics / R&D coordinator
Digital evidence and Biometrics
Nederlands Forensisch Instituut / Netherlands Forensic Institute
Ministerie van Justitie / Ministry of Justice
Den Haag / The Hague, The Netherlands

Second reviewer: Prof.dr. R.M. Heethaar
Head of dep. Physics and Medical Technology
VU Medisch Centrum / VU Medical Centre
Amsterdam, The Netherlands

Amsterdam, May 2007

Image on cover adapted from [1], figure 2

I. SUMMARY

The problem of truly identifying individuals in our society has become bigger in recent years, due to our complex, mobile and vastly interconnected information society. The most secure way of identifying people is said to be the verification of a concrete entity, inherently belonging to this person: something that he *is* or that he *does*. This is what biometrics is: the automated use of physiological or behavioural characteristics to determine or verify identity. The security of biometric identification has however been questioned, especially for established techniques like fingerprint verification. A relatively new biometric feature is the hand vein pattern. The Netherlands Forensic Institute is interested in biometric identification/verification methods and evaluates new biometric developments with regard to the technical and legal aspects of the method. Part of the evaluation programme is this literature study, which addresses the properties of the hand vein pattern in the context of biometric verification and identification.

The literature research is subdivided in three sections. The first section describes the physiological and physical properties of the hand vascular system: its uniqueness, time-invariance, optical properties and vein imaging methods. The pattern is highly variable amongst people, although not proven to be unique. The permanence and stability of the vein pattern are assessed: several circumstances cause the pattern to change. It depends on the matching process whether the changes are significant for performance of the biometric devices. Two imaging techniques can be distinguished: capturing naturally emanating thermal radiation from the hand and illuminating the hand with an infrared light source and capturing reflected radiation. The second part describes how the biometric devices work, that process the hand vein pattern for verification. Several patents, papers and websites of commercial biometric companies and scientific studies on hand vein pattern verification have been assessed, to give an overview of techniques that have been used in this field. Many different ways exist to extract the features of a vein pattern from an original image of the veins, to obtain a representation of the hand vein pattern only. The next step is to match this vein pattern to a previously stored template vein pattern of this person. Due to several causes for variance in vein pattern images of the same hand, the matching process should allow some misalignment. On the other hand it should be strict enough to reject non-similar vein patterns. Because identification is typically used in security contexts the devices are susceptible to attacks from impostors. The defence of the devices can rely on incorporating a liveness detector in the method to verify whether the vein pattern belongs to a living hand. Although many liveness detecting techniques are mentioned in the third subsection of this thesis, biometric devices will never be spoof-proof. In addition, matching algorithms can make matching errors. However, biometric vein pattern verification can be an appropriate tool to protect access to private areas, as long as one knows the vulnerabilities and subsequently adapts the biometric system design.

II. INDEX

III. DEFINITIONS

Defining the subject

This thesis is on hand vein pattern verification. The hand vein pattern is here regarded as a biometric feature. **Biometrics** is the automated measurement of physiological or behavioural characteristics to determine or verify identity [2]. Biological and behavioral characteristics are physical properties of body parts, physiological and behavioral processes created by the body and combinations of any of these. Distinguishing does not necessarily imply individualization [3]. The hand vein pattern is used as a **biometric feature**, in this case a biological characteristic of an individual which can be detected and from which distinguishing, repeatable biometric features can be extracted for the purpose of automated recognition of individuals.

Verification is confirmation by examination and provision of objective evidence that specified requirements have been fulfilled. Verification in a biometric application is the outcome true or false on a claim about the similarity of a biometric reference and a recognition biometric sample by making a comparison [3], a one-to-one match. Biometric **authentication** is often used as a synonym for verification, but formally this is deprecated. Biometric **identification** is the outcome of a biometric system function that performs a one-to-many search to obtain a candidate list [3].

The **hand vein** pattern is the network of blood vessels lying subcutaneously in the hand. In this thesis it can regard vessels at the back or palm side of the hand, in a finger or the wrist. Although veins are defined as the vessels carrying blood back to the heart, also arteries, the ones carrying blood away from the heart, are part of this vessel network used for biometric verification. This is an erroneous appellation of the biometric feature, but is common used in the biometric industry.

The actual **pattern** is the shape of the vascular network and its characteristics are the vein features. It has to be derived from the hand by **vein imaging**, followed by **image processing**: enhancing or changing an image to extract information or features. **Vein feature matching** is the biometric verification process. It involves a lot of digital signal processing.

A **biometric device** can be a part of a biometric system and contains the sensor which captures a biometric sample from an individual or it can be self-contained to perform the entire biometric verification within itself. The performance of the device, including the verification process, is an important property for usability of this biometric verification technique. It can be expressed in terms as **false acceptance rate** or **false rejection rate** which will be defined below.

False acceptance is the goal of a **biometric impostor**, who presents a biometric feature and attempts to be incorrectly recognized by generating a false match or by bypassing a positive claim in the biometric system [3]. A genuine user, wrongly recognized as someone else, is not an impostor. Sometimes **liveness detection** can prevent the success of a biometric impostor. It is regarded as the

capability for the system to detect, during enrolment and verification/identification, whether or not the biometric sample presented is alive or not [4].

This thesis encompasses the properties of the hand vein pattern, the processes towards biometric verification and methods for liveness detection. More definitions of concepts used in this thesis that require some explanation are listed next.

List of definitions

Absorption – The process by which the energy of a photon is taken up by another entity, for example, by an atom. The photon is destroyed in the process. The absorbed energy may be re-emitted as radiant energy or transformed into heat energy. The absorption of light during wave propagation is often called attenuation [5].

Algorithm – A sequence of instructions that tell a biometric system how to solve a particular problem. An algorithm will have a finite number of steps and is typically used by the biometric engine to compute whether a biometric sample and template are a match [6].

Binary Images - Binary images are images whose pixels have only two possible intensity values. They are normally displayed as black and white. Numerically, the two values are often 0 for black, and either 1 or 255 for white. Binary images are often produced by thresholding a greyscale or colour image, in order to separate an object in the image from the background [7].

Boolean function - A Boolean function is an evaluation that results in either of the truth values 'true' or 'false', often coded 1 and 0, respectively. The fundamental operations of Boolean logic, often called Boolean operators, are “and,” “or,” and “not”.

Coincidence Ratio - The coincidence ratio is used to compare two distributions. In using the coincidence ratio, the ratio in common between two distributions is measured as a percentage of the total area of those distributions. Mathematically, the sum of the lower value of the two distributions at each increment of X, is divided by the sum of the higher value of the two distributions at each increment of X. Generally, the coincidence ratio measures the percent of area that "coincides" for the two curves. The coincidence ratio lies between zero and one, where zero indicates two disjoint distributions and one indicates identical distributions [8].

Convolution - In mathematics and, in particular, functional analysis, convolution is a mathematical operator which takes two functions *f* and *g* and produces a third function *y* that in a sense represents the amount of overlap between *f* and a reversed and translated version of *g* [5]. In digital signal processing it is a fundamental operation, which is behind the notion of filtering: the output image *y* is image *f* filtered by *g*.

Dilation – A fundamental operation in image processing. The basic effect of the operator on a binary image is to gradually enlarge the boundaries of regions of foreground pixels. Thus areas of foreground pixels grow in size while holes within those regions become smaller. In formula [9]:

$$D(A,B) = A \oplus B = \bigcup_{\beta \in B} (A + \beta)$$

Where:

$$-B = \{-\beta | \beta \in B\}$$

Enrollee – A person who has a biometric reference template on file.

Enrolment – The process of collecting biometric samples from a person and the subsequent preparation and storage of biometric reference templates representing that person's identity.

Equal Error Rate (EER) – The equal error rate (also called the cross over error rate) is the point at which the false rejection rate and the false acceptance rate are equal. It is often expressed as a percentage. This has become ant important measure of biometric system accuracy [10].

Erosion – A fundamental operation in image processing. The basic effect of the operator on a binary image is to erode away the boundaries of regions of foreground pixels. Thus areas of foreground pixels shrink in size, and holes within those areas become larger. In formula [9]:

$$E(A,B) = A \ominus (-B) = \bigcap_{\beta \in B} (A - \beta)$$

Where:

$$-B = \{-\beta | \beta \in B\}$$

Euclidean distance – The Euclidean distance or Euclidean metric is the "ordinary" distance between two points that one would measure with a ruler, which can be proven by repeated application of the Pythagorean theorem [5].

Extinction coefficient - The extinction coefficient for a particular substance is a measure of how well it scatters and absorbs electromagnetic radiation (EM waves) [5].

Failure to acquire rate (FTA) - proportion of verification or identification attempts for which the system fails to capture or locate a signal of sufficient quality [11].

Failure to Enroll (FTE) Rate – The probability that a given user will be unable to enrol in a biometric system due to insufficiently distinctive biometric sample(s) [2].

False Acceptance – The event that a biometric system incorrectly identifies an individual or fails to reject an impostor. Also referred to as a type II error, a false acceptance typically is considered the most serious of biometric security errors as it gives unauthorized users access to systems that expressly are trying to keep them out.

False Acceptance Rate (FAR) – The FAR is defined as the percentage of identification instances in which false acceptance occurs. This can be expressed as a probability. For example, if the FAR is 0.1 percent, it means that on the average, one out of every 1000 impostors attempting to breach the system will be successful. In formula [6]:

$$FAR = \frac{NFA}{NIVA}$$

Where FAR is the false acceptance rate
NFA is the number of false acceptances
$NIVA$ is the number of impostor verification attempts

False rejection – In an instance of false rejection, the system fails to recognize an authorized person and rejects that person as an impostor, also referred to as a type I error. A rejection does not necessarily indicate a flaw in the biometric system; it can be due to failure of a biometric system to capture and extract biometric comparison data, for example due to dirty equipment. These rejections however are often not regarded as 'false rejections'.

False rejection rate (FRR) - The FRR is defined as the percentage of identification instances in which false rejection occurs. This can be expressed as a probability. In formula [6]:

$$FRR = \frac{NFF}{NEVA}$$

Where *FRR* is the false rejection rate
NFR is the number of false rejections
NEVA is the number of enrolee verification attempts

The FRR normally excludes failure to acquire errors (failure of a biometric system to capture and extract biometric comparison data).

Fast Fourier Transform - In mathematics, the Fourier transform is a certain linear operator that maps functions to other functions. Loosely speaking, the Fourier transform decomposes a function into a continuous spectrum of its *frequency components*, and the inverse transform synthesizes a function from its spectrum of frequency components. The *discrete* Fourier transform (DFT), sometimes called the finite Fourier transform, is a Fourier transform widely employed in signal processing and related fields to analyze the frequencies contained in a sampled signal, to solve partial differential equations, and to perform other operations such as convolutions. The DFT can be computed efficiently in practice using a *fast* Fourier transform (FFT) algorithm [5].

High-pass filter - In digital image processing, frequency filtering is based on the Fourier Transform. The form of the filter function determines the effects of the operator. A high pass filter yields edge enhancement or edge detection in the spatial domain, because edges contain many high frequencies. Areas of rather constant graylevel consist of mainly low frequencies and are therefore suppressed

Intra-variability – Variability within an individual

Inter-variability – Variability between individuals

Logical XOR operator – Literally means logical exclusive or, and generally symbolized by XOR or EOR. It is a logical operation on two operands that results in a logical value of true if and only if exactly one of the operands has a value of *true*.

Low-pass filter - In digital image processing, frequency filtering is based on the Fourier Transform. The form of the filter function determines the effects of the operator. A low-pass filter attenuates high frequencies and retains low frequencies unchanged. The result in the spatial domain is equivalent to that of a smoothing filter; as the blocked high frequencies correspond to sharp intensity changes, *i.e.* to the fine-scale details and noise in the spatial domain image [7].

Mahalanobis distance – In statistics, the Mahalanobis distance is based on correlations between variables by which different patterns can be identified and analysed. It is a useful way of determining similarity of an unknown sample set to a known one. It differs from Euclidean distance in that it takes into account the correlations of the data set and is scale-invariant, i.e. not dependent on the scale of measurements [5].

Median Filter - The median filter is a non-linear digital filtering technique, normally used to reduce noise in an image. It is rather good at preserving useful detail in the image. Like the mean filter, the median filter considers each pixel in the image in turn and looks at its nearby neighbours to decide whether or not it is representative of its surroundings. Instead of simply replacing the pixel value with the mean of neighbouring pixel values (mean filtering), it replaces it with the median of those values [5].

Multi resolution analysis (MRA) - MRA is the design method of most of the practically relevant discrete wavelet transforms (DWT) and the justification for the algorithm of the fast wavelet transform (FWT) [5].

Morphological thresholding algorithm - Morphological thresholding adds some complexity to normal thresholding because pixels are classified with regard to their morphology or structure. Usually, the structuring element is sized 3×3 and has its origin at the center pixel. It is shifted over the image and at each pixel of the image its elements are compared with the set of the underlying pixels. If the two sets of elements match the condition defined by the set operator (e.g. if set of pixels in the structuring element is a subset of the underlying image pixels), the pixel underneath the origin of the structuring element is set to a pre-defined value (0 or 1 for binary images). A morphological operator is therefore defined by its structuring element and the applied set operator [7].

Normalization - In image processing, normalization is a (linear) process that changes the range of pixel intensity values. Applications include photographs with poor contrast due to glare, for example. Normalization is sometimes called contrast stretching [5].
In general terms, normalization is any process that makes something more normal and in this thesis it is also used in the context of normalizing the size or position of the finger on the image.

Photosensitive pin diode - A diode used in electronics that exhibits an increase in its electrical conductivity as a function of the intensity, wavelength, and modulation rate of the incident radiation [12].

Principle component analysis (PCA) –In statistics, principal components analysis is a technique for simplifying a dataset, by reducing multidimensional datasets to lower dimensions for analysis. PCA can be used for dimensionality reduction in a dataset while retaining those characteristics of the dataset that contribute most to its variance, by keeping lower-order principal components and ignoring higher-order ones. Such low-order components often contain the "most important" aspects of the data [5].

Receiver Operating Curves (ROC) – A graph showing how the false rejection rate and false acceptance rate vary according to the threshold [6].

Reflection – The change in direction of a wave front at an interface between two dissimilar media so that the wave front returns into the medium from which it originated. Reflection of light may be *specular* (that is, mirror-like) or *diffuse* (that is, not retaining the image, only the energy) depending on the nature of the interface. Diffuse reflection is also referred to as scattering [5].

Region of Interest – A term often used in image processing. In this thesis it means the required area of the hand image where the hand vein pattern for matching is obtained.

Scattering - A general physical process whereby some forms of radiation, such as light or moving particles, for example, are forced to deviate from a straight trajectory by one or more localized non-uniformities in the medium through which it passes. This also includes deviation of reflected radiation from the angle predicted by the law of reflection. Reflections that undergo scattering are often called *diffuse* reflections and unscattered reflections are called *specular* (mirror-like) reflections [5].

Segmentation – Image segmentation is the process of isolating objects in the image from the background

Skeletonization/Thinning – Skeletonization is a process for reducing foreground regions in a region while throwing binary image to a skeletal remnant that largely preserves the extent and connectivity of the original away most of the original foreground pixels [7].

Template/Reference Template - Data, which represents the biometric measurement of an enrolee, used by a biometric system for comparison against subsequently submitted biometric samples [6].

Thresholding algorithm - In image analysis thresholding is the simplest method of image segmentation. Individual pixels in a greyscale image are marked as 'object' pixels if their value is greater than some threshold value and as 'background' pixels otherwise.

Watershed transformation - The watershed transform can be classified as a region-based segmentation approach. The intuitive idea underlying this method comes from geography: it is that of a landscape or topographic relief which is flooded by water, watersheds being the divide lines of the domains of attraction of rain falling over the region. The problem of this intuitive concept is that it leaves room for various formalizations, especially in digital images, since in the discrete case there is no unique definition of the path a drop of water would follow. Many sequential algorithms have been developed to compute watershed transforms [13].

Wavelet transformation - In mathematics the wavelet transform refers to the representation of a signal in terms of a finite length or fast decaying oscillating waveform (known as the mother wavelet). This waveform is scaled and translated to match the input signal [8].

1 INTRODUCTION

Although over 6.5 billion (6.500.000.000) people inhabit this world on this moment, the intuitively contradicting 'small world problem' was already recognized in 1969 [14]. In this experiment the average path length for social networks of people in the United States was examined, and the surprising conclusion was that people in the United States are separated by about six people on average. Later this phenomenon became generally accepted, and was referred to with the term 'six degrees of separation' [5].

This experiment and the many follow-up studies and discussions show how much the world has changed into a networked society. When people still lived in small villages, or much older, in tribes, it was enough to know perhaps one hundred people to get along in 'society'. Identification was important, but easily possible in such small networks by simply 'knowing' the features of your neighbours. Nowadays, determining the identity of a person is becoming very important, but also increasingly difficult in our complex, mobile and vastly interconnected information society [15]. Especially in an era in which terrorism and identity theft are mentioned in newspapers almost daily, a fast, secure way of verifying that you are who you say you are is a hot topic. Public awareness of security threats, whether it concerns your bank account, house, your data or the whole society, has put the identification problem on a high scale.

There are two fundamentally distinct types of identification problems [16]; the first is verification (Am I who I claim I am?) and the second is recognition, or popularly referred to as identification (Who am I?). Both problems are very challenging and have different complexities. A practical approach is to reduce the problem of verification of a person's identity is to the problem of verification of a concrete entity related tot the person. These entities can be categorized into [16]:

- *Something that you have* in your possession, such as an ID or member card. Or in a more general way: everybody allowed in a building has a key that identifies this group.
- *Something that you know,* such as a password and login for a computer. Some systems combine the first and second entities, e.g. the ATM card and PIN code combination.
- *Something that you are or that you do,* which is the measurement of the physical or behavioural characteristics of a person. This is essentially what biometrics is. Examples of biometric features are the fingerprint, iris, ear, gait, keystroke dynamics, voice, signature, DNA, hand geometry, hand vein pattern, etc.

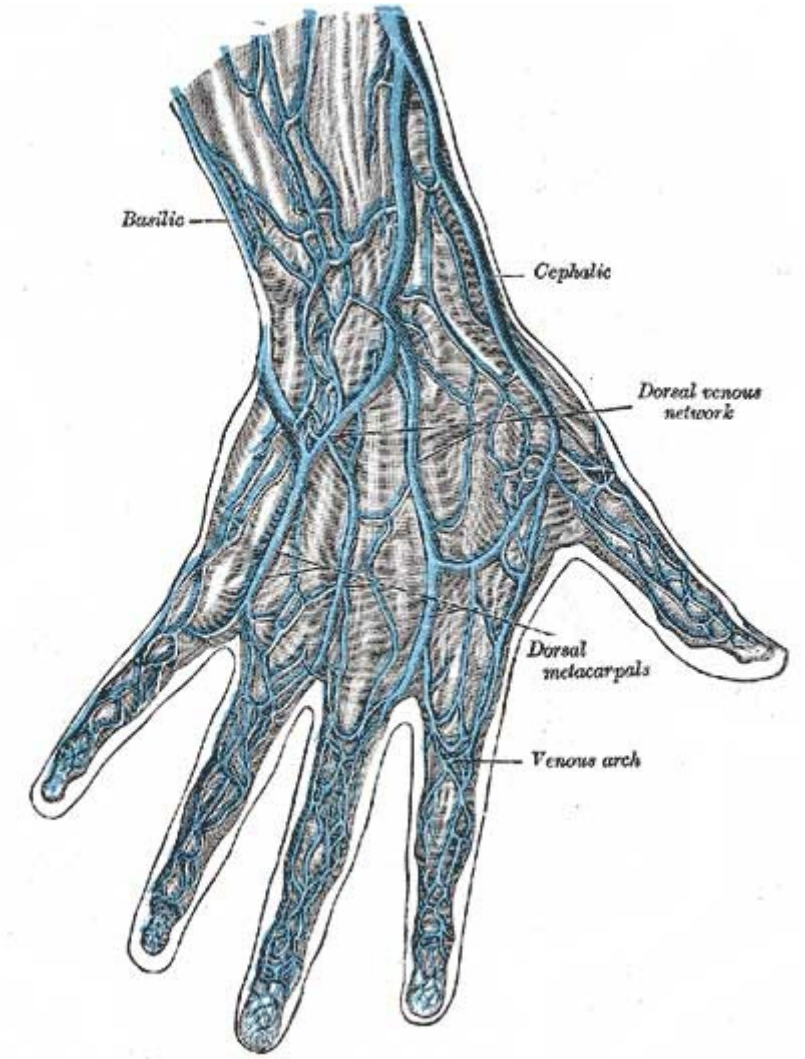


Figure 1. Drawing of the vascular network in the hand. Obtained from [17].

These three levels also incorporate an increasing level of security where the first category is the least secure, and the last one is said to reach the highest level of security [18]. Therefore, it is logical that the use of biometrics is seen as an exciting solution to many security and identification problems. Manufacturers tell beautiful stories on their websites and make high security and performance claims. However, a growing number of publications asses the risks of too much trust in biometrics [4, 11, 19-23]. A lot of drawbacks are still attached to this promising technology, and a lot of countermeasures have to be taken for the biometric identification systems to live up to their big promises. The many different biometric features that are optional for identification all have their individual pros and cons. Especially for the more established biometrics features, such as the fingerprint, the disadvantages are well-known. Many disadvantages are related to the reliability of the method, particularly in the light of impostor attacks at security systems. In fingerprint technology the main threat is the ease with which you can obtain somebody's fingerprint. People leave their fingerprints everywhere; on everything they touch. And in addition, many techniques to make artificial fingerprints with gelatine or silicon are available [4, 21], also on widely accessible internet sites, including recipes [20]. Partially to overcome these problems of leaving your biometric feature behind for anybody to copy, hand vein pattern recognition techniques are developed. The characteristics of the vascular structure in the hand or finger (see figure 1) are captured and used for identification. This relatively new biometric identification technique is thought to be a promise for the future [24-26]. However, due to its novelty not much is known about the critical issues of this biometric feature. The Netherlands Forensics Institute is involved in the evaluation of biometric identification methods, especially in legal contexts. Their interest in this new technique has resulted in this project: a literature research on the hand vein pattern recognition technique. The goal in this thesis is to asses multiple aspects of the hand vein pattern in the purpose of answering the main question: *how suitable is the hand vein pattern as a biometric feature?*

1.1 Biometrics

Biometrics is the automated use of physiological or behavioural characteristics to determine or verify identity. What qualifies a 'suitable biometric'? The answer is that any human physiological or behavioural characteristic could be a biometric feature, provided it has the following desirable properties [16, 27]:

- universality: every relevant person should have the characteristic
- uniqueness: no two persons should have the same characteristic, and each relevant person should only have one original characteristic
- permanence: the characteristic should be time-invariant
- collectability: the characteristic can be measured
- storability: the characteristic can be stored in manual or automated systems

- performance: the measurement and verification of the characteristic should be easy and not error-prone; high accuracy and robustness should be achievable; and the measurement should be precise enough to detect the smallest differences in the characteristic between individuals.

Other properties are maybe not compelled, but very important in practice:

- convenience: measuring and storing the characteristic should be fast and user-friendly
- cost: measuring and storing the characteristic should be affordable and in relation to its surplus value
- exclusivity: it should be used on its own without any further identity checks
- acceptability: relevant persons should be willing to accept the biometric system
- circumvention: the system should not be easy to fool by fraudulent users

1.2 Biometric properties hand vein pattern

The first property, universality, is quite straightforward for the hand vein pattern; every living hand possesses a vascular structure for necessary blood supply. People who are born without hands or have lost both their hands during life are excluded from this biometric identification method. The occurrence of these people is rather low, but should be taken in to account. The other properties listed above will be discussed in the three main chapters of this thesis. Each chapter assesses one of the three following sub questions, which are related to the main research question stated above:

1) How unique and time-invariant is the hand vein pattern and how can we perceive it? (Chapter 2, *Veins as a biometric feature*)
2) How does the vein pattern biometric identification technology work? (Chapter 3, *Biometric devices*)
3) How can the hand vein recognition systems defend themselves against impostor attacks? (Chapter 4, *Liveness detection*)

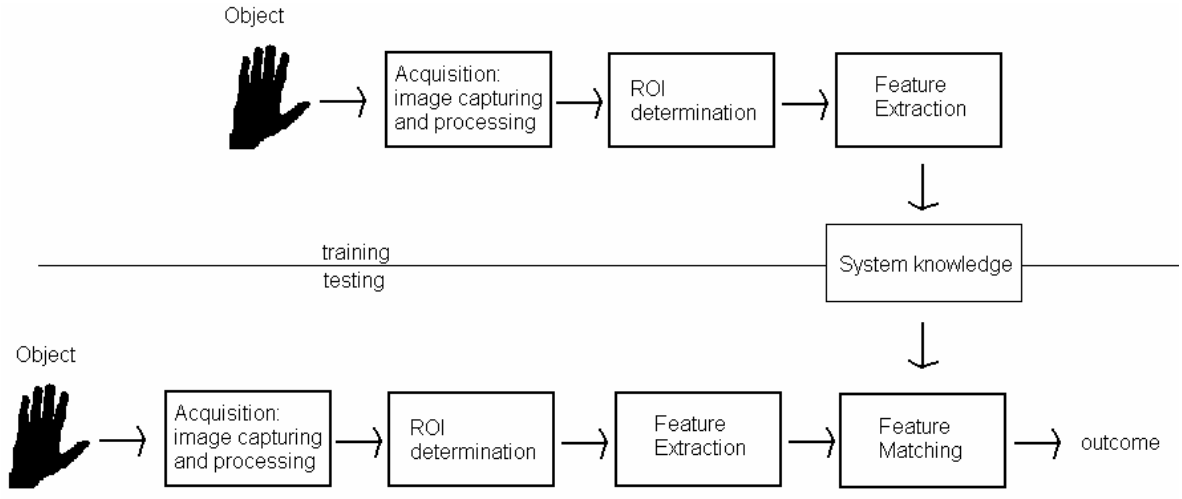


Figure 2. Architecture of a typical pattern recognition system. Adapted from [16] figure 1.17

In chapter 2 (*Veins as a biometric feature*) the properties universality, uniqueness, permanence and collectability of the hand vein pattern as a biometric feature will be discussed, in order to find the answer on the first sub question. Information on the physiological properties and development of the vascular structure in the hand is provided, as well as some physical properties of veins and blood cells that are utilized to visualize the vein pattern in a biometric application.

In chapter 3 (*Biometric devices*) the technical design of several biometric devices is described, and the properties storability, performance, convenience and costs are included in this chapter. It serves as an overview of different methods that have been used in this field. Biometric verification systems work in two modes: enrolment mode and verification mode [16]. During enrolment one or more measurements (often images) of the hand vein pattern are obtained to create a template that is stored in a database. During verification the system measures the presented vein pattern, and subsequently verifies whether the features of this vein pattern are present in the database of enrolled templates (one-to-many match). Another way is to ask the user to inform the system who he is, either with a PIN or other code. Subsequently the system will recall the claimant's template from the database and verify whether the biometric features match (one-to-one match). If no positive match occurs, the system will reject the claimant. The actual verification process consists of several processing steps: image capturing and processing, region of interest (ROI) determination, vein feature extraction and matching. The typical architecture is shown in figure 2. More detail on all these steps is given in chapter 3.

In chapter 4 (*Liveness detection*) the property circumvention is addressed. One way of fooling a biometric device is by presenting an artificial copy of the actual biometric feature to the detector. Liveness detection is the ability of the system to intercept such fake biometrics by verifying whether the presented feature is 'alive' or not. This liveness detector should be implemented in figure 2, at some stage before the outcome is given. More anti-spoofing measures are also mentioned in this chapter.

All chapters conclude with a discussion on each individual research question. Chapter 5 comprises a final discussion and conclusion regarding the main question of this thesis.

1.3 Goal

The goal of this literature thesis is to give the reader objective information on the usability of the hand vein pattern as a biometric identification feature. It is part of an evaluation programme of the Netherlands Forensic Institute on biometrics. All information is derived from literature of both scientific and commercial origin. Due to its use for security and identification purposes, biometrics and related topics have a 'secret nature' which can sometimes blur your vision, and make you believe all the beautiful promises of the biometric industry in our highly networked and demanding society. So look after your veins…

2 VEINS AS A BIOMETRIC FEATURE

One of the most important conditions of an identification system based on a biometric feature is that it is a unique and time-invariant property for every individual, and that this property can somehow be perceived by a device. Moreover, if it is unique, the differences between individuals should be big enough to be picked up by the device that captures the biometric feature. In other words, both the intra-variability of the feature compared to the inter-variability between individuals should satisfy the demands of a proper biometric feature. Therefore, if the hand vein pattern is the property upon which the identification process is based, it should comply with these conditions. In the section below, the properties of the hand vein pattern concerning uniqueness and time-invariance are discussed, followed by the optical principles on which capturing a hand vein pattern is based. Finally, several methods of vein imaging are mentioned.

2.1 Uniqueness

Many resources state that the vein pattern is a unique property of each individual, both in the retina [15, 28]or in the hand [24-26, 29, 30], but also the whole physical arrangement of blood vessels, veins and capillaries within the human body is considered to be different for each individual [31]. Scientific research on the uniqueness of veins in the hand is sparse. The mechanisms underlying the development of the vascular system that are known so far, and studies on the spatial arrangement of the final vascular network could provide more insight into the probability that no vein pattern will be the same between two individuals.

2.1.1 Vascular Development

This section is based on a review article by A. Eichmann [32]

Histological, the structure of blood vessels is rather simple. The smallest vessels of the vascular system, the capillaries, are composed solely of endothelial cells and are surrounded by a basement membrane. Larger vessels have additional layers constituting the vessel wall, which are composed of a muscular layer, an outer connective tissue layer and nerves. The endothelial cells represent the major cellular compartment of the vascular system.

The cardiovascular system is the first organ system to develop during early embryonic development. It starts with differentiation of the endothelial cells from cells of the blastula (a hollow ball of cells that an early embryo consists of) during gastrulation, the phase early in the development of animal embryos, during which the morphology of the embryo is dramatically restructured by cell migration. These cells form one of the embryonic germ layers: the mesoderm. The mesoderm will

later differentiate into more substructures, continually developing towards a determined and functioning organ system. The lateral and posterior mesoderms are found to give rise to blood cells and endothelial cells. An important discovery was that these systems expressed the vascular endothelial growth factor receptor (VEGFR2). Vascular endothelial growth factor (VEGF) and its receptor (VEGFR2) are the most critical drivers for embryonic vessel formation.

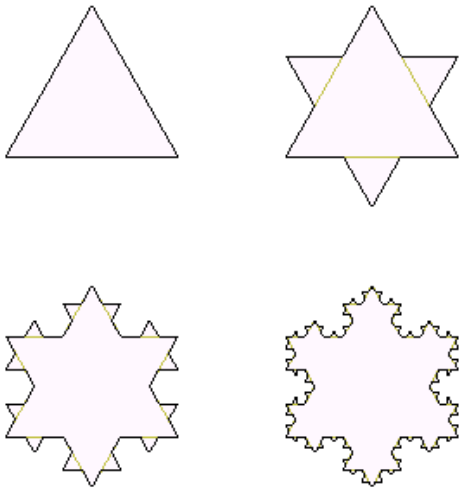


Figure 3. Example of a fractal: a Koch Snowflake. Obtained from [5].

The in situ differentiation of endothelial cells from the mesoderm and there fusion into tubes of the primary capillary system under influence of VEGF is called vasculogenesis. Vasculogenesis results in the formation of the major embryonic vessels. Next, this primary system has to be remodelled into a system with arteries and veins, to accommodate the heart and to establish the primary circulation.

For a long time it was believed that differentiation into veins and arteries was influenced by hemodynamic forces. Recently, signalling molecules have been discovered that are present in early development stages in endothelial cells, already labelling them arterial or venous. The same molecules have also been found in the nervous system, where they regulate cell fate decisions and guidance of migration of neuronal precursors as well as of developing axons. Thus speculations have been made with regard to similarities in function of these molecules in the development of the nervous and the vascular system.

Also, other recent research identified neural guidance receptors, which are expressed on arteries and veins. In the nervous system, these molecules are implicated in establishment of cell boundaries and in the guidance of developing axons. It is thus tempting to speculate that these receptors may also play a role in vessel guidance during embryonic development. Indeed, recent studies have shown that specialized cells ('tip' cells) are present at the ends of developing vessel sprouts, with extending sensors that explore their environment in much the same way as the growth cone of a developing axon. Moreover, the patterning of developing arteries in the limb skin of mouse embryos has been shown to depend on interactions with nerves.

2.1.2 Spatial arrangement

In vitro studies of cells randomly spread and cultured on a cell matrix show autonomously organized blood vessel formation, and development into a connected vascular network. The process of migration and dynamical aggregation results in a network that exhibits fractal behaviour on a small scale, and on a large scale due to coalescence of aggregates [33]. A fractal denotes a shape that is recursively constructed or self-similar, that is, a shape that appears similar at all scales of magnification and is therefore often referred to as "infinitely complex" [5]. An example in nature of an approximate fractal is the snowflake, a mathematical example of a snowflake fractal is shown in figure 3.

Whether the in vivo spatial arrangement of vascular systems also exhibits fractal behaviour is a popular basis for some of the proposed models for vascular spatial arrangement [34-36], especially the branching of the pulmonary vascular network [37-39]. If the blood vessel system can be considered having a fractal-like structure, it should be quite homogenous and containing the same branching characteristics throughout the body.

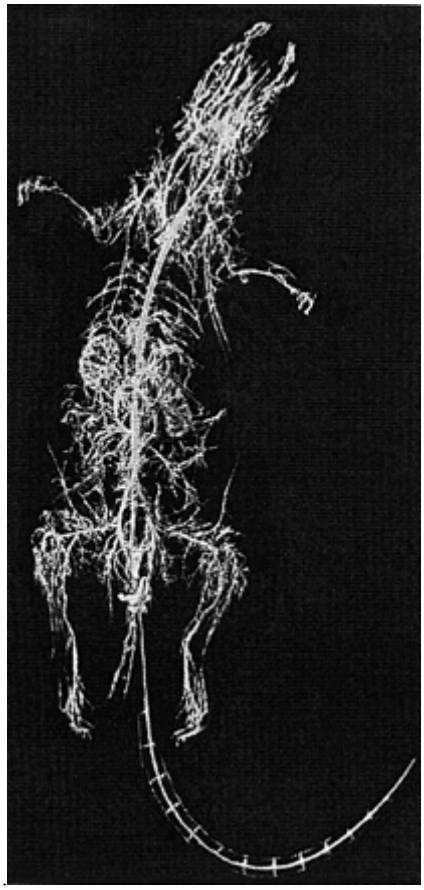


Figure 4. Reasonably complete cast of the arterial system of a rat, obtained from [40]. Branching is highly nonuniform and is dictated by reasons of anatomy, local flow requirements, and other constrains.

Several studies found quasi-fractal structures in coronary patterns, because the branching parameters where not always identical but ranged between certain values [41]. These parameters include relations between diameters of the three vessels involved at an arterial bifurcation and the angles that the two branches make with the direction of the parent vessel. A distinction should be made between the pulmonary (lung) or renal (kidney) vascular network and the remaining vascular system. The pulmonary or renal vascular networks provide a processing function, which is supported by a uniform distibuted vascular system. The remaining vascular network on the other hand, has a purely metabolic function that is primarily based on providing blood to all parts of the body, and is less uniformly distributed (see figure 4). Therefore the latter is unlikely to contain a higher degree of fractal character, than the first and a model based on branching geometry may be more appropriate for trees with a methabolic function such as the hand vein system.

A study on parametric Lindenmayer systems (L-systems) [42] that are formulated to generate branching tree structures that have fractal structures and can incorporate the physiological laws of arterial branching, did not result in a good model for the vascular tree; the model fractal tree structures did not have the variability in branching parameters observed in arterial trees. The main reason is that the source of variability in branching parameters of a real physiological vascular system is not known, but it cannot be simulated with random values for branching parameters: these values may be influenced by local anatomy, local flow requirements, and other constraints, and therefore the variability may not be purely random.

A general biological model developed by West et al. [36] predicts the essential features of transport systems and is based on three unifying principles: 1. a space-filling fractal-like branching pattern to supply the entire volume, 2. final branch of the network is a size-invariant unit and 3. the energy required to distribute resources is minimized (minimizing the total hydrodynamic resistance of the system). The last restriction will reduce homogeneous diffusion, according to an optimized model for arterial trees that incorporates homogeneous perfusion and uniform shear stress relations to represent a general principle of vascular systems [43]. Perfusion heterogeneity is also described by [44], in a model based on two parameters: branching asymmetry and the scaling properties (or fractal dimensions) of vessel resistance. Branching asymmetry is based on the tissue volume that is fed by each vessel, and the fractal relationships for the length and diameter exist as a function of scale. Data on pig hearts [45, 46] show a large degree of fluctuation of length and diameter measurements. Another study on the rat hepatic portal vein tree showed branching angles to oscillate between those predicted by two optimally principles of minimum power loss and volume, and of minimum shear stress and surface [47]. The liver shows a variation in branching morphology similar to that of other organs.

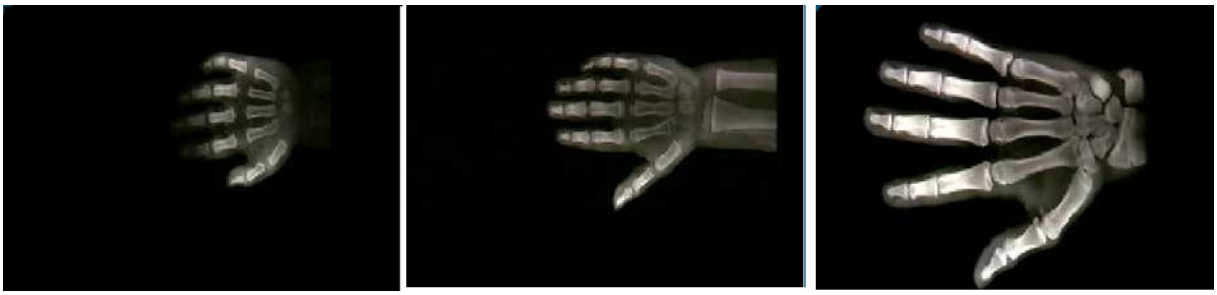


Figure 5. X-ray of human hand at age 2 (left), approximately 8 (centre), and 20 (right) years old. Obtained from [48].

2.2 Time-invariance

A biometric property used to identify individuals is only useful when the property measured at different instances in time has not changed. For example the electronic representation of a biometric property stored in a database should match the biometric property captured and processed at a later instance in time to authenticate the individual. In other words, the features of the biometric property should be time-invariant. In case of the human hand vein pattern, there are three processes that might change the pattern: natural changes in the vascular system throughout the life span of a healthy human being, natural changes in the vascular system that are associated with some diseases and changes in the vascular system induced by drugs or surgery. The section below will reflect upon these three processes and the significance for the hand vein pattern authentication method will be discussed.

2.2.3 Natural vascular changes – healthy life

The changes in the vascular system throughout a human life actually start with the development of the vascular tree in the embryonic phase, which is already discussed in section 2.1.1. In this phase the biggest changes are made as it grows from single cells into a whole network.
After birth, the sizes of veins grow as human beings grow. The length of the veins in the body will extend while your body is extending: in the first 18 to 20 years of your life [48, 49]. In our hands cartilage is being replaced by bones and they will develop into longer and thicker bones during childhood and puberty (see figure 5). During adult life, no major skeletal growth occurs. On the contrary, on a certain point in life, the balance between bone formation and resorption is reversed. This leads to a loss over a lifetime of about 15% of the total skeletal mass in men and 30% in women. The function of the vascular networks is to provide oxygen to all places in the body and therefore it will adapt to the size of the body. It will extend and shrink throughout life, with major changes before 20 and minor changes during the ageing process from 20 years on. Also there is an inevitable slow decline in strength of bones and muscles in an ageing body due to a poorer blood supply to muscles. [50].

Other factors that influence the vascular system during a normal life are the environmental temperature, physical activity and the use of alcohol. This last factor should be considered as healthy use of alcohol with no permanent pathological changes in the vessels, but rather the temporary influence of alcohol while it is in the body. In this way alcohol is a vessel dilator: in healthy persons it increases blood flow, reduces vessel resistance and therefore the blood volume increases, as is shown for the second toe [51]. Vessels also dilate if the body temperature is too high; the blood flow can increase 150 times to loose excess heat. In cold weather skin will constrict blood vessels and release heat loss [52, 53]. During physical activity the vessels will also dilate [54] to provide enough oxygen to the muscles.

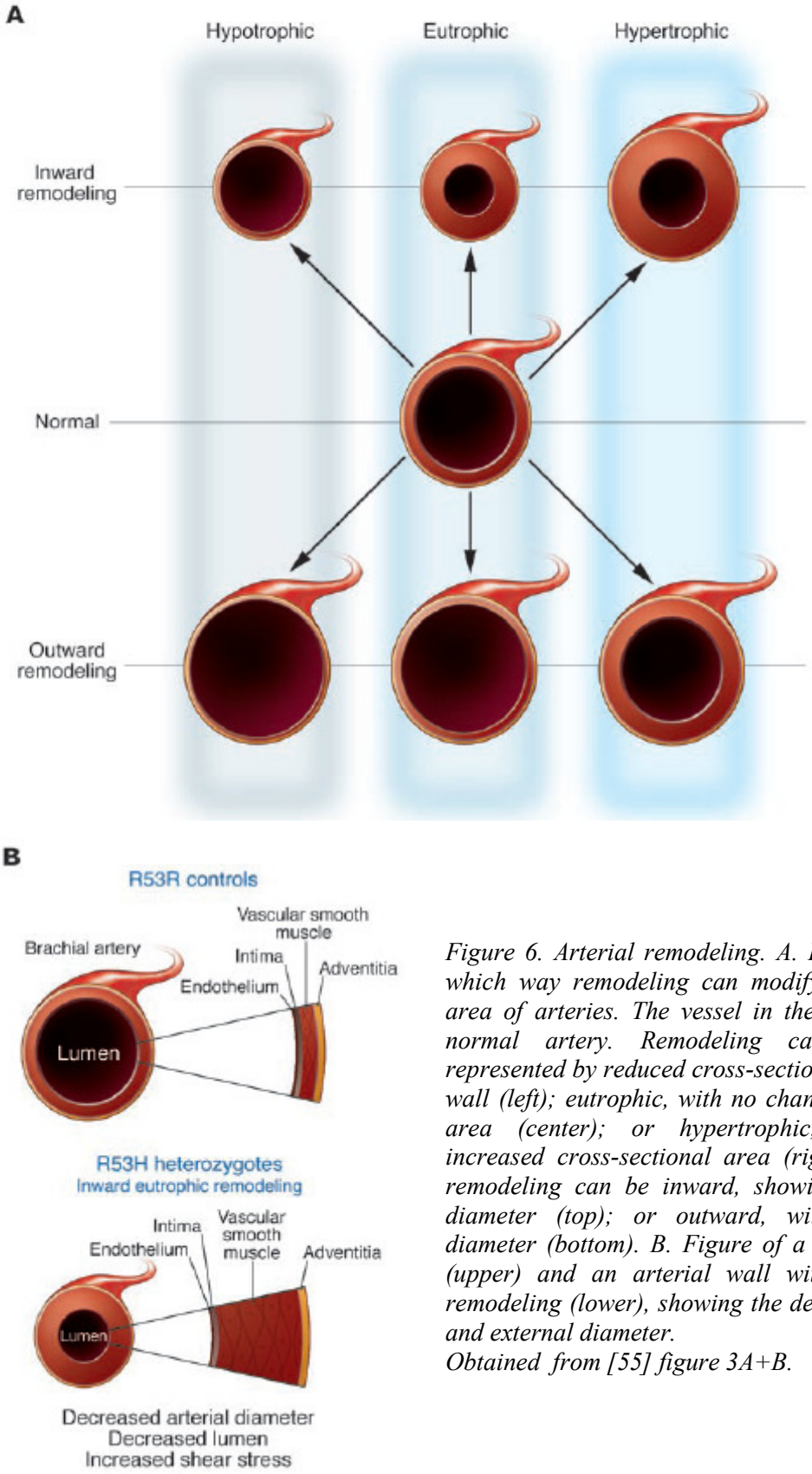


Figure 6. Arterial remodeling. A. Examples showing in which way remodeling can modify the cross-sectional area of arteries. The vessel in the center represents a normal artery. Remodeling can be hypotrophic, represented by reduced cross-sectional area of the vessel wall (left); eutrophic, with no change in cross-sectional area (center); or hypertrophic, characterized by increased cross-sectional area (right). These forms of remodeling can be inward, showing decreased lumen diameter (top); or outward, with increased lumen diameter (bottom). B. Figure of a normal arterial wall (upper) and an arterial wall with eutrophic inward remodeling (lower), showing the decrease in both lumen and external diameter.
Obtained from [55] figure 3A+B.

2.2.4 Natural vascular changes – associated with disease

The vascular system is a large and essential system in the human body. Like almost all tissue, throughout life cells of the vascular system are continually replaced by new cells, and form a dynamic structure of several layers. Due to the dynamic character of the vascular system, it is sensitive to conditions of the body that deviate from normal or healthy.

Diabetes, hypertension, atherosclerosis [56], metabolic diseases [55] or tumors [57] are deviated conditions which can remodel the vascular system. The first four examples induce an effect on the mechanical properties of the vessel wall which gives rise to hemodynamic changes. The endothelium is thought to be the main shear sensor and the cytoskeleton (the structural component in the endothelium of a vessel wall) plays in general a key role in biological responses to mechanical factors [56]. But also mechanisms that are independent of the changes in pressure, e.g. new signaling pathways and signaling molecules, can participate in the mechanisms of vascular remodeling, shown by research on hypertension [58]. The remodeling process results in thickening or thinning of the vessel wall, in both lumen and the external diameter, see figure 6.

Another process that influences the vascular system during disease is angiogenesis, a hallmark of cancer and various ischaemic and inflammatory diseases [57, 59]. 'Angiogenesis is a physiologic process which refers to the remodeling of the vascular tissue characterized by the branching out of a new blood vessel from a pre-existing vessel' [60]. It is close related to the proliferation and migration of endothelial cells (EC's). In section 2.1.1 it is said that during embryonic development the endothelial cells are particularly active, but during a normal adult life EC turnover is very low. This is due to the 'angiogenic switch' that is 'off' when the effect of pro-angiogenic molecules is balanced by that of anti-angiogenic molecules, and is 'on' when the net balance is tipped in favour of angiogenesis. This switch is triggered by various signals associated with disease [57]. It is not fully understood how, but when tumour cells begin to duplicate indiscriminately, they induce a shift in this equilibrium towards pro-angiogenic factors to promote the formation of a vascular network surrounding them. This is a clever mechanism in order to satisfy the growing need for oxygen and nutrients, which are essential for the exponential growth that is seen in tumours. Various triggers have been proposed to account for this pro-angiogenic state [57], the major ones influencing the VEGF and its receptors that target and activate the ECs.

The resulting vascular network around a tumour is structurally and functionally deviant from the normal vascular network. Tumour vasculature is highly disorganized; vessels are tortuous and dilated, with uneven diameter, excessive branching and shunts [57]. Figure 7 shows an image made with scanning electron microscopy of the luminal (inner) surface of a blood vessel in a murine mammary[i] tumour, showing various abnormalities. These vessels are around 20-50 μm wide.

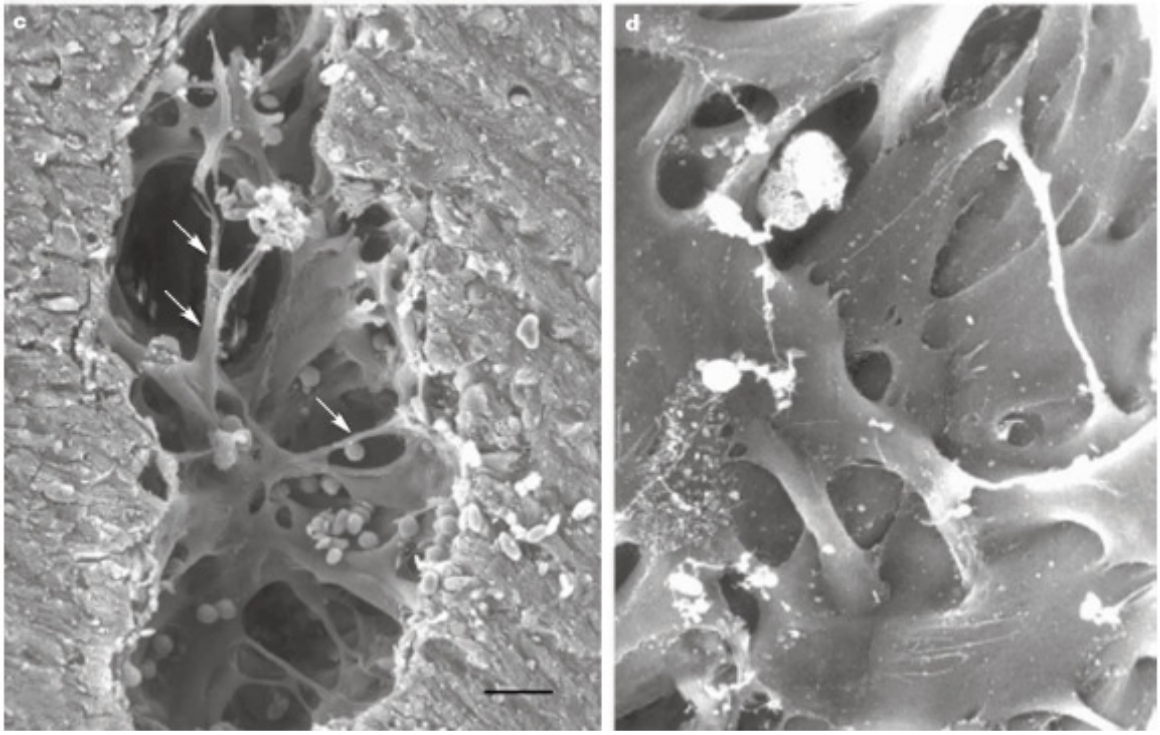


Figure 7. Scanning electron microscopy images of the luminal surface of a blood vessel in a murine mammary[i] tumour, showing the disorganized, tortuous and branched characteristics. On the left the arrows point at abnormal endothelial cells that partition the lumen. Bar length represents 15 μm. On the right a close-up of multiple intercellular openings of the order of 1-5 μm. Obtained [57], figure 1 c+d.

[i] Murine: rodent related particularly rat or mouse. Mammary: related to breast or milk glands

2.2.5 Drug based or surgical vascular changes

The ability of tumours and other diseases to induce angiogenesis or vascular remodelling inspired scientists to search for the triggers that are responsible for this growth or remodelling of vessels. Being able to activate or inhibit these triggers can result in an effective therapy against e.g. cancer. Over 60 compounds, stimulators and/or inhibitors, are currently in a clinical phase for a number of different types of cancer pathologies and heart diseases [60].

In cancer treatment anti-angiogenic therapy is a promising approach [57]. One of the targets of the angiogenic inhibitors are the active EC's, who support tumour growth, but are less prone to mutations than the tumour cells themselves. Most of the anti-angiogenic therapies inhibit the EC/VEGF mechanism somewhere in its pathway to vessel growth.

Stimulating revascularization in ischemic[ii] regions is an attractive novel therapeutic strategy and several angiogenic agents have been clinically evaluated in recent years [60]. Because VEGF and its receptors are over expressed in pathologic angiogenesis, admission of VEGF or modulators in the EC/VEGF pathway is used as therapeutic pro-angiogenesis compounds. It has already shown to promote capillary formation and organization in an in vitro assay [61], and another study on VEGF overexpression showed promotion of growth of arteries and veins and induced capillary arterialisation leading to supraphysiological blood flow in target muscles [62].

Another clinical interference in vessel formation can be in a surgical way. The most common being the so-called bypass operation. The goal of coronary bypass surgery is to increase coronary artery blood flow. Healthy arteries or veins are 'harvested' and used to channel the needed blood flow around the blocked portions of the coronary arteries. The arteries or veins are connected from the aorta to the surface of the heart, thereby 'bypassing' the narrowed or closed points in veins. The harvested arteries or veins can come from the mammary artery in the chest, the radial artery in your forearm, or the saphenous vein in your leg. [63]

Arterial bypass surgery is also performed on patients with severe ischaemia in the leg. There are three different kinds of locations for peripheral arterial bypass surgery. Aortobifemoral bypass surgery is used to bypass diseased large blood vessels in the abdomen and groin. Femoropopliteal (fem-pop) bypass surgery is used to bypass diseased blood vessels above or below the knee. Tibioperoneal bypass surgery is used to bypass diseased blood vessels in the lower leg or foot. The grafted blood vessel may be a healthy blood vessel that has been transplanted, but can also be man-made graft of synthetic material material (such as polytetrafluoroethyline [PTFE] or Dacron), which is sewn to the existing artery [64].

[ii] In medicine, ischemia (Greek ισχαιμία, isch- is restriction, hema or haema is blood) is a restriction in blood supply, generally due to factors in the blood vessels, with resultant damage or dysfunction of tissue [5 www.wikipedia.com. .

A second example of surgical vascular treatment is used for patients with varicose veins. Varicose veins are enlarged, twisted, painful superficial veins resulting from poorly functioning valves. In varicose vein therapy, the unhealthy veins (most common in the legs) can be treated by surgical removal (vein stripping) or occlusion of the vein [65].

A last example is a surgical procedure where the remodelling of veins is a secondary effect of bone lengthening. This study on the effects of lengthening of the metacarpal bone on peripheral nerves and blood vessels showed successful lengthening of the palmar[iii] nerve and palmar blood vessels. This was studied in 8 calves. During the first period the palmar nerve and blood vessels showed morphologic alterations (e.g. thinning of the vessel wall), but they recovered their normal structure almost completely 2 months after the end of the lengthening procedure [34].

2.3 Optic properties tissue and blood

2.3.1 Natural radiation

The human body radiates infrared light, with a maximal intensity of 10mW/cm^2 in the range of 3000-14000nm [66]. The amplitude of infrared energy emanating from the human body will vary in relation to the spatial arrangement of blood vessels, veins and capillaries.

The vein differs in temperature from the surrounding skin and the skin tissue containing veins possesses a temperature gradient. Together with the Stefan-Boltzmann heat radiation law, thermal images can be generated according to [67]:

$$W = \varepsilon \cdot \sigma \cdot T^4 \qquad [1]$$

where W = radiant emittance in W/cm^2

ε = emissivity, 0.98 or 0.99 for human skin

σ = Stefan-Boltzman constant $\approx 5.6705 \times 10^{-12}$ W/cm^2 K^4

T = temperature of the skin surface in K

For individuals ε is constant, σ is a constant, so the temperature T of the skin is the only variable to influence the emittance W. The emittance will be greater when measured at a point above a vessel, than at a point between two blood vessels. In this way, the blood vessel pattern can be captured with a detector sensitive for wavelengths above 3μm, and digitized into a thermal image [31]. The quantitative differences in temperature of the skin will influence W and consequently significantly affect thermal image contrast and quality.

[iii] palmar - relating to the palm of the hand or the sole of the foot

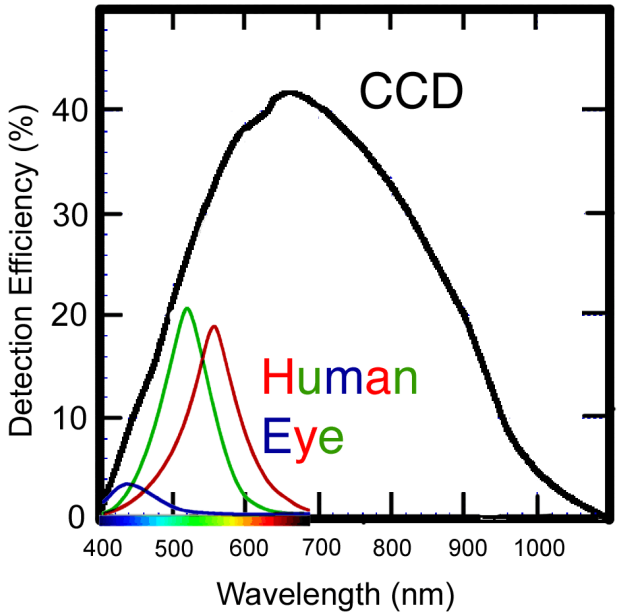
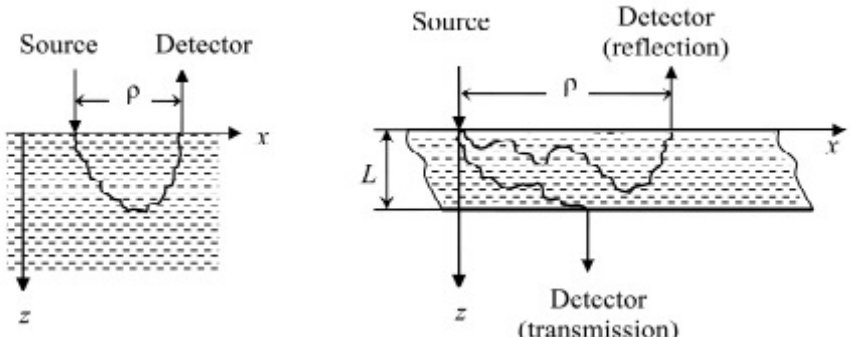


Figure 8. Light detection efficiencies of CCD compared to the three types of cone cells (red, green, blue) in the human eye. CCD is more efficient than cones, and are sensitive to infrared (invisible) light with wavelengths out to ~1100 nanometers (nm). Obtained from [68]



A. B.

Figure 9. Examples of geometric structure most often used to model the tissue. A. A semi-infinite space bounded by a flat plane. B. A slag of finite thickness and unbounded surfaces. In both A and B ρ is the distance between the light soured and the detector. Obtained from [69]

2.3.2 Reflected radiation

In commercial biometric vein recognition systems the imaging device is often the relatively cheap CCDcamera . But as can be seen in figure 8, the CCD camera has no sensitivity in the 3000-14000nm region. Within the sensitivity range of CCD, any natural radiation by the human body of near infrared (NIR) light is far too weak to be detected [54] and the human body is not a natural radiator of visible light.

Therefore, most vein imaging methods irradiate the region of interest with light, and make use of the absorption and reflection properties of human tissue and blood to capture a useful image of the subcutaneous vein pattern. Being composed of water as well as proteins and lipids, the chemical make-up of the skin influences its optical absorption properties. Water, the dominant tissue chromophore, strongly absorbs photons at wavelengths below 300 nm and above 1000 nm. In the visible part of the spectrum (400-650) absorption from haemoglobin and melanin dominates and other proteins are strongly absorbing in the violet and ultraviolet region. This leaves one region, known as the 'tissue optical window', ranging from 650 to 1100 nm (NIR region), where overall absorption is sufficiently low for light to penetrate a little distance into the skin. Moreover, in this region the major absorptive proteins are deoxy- and oxyhemoglobin, the main components of blood. This property results in more absorption of the irradiating light by the veins than the surrounding tissue, when NIR light is used. This is suitable for acquisition of a vein pattern [70].

2.3.3 Photon diffusion theory

The tissue optical properties have been modelled based upon photon diffusion theory. The epidermis (the outermost layer of skin) only accounts for 6% of scattering and can be regarded a primary absorptive medium. Therefore, a simplified model on the reflectance of blood and tissue considers the reflectance from only the scattering tissue beneath the epidermis [71]. The skin is assumed to be a semi-infinite homogeneous medium, under a uniform and diffusive illumination. Diffusion theory is the modelling of photon transport due to photon movement down concentration gradients. Diffusion theory is appropriate in medium dominated by scattering rather than absorption so that each photon undergoes many scattering events before being terminated by an absorption event. The photon has a relatively long residence time which allows the photon to engage in a random walk within the medium, see figure 9.

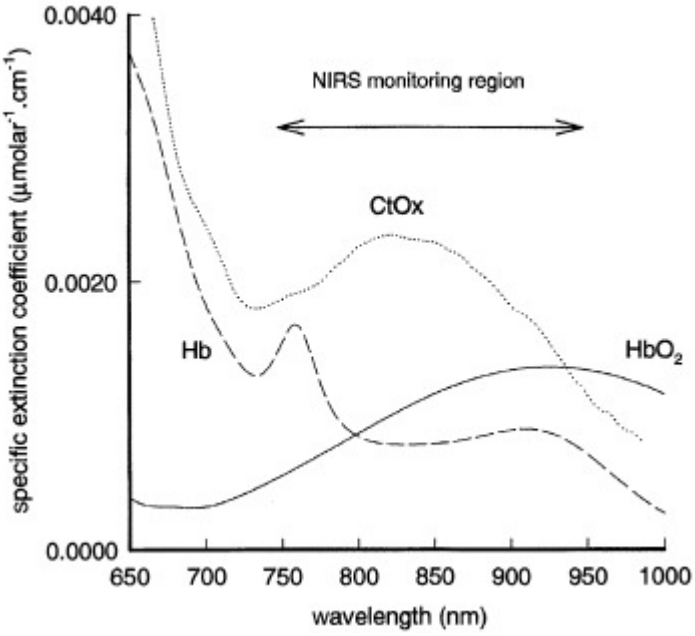
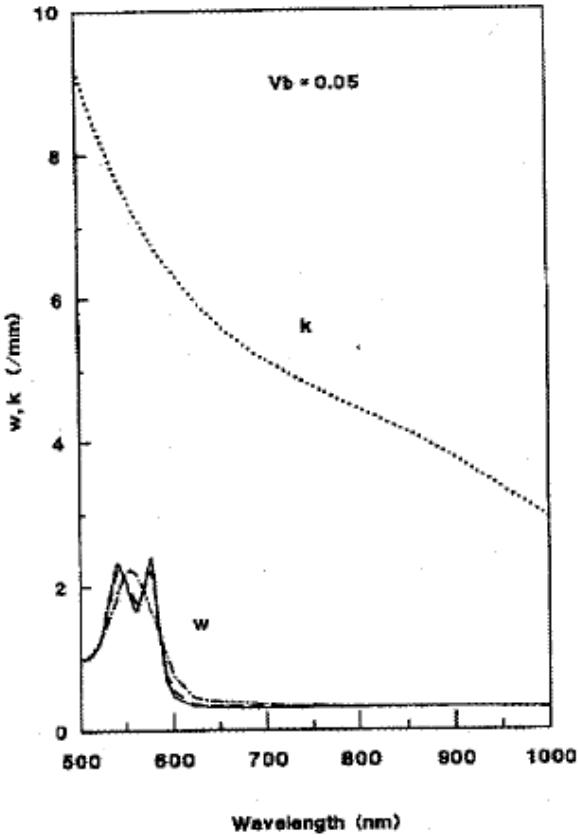


Figure 10. Specific extinction coefficient for Hb, HbO_2 and CytOx (oxidized minus reduced) in the NIR spectrum. Note that in vivo, the contribution of CytOx to overall absorption is considerably less than that of the hemoglobin because of its lower concentration. Obtained from [72], figure 1.



Curve	Solid	Dashed	Dashed-dotted
Arterial blood O_2 saturation	97%	70%	0%
Skin tissue blood O_2 saturation	80%	60%	0%

Figure 11. The scatttering and absorption coefficients (k,w) of a model of tissue containing blood. The value of k is independent of blood O_2 saturation and is a single curve; the values of w are given for three different O_2 saturation values, shown in the table below the diagram. Obtained from [71]. figure 1.

The photon diffusion depends on the absorption and scattering properties of the skin, resulting in the reflectance R, which is the ratio of the reflected light intensity to the incident light intensity: [71]

$$R = \frac{k}{k + w + \sqrt{w(w + 2k)}}$$

where k and w are the scattering and absorption coefficients of the tissue, respectively. The model is valid when k exceeds w. These coefficients depend on the fractional volume of blood per volume of tissue, according to:

$$k = k_t(1 - V_b) + k_b V_b$$
$$w = w_t(1 - V_b) + w_b V_b$$

The coefficients k_t and w_t are the scattering and absorption coefficients of tissue respectively. The absorption coefficient of bloodless dermis in vitro is almost constant [73], and the scattering coefficient of the dermis increases with decreasing wavelength [74]. The coefficients k_b and w_b are the scattering and absorption coefficients of skin tissue blood respectively, dependent on a combination of venous, capillary and arterial blood. The scattering coefficient of blood cells is constant, independent of wavelength and oxygen saturation [74]. The absorption coefficient is dependent upon both light wavelength and oxygen saturation. The latter is due to the fact that hemoglobin exists in two different forms: with and without oxygen attached (oxy-, and deoxyhemoglobin) dependent on the quantity of oxygen available [75]. Oxy-, and deoxyhemoglobin give different absorption coefficient spectra [72, 76], and as a result different extinction spectra, see figure 10. Another chromophore that exists in blood cells is shown in this figure as well; CytOx (cytochrome oxidase), an enzyme involved in oxidative metabolism and found in the cell mitochondrial membrane [72]. Relatively this enzyme does not influence the optical tissue properties much, as it exists in low concentrations.

The resulting scattering and absorption coefficients (k resp. w) of *tissue containing blood* are shown in figure 11. The wavelengths range from green (500 nm) up to near-infrared (1000 nm). The values of w and k are shown for three different oxygen saturations, shown in the table below the diagram. Normal arterial O_2-saturation values are between 95-100% [77]. The value of k is independent of blood oxygenation and is therefore a single curve for all saturation conditions.

In figure 11 it is clearly seen that the tissue optical window starts where the value of w drops; from 600-650 nm onwards, while the value of k is still a lot higher ($w << k$). This is the essential property on which infrared vein imaging is based. The main absorption components are now oxy- and deoxyhemoglobin, therefore absorption of light is mainly due to the veins.

2.4 Vein Imaging

In the former section the optical properties of tissue and blood have been discussed. Based on these properties imaging of veins is possible using infrared light. Near infrared (reflection) imaging is the common choice for the biometric vein pattern industry and thermal imaging in the mid-IR range a good second. In the medical world, there are several other non-invasive vascular imaging techniques available, like magnetic resonance angiography (MRA), ultrasound imaging or computer tomographic angiography (CT-A) [78]. These last techniques are not (yet) suitable for biometric vein imaging due to costs, addition of contrast fluid, resolution, hazardous radiation, time needed for capturing an image or other practical implications. Infrared vascular imaging was first used in a medical environment and it is reasonable to keep track of medical vascular imaging developments to improve biometric vein imaging. So far, only (near) infrared imaging has been used in biometric devices.

2.4.1 Near infrared imaging

The tissue optical window is in the NIR region of light. In this region light can penetrate relatively deep into the skin and illuminate underlying structures. Therefore infrared imaging is important in vascular imaging, and especially for biometric use. The radiation is safe and offers no significant hazard to the skin, unless it is concentrated to such high degree that it causes burning [79]. Infrared radiating light sources are relatively cheap and commercially available. Infrared sensors to obtain images are also relatively cheap and commercially available in devices such as a CCD cameras. They produce infrared images where regions with a higher intensity of emanating NIR light are brighter, whereas low intensity regions are visualized as dark regions. By making use of the reflectance and absorbance properties of tissue and blood infrared images captured after illuminating tissue with NIR light will show darker pixels for vascular regions compared to nonvascular regions. This is the basic principle for extracting a vein pattern from an infrared image.

CCD camera [5]

A relatively cheap commercially available device is the conventional charged coupled device (CCD) camera. The CCD camera is often the image capturing device in vein pattern authentication products [30, 54, 70, 80-83]. Originally, they are designed to capture visible light, but CCD cameras are also sensitive to near IR wavelengths of the electromagnetic spectrum up to approximately 1100 nm. (figure 8). A CCD is an image sensor, it consists of an integrated circuit containing an array of linked, or coupled, capacitors sensitive to light. To transfer an image into a digital signal, the image is projected by a lens on the capacitor array, causing each capacitor to accumulate an electric charge proportional to the light intensity at that location. CCDs containing grids of capacitors (pixels) are used in digital cameras, optical scanners and video cameras as light-sensing devices. A one-

dimensional array of capacitors, used in line-scan cameras, captures a single slice of the image, while a two-dimensional array, used in video and still cameras, captures the whole image or a rectangular portion of it. Once the array has been exposed to the image, a control circuit causes each capacitor to transfer its contents to its neighbor. The last capacitor in the array dumps its charge into an amplifier that converts the charge into a voltage. By repeating this process, the control circuit converts the entire contents of the array to a varying voltage, which it samples, digitizes and stores in memory. CCDs commonly respond to 70% of the incident light, which corresponds to a high a quantum efficiency of about 70%. CCD cameras are found in all sizes, up to several mega pixels. Some examples of image size used in biometric vein imaging are 640 × 480 pixels [54, 70, 83], 240 ×180 pixels [82] and 160 ×120 pixels [84]

2.4.2 Mid infrared imaging

The natural radiation of infrared light by the human body is in the mid infrared (MIR) region. The emission depends on the spatial arrangement of blood vessels, veins and capillaries. It can be captured by a thermal detector to construct an image of this vascular structure. The vascular regions emanate light with higher intensity and will show up as brighter regions in a thermal image.
Imaging devices in the MIR region are more expensive than the conventional CCD camera and are not as common in the biometric vein imaging industry. An example of a thermal camera is a microbolometer.

Microbolometer

A bolometer is a device for measuring incident electromagnetic radiation. It was invented in 1978 by the American astronomer Samual Pierpont Langley. A microbolometer is a specific type of bolometer used as a detector in thermal imaging. In general, these detectors measure the temperature rise due to infrared radiation absorption by a thermally insulated element. This infrared absorber is embedded in closed contact with a thermometer element, for example vanadium oxide. When vanadium oxide senses infrared induced temperature rise, it changes resistance. The underlying grid of silicon provides electrical contact between a Complimentary Metal Oxide Semiconductor (CMOS) chip and the vanadium oxide. The CMOS circuit is used to digitize the incoming signal. The resistance change is measured and the charge for every single pixel is processed into a voltage that can be used for the graphical representation of the infrared image. The microbolometer is sensitive in much longer wavelength regions than the CCD camera, namely in the long wavelength infrared region (5 – 13.5 μm) [85].

The microbolometer grid is commonly found in two sizes, a 320×240 array or less expensive 160×120 array. Both arrays provide the same resolution with the larger array providing a wider field of view. The sensitivity increases with higher thermal coefficient of resistance, while the speed is limited by the thermal heat capacity divided by the thermal conductance [5, 86].

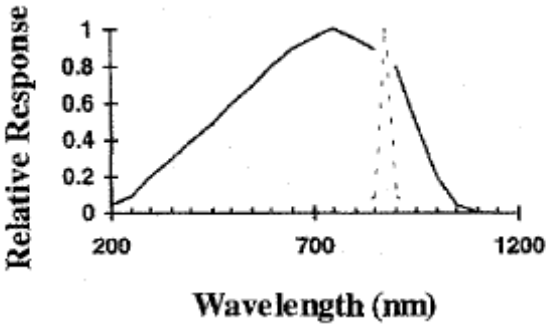


Figure 12. Emission curve of a typical 880±25 nm LED, superimposed on the response curve for a typical silicon-based CCD sensor. Obtained from [54] figure 3a.

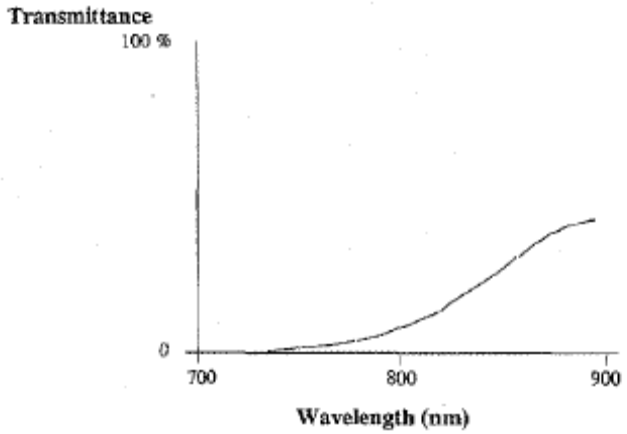


Figure 13. Transmission curve for a 900nm high-pass filter. Obtained from[54], figure 4.

2.4.3 Optical filters

In most devices that capture a vein image an optical filter is introduced, which only permits the infrared light to enter the imaging device (often CCD). This can be either a band-pass filter or a long-pass filter, which will attenuate wavelengths outside the band respectively shorter wavelengths and transmit band wavelengths respectively longer wavelengths over the active range of the target spectrum. Depending on the quality of the filter unwanted (visible) radiation is substantially reduced, thereby enhancing the visibility of the veins and the quality of the vein image [87]. An example of the use of filter to enhance a vein image is shown by figures 12 and 13. Figure 12 shows the emission curve of a typical 880nm IR-LED, superimposed on the response curve for a typical CCD sensor. In a normal vein imaging environment there will be a lot of contaminating light from wavelengths below the LED emission curve on the CCD sensor. Therefore a high-pass filter is used to filter out the lower wavelengths. The filter used is shown in figure 13, and is designed to transmit wavelengths greater than 900nm. As can be seen, the filter will also reduce the wanted wavelengths from the LED and is therefore not ideal, though it is used in a biometric vein imaging study. This shows the need for good filters and light sources, which is probably restricted due to costs.

2.5 Discussion

This first section on veins addresses the question whether the vein pattern is a suitable biometric feature or not. To come closer to the answer, the uniqueness, time-invariance, optical properties and imaging methods are described. A discussion on these subjects will follow below.

2.5.1 Uniqueness

The development of the vascular structure in the human body starts very early in embryonic stages of life. It is believed that hemodynamic forces as well as signalling molecules are responsible for the differentiation into veins and arteries [32]. These signalling molecules share similarities with molecules responsible for the development of the nervous system. Specialized cells are present at the ends of growing vessels that sense the environment and 'guide' the vessel through the body.

The process of arranging the vascular system is therefore not totally random: the discovery of 'guiding' molecules suggests some sort of organized growing. The main goal of the vascular network is to provide means for transporting oxygen and waste products from and to everywhere in the body. Regarding the hand, its broad features are quite similar in almost every human being: five fingers on specific spots around a square-like centre. So for each hand the vascular system has to provide blood to all five fingers and the vessels are guided to these peripheries in the body. Therefore there might be some sort of optimal vessel structure to provide blood to five fingers and this may reduce the uniqueness of each hand vein pattern.

In addition, hemodynamic forces are thought to influence vascular arrangement due to the body's tendency to minimize pumping energy. Several processes have been identified in relation to vascular growth. They provide a mechanism of efficiently generating complex blood transport systems from limited genetic information. This suggests that hemodynamic factors can instruct embryonic vascular remodelling toward optimality [88].

The human vascular network will be as optimal as possible, due to hemodynamic forces and signalling molecules. Optimality is not an uncommon goal of natural processes. Nevertheless for individuals an optimal vascular network will depend on individual features, and is probably not the same for each human. Moreover, within an optimal structure, there might still be room for variance and random growth. Studying the finished vascular spatial arrangements gives insight into this variation amongst individuals.

Factal-like models as well as models based on branching geometry have been put forward. Fractal-like structures are found in vascular networks in organs such as the lungs or the kidneys [35-39]. For peripheral vasculature, models based on branching geometry are found more often in literature [42, 44]. The final goal of the system is to supply blood to the whole human body in an energy efficient way. Branching of vessels depends on the tissue volume that is fed by each vessel, the length/diameter relation, local anatomy, and several other (unknown) constraints. Due to high variety

in branching parameters found in vivo, for which the origin is unknown, no model has fully simulated the vascular system, although it is known that it cannot be simulated with random variables [42].

It can thus be said that the inter-variability of individual vascular structures is high, although they will all be influenced by similar factors and satisfy on the aim of optimality. Reliable models of the vascular system do not exist and specific data on the hand vascular spatial arrangement has not been found in literature. So far, no resource has reported the existence of similar hand vein patterns, not in the right and left hand of one person [29], not in fingers of the same hand [24], and not between identical twins [28], although these studies are not in-depth.

2.5.2 Time invariance

The only variation in vascular structure that is reported by the biometric industry is the variation due to growth [54, 67]. During life the human skeleton grows in the first phases and shrinks in the last phases. The vascular networks function is to provide oxygen to all places in the body, and therefore adapts to the size of the body. It will extend and evolve throughout life, with major changes before 20 and minor changes during the ageing process from 20 years on. Other natural vascular changes are due to weather conditions, physical activity and alcohol intake.

But in pathological conditions vascular changes can also occur. Vascular remodelling under hypertension results in thickening or thinning of the vessel wall, in both lumen and external diameter. Formation of new vessels occurs during angiogenic processes associated with tumour growth. This can lead to a whole new network of vessels around a tumour. The influence of both processes on the hand veins is hard to estimate. Remodelling under influence of changed hemodynamic forces (due to food habits, smoking, and other vascular diseases) can happen in peripheral veins, such as the hand. This will merely result in changed diameters of the veins and not in a changed structure. The subcutaneous area is not a common site for human tumours [57], and bone tumors and soft tissue tumors of the hand and upper limb are uncommon [89]. Nevertheless, several cases are known of tumours in the hand area. The vessels formed due to tumour angiogenetic over-expression of VEGF are leaky and tortuous, in combination with other compounds they might become less leaky, and the diameter of the resulting vessels is not uniform [57].

There are several methods mentioned where man-made changes in vascular structures occur: anti-angiogenic cancer treatment [57], angiogenic treatments to promote the growth of arteries in ischemic regions [60, 62], by-pass surgery, varicose vein stripping and skeletal remodelling with indirect consequences for vascular remodelling [34]. Because of the major role of angiogenesis in several pathologies of significant medical as well as social impact, there is great interest in the possibility of modulating this mechanism pharmacologically. According to the angiogenesis foundation “at least 184 and 310 million patients in the western nations can benefit, respectively, from anti-angiogenic and proangiogenic therapy. Currently, more than 200 biotech companies, as well as large pharmaceutical companies have programs aimed at the development of new pharmaceuticals

which act on the angiogenic process and it has been estimated that so far the research and development of angiogenesis-based molecules is one of the most well-financed field of medical research" [60]. In the future these therapies are likely to improve significantly. Because it is not possible to 'program' angiogenesis to specific structures, (anti)angiogenic therapies cannot exactly copy someone's vein pattern, they can possibly change it. And although bypass operations don't occur in the hand, surgically it is possible to rearrange veins [90, 91], and maybe in the future in any required position.

2.5.3 Optical properties and vein imaging

The quality of vein images using natural emanating mid-IR-light depends highly on the quality of the thermal cameras (which are also rather expensive) and of the contrast in temperature between different tissues and veins of the hand. This is a problem, for example in the case of a thick layer of subcutaneous fat on the hand [67] or in an outside setting in extreme environmental conditions [1]. The advantage is that thermal images can be made even in the total absence of light, so that the method is not constrained by lighting conditions in contrast to NIR-vein imaging [67].

On the other hand, the distinct absorption and scattering coefficient of tissue and blood modelled with photon diffusion theory make it possible to image veins using information from reflected light. The coefficients k and w are dependent on wavelength. In near-infrared light, the absorption coefficient is very small while the scattering coefficient is still large. The weak absorption of NIR radiation means that NIR light can traverse a greater distance in tissue before it is completely attenuated by tissue absorption.

The thickness of the epidermis (the outermost layer of the skin) including the stratum corneum ('the horny layer') is 10-150 μm. The dermis lying beneath the epidermis consists of connective tissue and contains blood vessels of different sizes, sweat glands, sebaceous glands and hair follicles. The thickness of the dermal layer is 1-4 mm [71].

To visualize the veins, the light must illuminate the subcutaneous region. Statements on penetrations depths differ between literatures. Depths of several centimetres can be sampled in tissue using NIR light [92], while other reports state that 'the light may go through dermis (1-4 mm) and reach into subcutaneous tissue for the longer wavelengths (770 – 1000 nm)'[71]. In [72] is mentioned that 'NIR light to be detected across many centimetres of tissue' while [74] states that the light within the optical window 'allows light to penetrate from a few hundreds of micrometers to a few millimeters into the skin', wherein '904 nm wavelength is particularly interesting, because the optical penetration in the skin close to this wavelength is the deepest'. Others [79] report that 'within the 650-1000 nm window, it is possible with sensitive instrumentation to detect light which has traversed up to 8 cm. of tissue'.

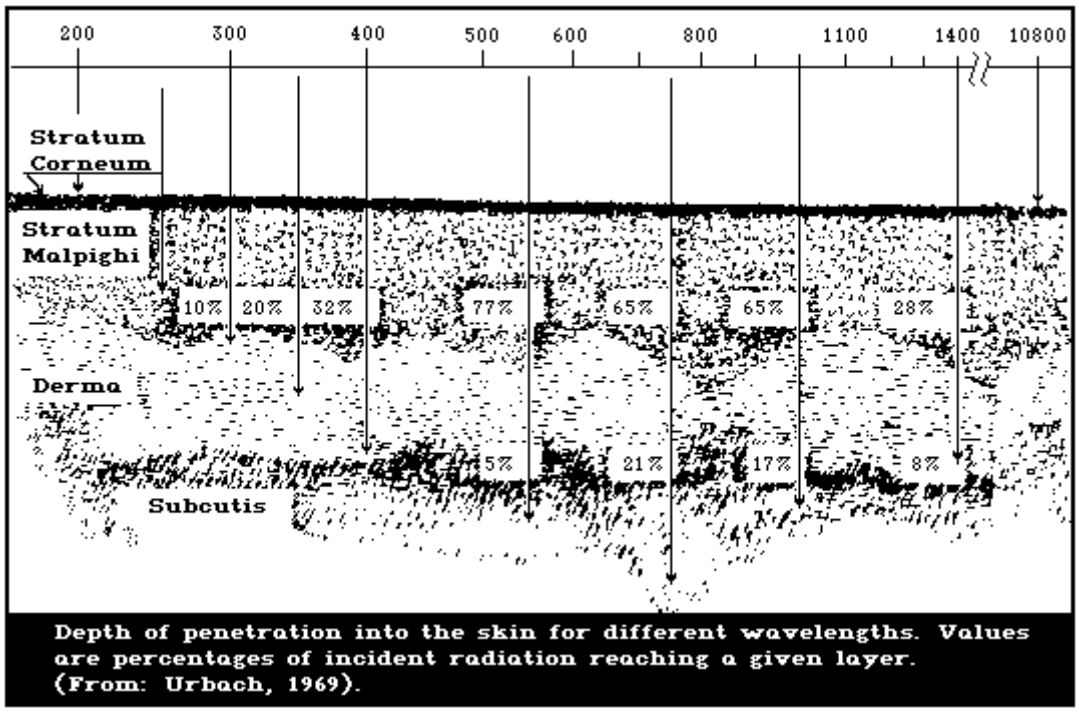


Figure 14. The depth of penetration of the optical radiation into the skin. Obtained from [93]

Figure 14 shows the results of another study on penetration into the skin for different wavelengths ranging from 200nm (near UV) to 10800nm (far infrared). Other factors influencing the penetration depth (which might be responsible for the non consensus in literature) are blood oxygenation and blood volume.

Absorption and scattering properties of tissue containing blood are as said dependent on mean blood fractional volume. A higher mean blood fractional volume will cause more absorption of the incident light, and vice versa. Variation in mean blood fractional volume *within* body parts occurs with arterial blood pulsation and with random fluctuations (i.e., physiological noise) [71]. Variation in mean blood fractional volume *between* different body parts also exists. The blood fractional volumes are expected to be in decreasing order starting from finger tip (highest), cheek, palm, forearm, and anterior surface of the lower leg (lowest) [71].

The main components responsible for tissue absorption in the NIR region are deoxy- and oxyhemoglobin. Therefore, veins will absorb more light than the surrounding tissue. The absorption coefficient *w* is also dependent on blood oxygen saturation (see figure 10 and 11 above). This property is the basis for measurements of non-invasive blood oxygen saturation in patients [5]. In case of vein pattern extraction it is important to be aware of this property, because absorption and scattering of the NIR light will depend on the exact wavelength used for imaging. At some wavelengths arteries containing mainly oxyhemoglobin will absorb more radiation than veins containing mainly deoxyhemoglobin. The same pattern captured at a lower wavelength were the oxyhemoglobin absorbs less than deoxyhemoglobin will show the same veins and arteries but with different relative intensities. At one wavelength, called the isobestic wavelength, the absorption and extinction coefficient for oxy- and deoxyhemoglobin are exactly the same. This is at 805 nm (see figure 10).

The penetration into the skin due to a high scattering coefficient together with a lower absorption coefficient not only introduces an unknown light loss, but also results in a non-linear relationship between absorption changes and the resulting attenuation changes. The consequence of a high scattering coefficient is that the light entering the tissues rapidly becomes a diffuse photon density which then propagates through the tissue [72]. The deep penetration of NIR light into tissue therefore has the advantage to illuminate subcutaneous veins and visualize them due to their distinct absorption properties, but it has the disadvantage that the scattered photons change directions along a long way back to the detector which makes the image slightly blurred.

The uniqueness, time-invariance and optical properties of the hand vein pattern that have just been discussed will have implications on the validity of a hand vein pattern as a biometric feature, but this also depends on the techniques available. The topics of the next section are the techniques that are used in commercial and scientific exploration of biometric hand vein pattern verification methods.

3 BIOMETRIC DEVICES

The biometric industry has a commercial basis and a built-in mysterious nature due to it's relation to secure systems and identification related privacy issues. Therefore, it is sometimes hard to find reliable literature or information about the industry. For clarity, literature found on the techniques that are used for biometric identification based on the hand vein pattern is divided in two parts: 1. commercial available information or descriptive literature like patents and 2. scientific literature based on research. The first includes websites, newspaper articles, company flyers and patents, and the second includes literature found in books or journals. When possible, in the commercial section some information on the company is also given. In both sections information regarding the devices is subdivided in five steps: image capturing and processing, ROI determination, vein feature extraction and matching. The scientific section also includes information on reliability. The two literature parts will separately be described below.

There are four different regions in use where devices capture the hand vein pattern: the veins in the back of the hand, the veins in the palm of the hand, the veins in the finger and, for completeness, the veins in the wrist are also included in this thesis on hand vein pattern recognition. All four will sequentially be described below.

3.1 Commercial literature

3.1.1 Veins in back of the hand

Luminetx

The company Luminetx (Memphis, Tennessee) states to be the first to patent the technology to locate subcutaneous veins using infrared light. This invention was originally utilized for medical purposes: the VeinViewer™ Imaging System. In response to other companies, the invention is patented and utilized for biometric purposes within Snowflake Technologies, a subsidiary of Luminetx Corporation. The company site reports a lot publicity (references; news articles), but provides sparse information on the technology [94].

The utilized patent was invented by Clayden [87] and assigned by British Thechnology Group Ltd. A short description of the patent is given below.

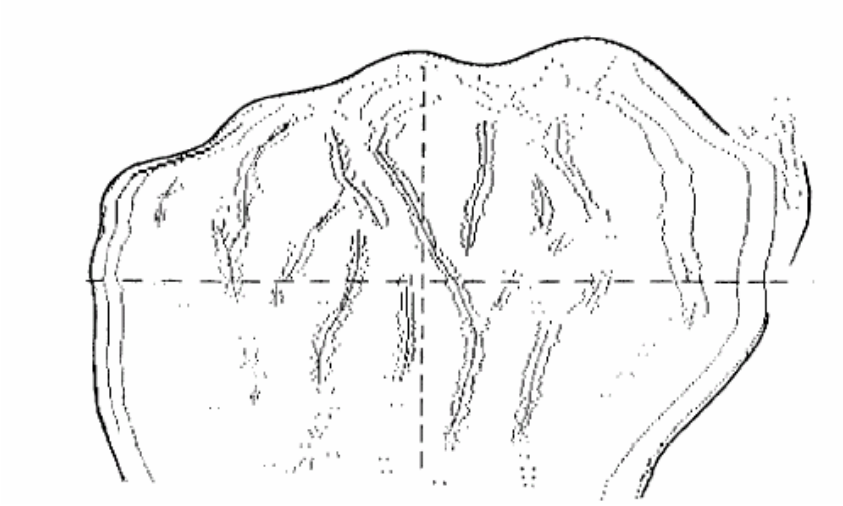


Figure 15. Pattern of vectors imposed on the veins of the captured vein image. Obtained from [87], figure 6.

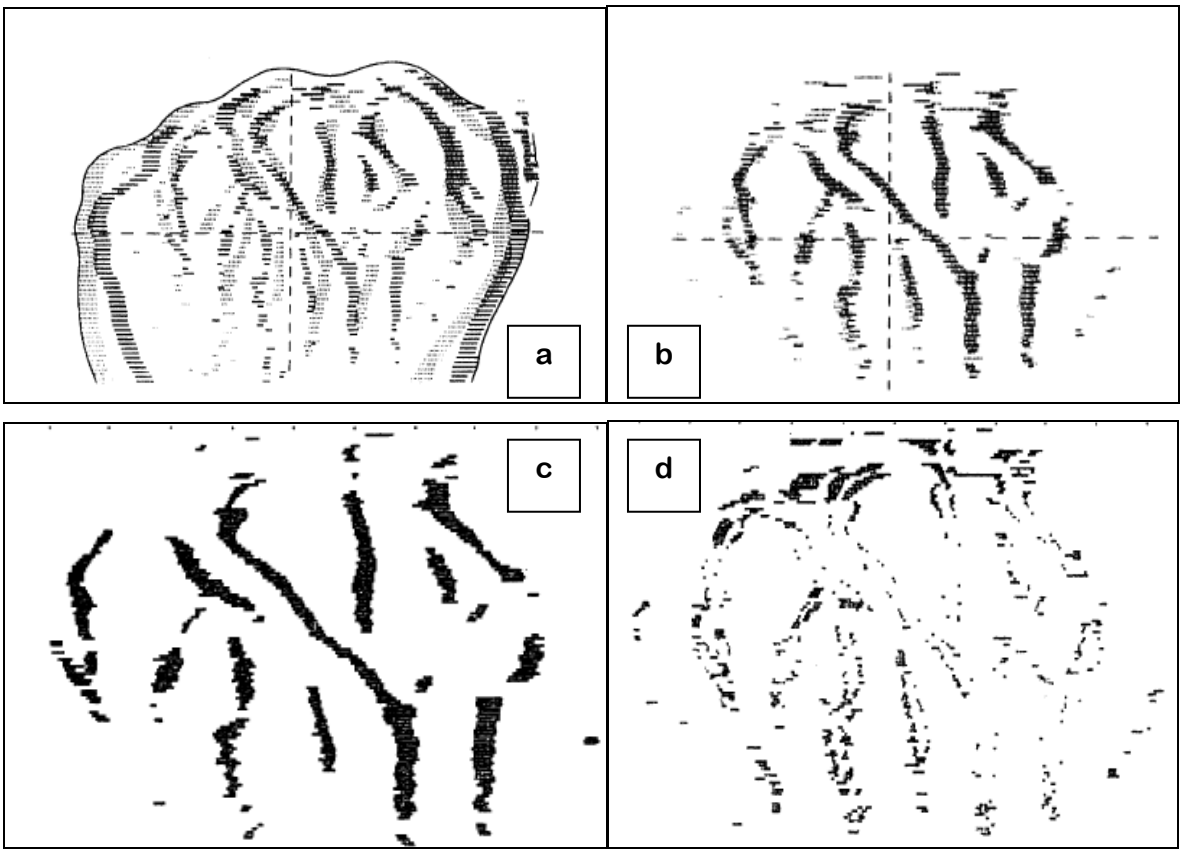


Figure 16. Matching of vein patterns. a. Image of two superimposed vein patterns b. The same image after alignment of the vein patterns. c. Matched portions of the two superimposed patterns d. Mismatched portions of the two superimposed patterns. Obtained from [87], figure 7, 8, 9 and 10.

US patent 5787185 'Biometric identification of individuals by use of subcutaneous vein patterns' - 1998

Inventor: Clayden, David Oswald

Assignee: British Technology Group Ltd.

"This invention relates to the biometric identification of individuals and, in particular, to methods and apparatus for detecting the locations of subcutaneous blood vessels and for encoding such locations for storage on identity cards. It finds particular application in the verification of identity in transactions involving such cards."

The apparatus consists of a hand grip plus a side stop to position the hand, four laterally incandescent lamps which provide an IR-rich spectrum, and a video camera.

Image capturing – The video camera positioned directly above the hand produces a raster scan image of the back of the hand. A band-pass filter extracts an IR image and reduces visible radiation, thereby enhancing the visibility of the veins

Image processing - The raw image from the video camera suffers from poor contrast and varying brightness. First weighing convolution is performed on the raw image captured from the video camera: for each of six points in a line transverse to the axis of the hand, +20 and –20 pixels in width are incorporated in the weighted convolution. The effect is to produce a blood vessel pattern with an enhancement of the longitudinal blood vessels at the expense of the transverse ones. The longitudinal blood vessels have shown to be sufficient for adequate identification. Next, a threshold process produces a black and white pattern.

Vein feature extraction and matching – This method uses a method for characterisation of the captured image based on series of vectors: series of small straight lines approximating to the centre line of each blood vessel. The vectors are used for: 1. Measure misalignment of one image relative to another 2. To obtain a score for the probability that the two compared images are of the same blood vessel pattern 3. To provide compressed data description that can be used as a reference template. Figure 15 shows a pattern of vectors imposed on the image of the extracted hand vein pattern.

Comparison between the two vein patterns can be based on several methods:
1. A logical XOR operator gives an image of the non-coinciding parts of the vein pattern. The image containing the coinciding part of the pattern is divided by the area of the non-coinciding plus the coinciding part of the patterns. The result gives a similarity value, which is compared to a predetermined threshold value. The images after superimposing two patterns and extracting similar features are shown in figure 16.

2. A second variation involves measuring the total length of vein centre-line which falls within a pre-determined tolerance of the centre-line of the other image.

3.. By using a compressed template and a test pattern, after alignment a score can be calculated by counting the number of vector ends (or vector centres) which fall within (or close to) the outline of the test pattern. The ratio of these two values will give a score similar to that of method 1.

4. Variation 4 involves using a compressed template and the centre-lines of a test pattern. The test is set by the length of centre-line which falls within a predetermined tolerance of the vectors of the template after alignment.
5. A fifth method uses two sets of vectors, a test pattern and a corresponding pattern derived from measurements on an individual, and accesses the misalignment of the vector ends of one pattern and the vectors of the other pattern.

TechSphere, BK systems or Nextern

In the introduction of the website of TechSphere (Seoul, Korea) the following information can be found: "TechSphere specializes in Hand Vascular Pattern Person Identification Technology, the next-generation biometric technology, which provides ultimate system "usability" of 99.98% (the percentage of unspecified adult population that is the capable of using a system)." Lack of system usability is said to be the major technical obstacle preventing market dissemination of biometric technology. Furthermore, they state that their developed product for hand vascular pattern person identification (VP-II™) is usable in harsh environments and has got a high level of security (FAR 0.0001%, FRR 0.1%) [95].

Technical specifications of the VP-II™ found on the site are limited. The technology originated from a conventional vein pattern recognition system. It's based on extracting a hand vascular pattern with an infrared optical sensor system and verifying the pattern with special recognition algorithm [95].

The President of TechSphere is H.S.Choi. An US patent by Choi [30] on an 'Apparatus for identifying individuals through their subcutaneous vein patterns and integrated system using said apparatus and method' is assigned by BK systems. The site associated with BK systems, 'http://www.soluniverse.com.hk/bksystem.htm' obtained from 'Study on biometrics in US Patent Literature'(Geradts 2002) [96], is not available anymore. The company Nextern (Seoul, Korea), founded in 1996, is now making use of this patent and commercializes the BKsystems. The information available on the company site is also very limited [97]. In the patent more specific product information can be found [30].

US patent 6301375 'Apparatus for identifying individuals through their subcutaneous vein patterns and integrated system using said apparatus and method'- 2001

Inventor: H.S. Choi

Assignee: 'BK systems'

The invention provides a new and effective apparatus and method for verifying the identification of an individual through his vein structure in the back of the hand. It provides a method to obtain discriminative features as well as efficient image processing. For usability, the invention wants to provide an integrated verification system, by storing features of individuals in databases, which are localized depending on each individual's access authority (local or global).

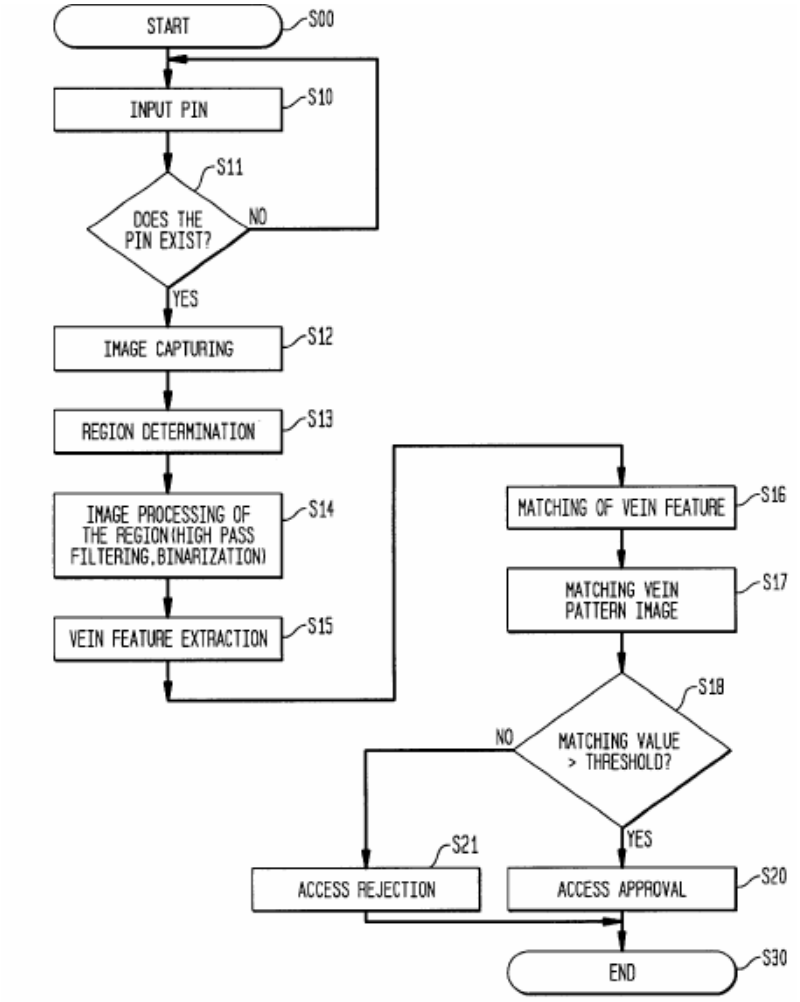
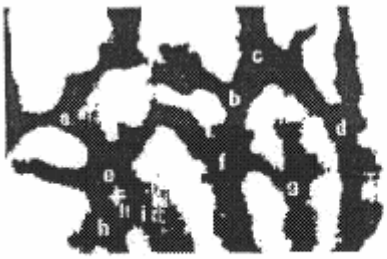


Figure 17. Flow chart of an algorithm for verifying the identity of an individual. Obtained from[30] figure 2.



sub-image of back of hand with corresponding vein features in table

THE NUMBER OF BRANCHING POINTS : 9		
BRANCHING POINT	THE NUMBER OF CONNECTED BRANCHES	THE CONNECTED BRANCHING POINTS
a	3	e
b	3	c,f
c	4	b,d
:	:	:
i	3	e,h

Figure 18. Sub-image and features of hand vein pattern. Obtained from [30], figure 5a and 6.

Figure 17 represents a flow chart of an algorithm for verifying the identity of an individual in this apparatus. An existing PIN starts the image capturing process of a hand positioned in the cavity of the apparatus. The apparatus contains an enclosure with a NIR light source and a CCD camera attached to it. There exist two different models of this invention: 1. including a hand grip bar for appropriate positioning of the hand, and 2. with a configured interior and contact sensor switches to check whether or not the fist is located at a predetermined position without using the hand grip bar.

Image capturing - A near-IR light source radiates from the top of the cavity down on the hand, after passing a near-IR light filter. The portion of the near-IR light that reflects from the hand upwards passes the same filter and is detected by a CCD-camera placed also at the upper side of the cavity. This video signal is fed to a frame grabber who obtains a still image of the back of the hand.

Region determination and processing - Next step is binarization of the still image to obtain binary (black-and-white) image data. The largest rectangular area of white-pixel area (which is the hand) is determined as the region of interest. This region of the original still image is high-pass filtered to find regions of contrast, and this sub-image is binarized by histogram-based binarization. Then, the image is median filtered to remove irrelevant pixels around the vein patterns in the binary image, resulting in an image containing only a vein pattern.

Vein feature extraction - The microprocessor computes the branching characteristics of the veins by thinning the vein pattern. These characteristics are: branching points, number of branches at each branching point, and connection relationship between branching points. Figure 18 shows the sub-image and the extracted vein feature table.

Matching of vein feature - Two or more branching points from the captured vein image are chosen as reference points. The reference vein features corresponding to the PIN are recalled from a database. The branching points in both of the vein patterns corresponding to the chosen reference points are superimposed in view of xy-coordinate values. After correction for different orientation of the two images, a correlation of the pixel value is calculated between both vein patterns. If the matching indices of both branching points are greater than a predetermined threshold, the identity of the individual corresponding to the PIN is verified. Access is granted.

This system can integrate over thousands of persons, by using global and local storage of images. It can be provided by reasonably low cost hardware because the algorithm is simple and the computing load to the microprocessor is low.

3.1.2 Veins in palm of hand

Fujitsu

The leading company in the market of palm vein based identification systems is Fujitsu, who has launched their Contactless Palm Vein Pattern Biometric Authentication System in March 2003 [25]. No patent on this technology is found by the author. On the website and in press reports some information on the product is found. A NIR light beam, generated by the sensor, is used to scan the hand [98]. The deoxidized hemoglobin in the PalmSecure™ absorbs this light, thereby reducing the reflection rate and causing the veins to appear as a black pattern, see figure 19. This vein pattern is then verified against a pre-registered pattern to authenticate the individual.

Furthermore, on their website they state that each individual's palm vein pattern is unique, even in the case of identical twins, and have a wealth of differentiating features. This system has already been implemented in real life situations, such as universities and hospitals for room and data access, and by several banks for account and ATM security.[99-102].

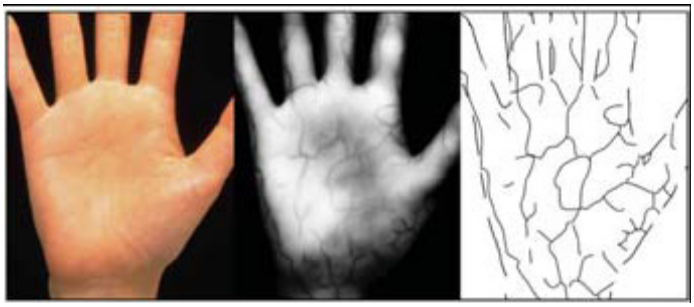


Figure 19. NIR image (centre) and vein features (right) captured from the palm of a hand (left). Obtained from [103]

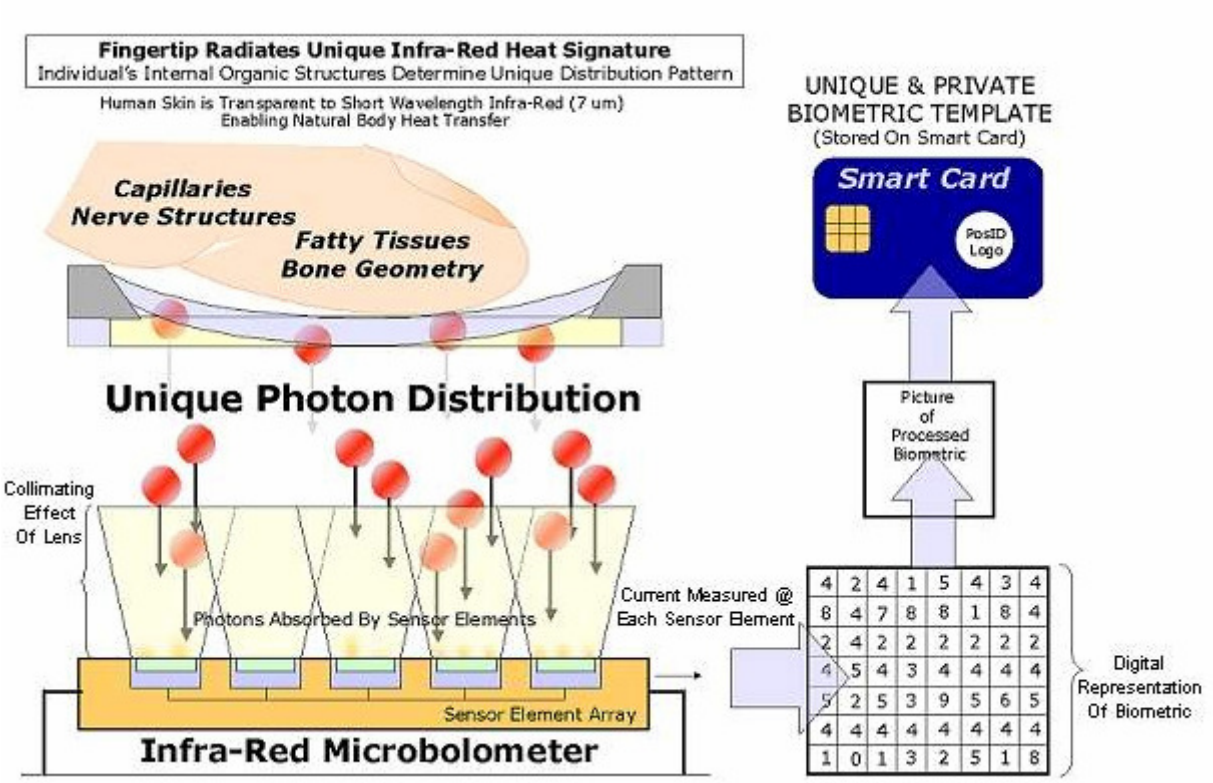


Figure 20. Mapping of the infrared radiation pattern from an individual's fingertip, and comparison to stored template. Obtained from. [104].

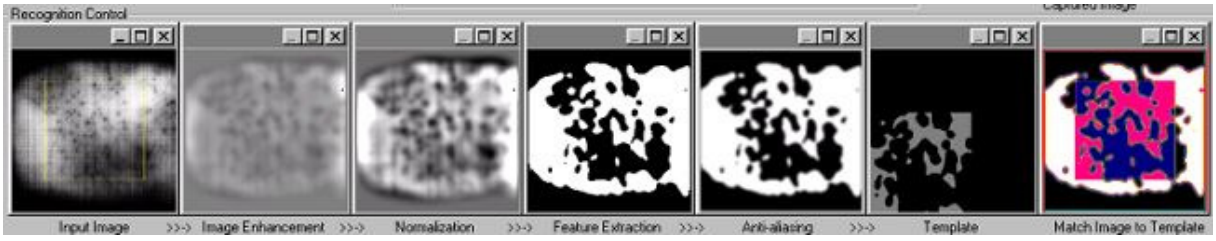


Figure 21. Process of infrared feature extraction of fingertip. Obtained from [105].

3.1.3 Veins in finger

PosID

PosID (Maryland, USA) is using a different approach to identification based on internal biometric features of the hand. Their product Thermo-ID is an infrared scanning technique of the fingertip, that 'maps' the energy (infrared light) levels emanating from an individual, thereby imaging the internal fingertip. The infrared microbolometer represents the fingertip as an array of digits, which is compared to the previous stored individual's energy map, for example on a Smart Card. They use a bolometer sensitive for 7μm light. A proprietary pattern matching algorithm insures positive identification (or rejection) in less than three seconds. See figure 6 for a visual representation. [104]

The invention of PosID is patented in

US patent 5351303 'Infrared imaging and pattern recognition system' - 1994

Inventor: Michael R. Willmore [31]

The invention involves an identification and verification system for use between a transaction media and a transaction device, based on the unique infrared energy pattern emerging from a large concentration of nerve endings and associated blood vessels of an individual's fingertip. The infrared pattern can also be extracted from other body parts with a large concentration of nerve endings and blood vessels, such as the nose or ear lobe. The application includes an infrared CCD, several processors and memory means. It should be noted that the patents mentions an IR-CCD, while the products utilizes a microbolometer. Restriction is that the device should be sensitive for mid-IR light.

Image capturing – A finger is placed over the IR-CCD detector element and the infrared energy will activate the Image Processor. The IR-CCD captures the infrared energy emanating from the fingertip.

Region determination and processing – The finger is placed on a predetermined region in the interface. The activated Image Processor will invoke a software program to sample the infrared energy level incident on each pixel of the IR-CCD detector element and after processing the primary image (see figure 20) the pixel energies are converted into scalar values.

Matching of the infrared energy pattern – When the Image Processor has mapped the last scalar value, the Pattern Recognition Processor is activated, which contains software algorithms to compare one or more sections of scalar values to one or more sections of scalar values of one or more of the permanently stored IR image patterns. These software algorithms can be any one of several existing pattern recognition techniques. If the processor confirms a pattern match does exist, the transaction media will be activated for use for the identified true owner of the transaction device. The image processing steps are also shown in figure 21.

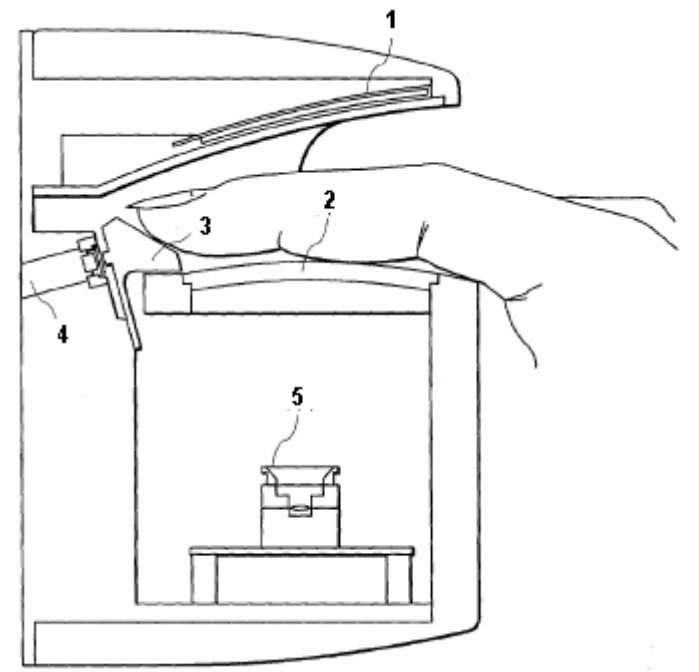


Figure 22. Cross-section of a possible configuration of an apparatus for capturing a finger vein pattern. 1. infrared radiating light source, 2. opening covered by a glass plate, 3. button switch, 4. contact switch, 5. camera. Obtained [80], figure 13.

Hitachi

"Finger vein authentication uses leading-edge light transmission technology developed by Hitachi (Shinagawa-ku, Tokyo) to undergo pattern-matching and authentication. Near-infrared light is transmitted through the finger and partially absorbed by haemoglobin in the veins to capture a unique finger vein pattern profile, which is then matched with a pre-registered profile to verify individual identity.[106]"

On the company website applications for the finger vein authentication system such as security system for banks, controlling physical access of persons, and computer login protection are mentioned. Reports are found where the finger vein authentication system is demonstrated as a high-security access system for cars, and recently to be utilized in a bank in New York [107, 108]. Hitachi has several patents on finger vein authentication methods [80, 81].

US patent 6970234, 'Personal identification device and method' - 2005

Inventors: Nagasaka et al.

Assignee: Hitachi, Ltd.

"The present invention relates to an identification apparatus for identifying individuals using vital information, and, more particularly, the present invention relates to a finger identification apparatus that utilizes a hemal pattern of a finger and methods therefore." As a main feature it wants to keep the conditions for imaging uniform among identifications and directs a user to perform only a series of simple manoeuvres. The apparatus comprises a guide unit to position the finger, a switch member turned on or off with the fingertip, a light source, an imaging unit and an identifying unit.

Image capturing – The configuration of the device is shown in figure 22. The device consists of an opening for a finger into a space that is shielded from surrounding light by the remaining sides. By inserting the finger the main part of the opening is also blocked. The finger is positioned under a light source that radiates near-infrared light whose wavelength is about 810 nm, and above a camera. The camera is equipped with an optical filter that transmits only light whose wavelengths fall within the near-infrared band. Near-infrared light is transmitted through the finger and picked up by the camera. At the backside of the cavity a button can be pressed, that initializes the identification process. An additional feature of this invention is that it can correct for finger thickness, when the light source is controlled by the same switch via an electronic control circuit, so-called 'pulse width modulation'. Through a step-wise control of the amount of light, a finger may be imaged continuously until the hemal pattern is successfully visualized. Finger thickness can also be measured by a sensor, which subsequently sets the light intensity to a corresponding value, thereby reducing the number of picked up images.

Region determination - In this invention much attention is given to adequate positioning of the finger. First of all, the opening is small and the cavity is narrow and arc-shaped. The switch-button is

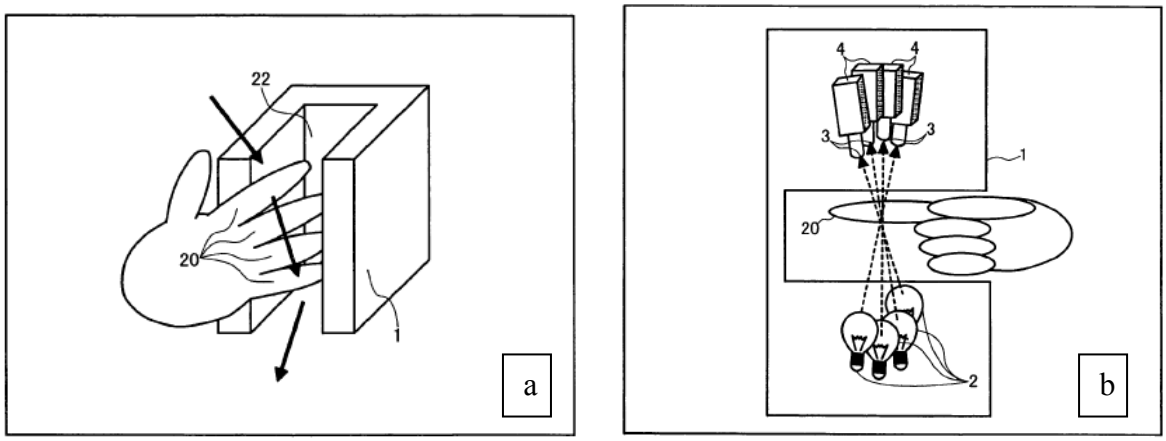


Figure 23. a. Example of configuration of an input interface for acquiring a finger vein image, possibly of a plurality of fingers b. Example of an arrangement of light sources and CCD cameras in an input interface for imaging a vein pattern in many directions. Obtained from [81], figures 2 and 5.

concave-shaped so that the fingertip will fall within the concave part. Every time the identification process starts by pressing the button with the fingertip, so the user's fingertip is located at a substantially fixed position. Moreover, due to this action, the joints bend naturally, and the epidermis will not be stressed. Therefore, the digital (refers to finger) blood vessels will not be compressed. Consequently, every time a finger is inserted, the fingertip is located at the same position with high accuracy and identical circumstances for the finger veins.

For sanitary reasons, the switch button should be made of antibacterial material. When sanitary issues are still a problem, a contactless switch, i.e. a combination of a light source and an optical sensor, can be used.

Image processing, vein feature extraction and matching process – The identification process, initiated by pressing the button, is continued by converting the image signal from the camera into digital data and storing the digital image in a memory. Then, a software program is activated that performs identification: first, the image is further processed to extract the features of a hemal pattern. Second, the captured pattern is matched to registered patterns in a database. If any registered pattern corresponds to the hemal pattern, correct authority is identified.

US patent 6993160, 'Personal identification device and method'

Inventors: Miura et al. - 2006

Assignee: Hitachi, Ltd.

"The present invention relates to a device and a method for identifying a person by utilizing a vein pattern obtained by imaging light transmitted through his or her finger." One of the main intentions of the invention is to provide such a device and method for identification whereby no physical contact is needed, to make it acceptable for environments where high hygienic standards are required. The device consists of a cavity in where the finger should be inserted, a light source, an optical filter, a CCD camera, and temporal and permanent storage media for the captured vein images.

Image capturing – Image capturing is done by a CCD camera, which receives the portion of light emitted by light sources on the opposite side of the finger that is not absorbed by the finger. The CCD camera is equipped with an optical filter. Many different shapes of the entrance gap can be used to support the finger into the right location. Some configurations (see figure 23a) can pick up vein patterns derived from a plurality of fingers by swinging down a plurality of fingers through the slot. In figure 23b, an entrance suitable for one finger is shown. In this configuration, a plurality of light sources and imaging devices ensure that a vein pattern can be picked up in many directions.

Region determination and image processing – After image capturing the first step is determination of the finger outline. A tracking point is positioned in the centre of the image, and consequently shifted upwards and downwards. Then subtraction of intensities between pixels higher and lower than the tracking point is performed. The location where the greatest difference value is found is determined as the boundary between the background and the finger. Further tracking to the

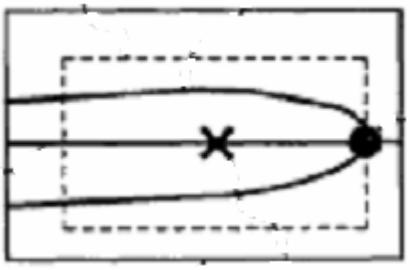


Figure 24. The outline of the top of a finger after rotational correction, and it's normalized region for further processing. Obtained from [81], figure 12.

left and to the right constitutes the whole finger outline. Next, because a non-contact image receiving method is used, the received finger image inevitably requires rotational correction. The upper and lower outlines of the finger are used for two-dimensional rotational correction, by rotating them relative to a straight horizontal line. The last step in determining the region is normalization of the size of the image by cutting out an image of smaller size than the original image that matches with a specific part of the finger tip that is used all the time. The area within the dashed line in figure 24 is the region used for further processing.

Vein feature extraction - Since the transmitted light is of a wavelength absorbable by haemoglobin in the blood, the blood vessel part takes on a dark luminous intensity. For tracking of the veins a table the size of the image is initialized with zeros. Random pixels within the finger outline are picked and given an intensity and probability as a function of intensity. Lower intensities have a higher probability to represent a blood vessel. An initial tracking point is determined and is given a random length for shifting. As long as this track length is not reached and there are surrounding pixels to shift to, the tracking is continued over the pixels with the lowest intensity. Otherwise, a new initial starting point is chosen and the process repeats itself. The execution of such a process for blood vessel tracking is repeated many times, and some pixels may be tracked a greater number of times, i.e. parts that are given a higher probability to be a blood vessel. Therefore, the scores corresponding to those positions in the score table are higher. The locations with lower scores are more probably not to be blood vessels.

The pixels are classified into four categories: 1. No blood vessel is supposed to be present in pixel locations with low scores. 2. Pixel locations with high scores are supposed to be highly likely to represent a blood vessel. 3. Pixel locations with medium scores are supposed to be ambiguous regions that may, but are not certain to, contain a blood vessel, and 4. Pixels outside the finger location are denoted background. By giving these four categories a certain luminous intensity, an image of a vein pattern is acquired.

Matching of vein feature – Two matching techniques are described, a global and a local pattern-matching algorithm. For global vein feature matching, one of the two images that have to be compared is reduced in size by cutting out pixels on the circumference of the image. Then, the images are superimposed with their central parts aligned, and their given luminous intensities are compared for each pair of superimposed pixels. If a pixel from category 1 corresponds to a pixel from category 2, these pixels are said to be mismatched. This is done for the whole area of the smaller image, and the total of mismatches is counted. Next, the images are shifted one pixel or a few at a time within a range for which no part of the smaller image protrudes out of the larger image, and the number of mismatches is counted in each shifted location. The smallest value of mismatches that is found is divided by the total number of pixels highly likely to represent a blood vessel in the two images. This mismatching ratio is small when the two vein patterns are similar, but can be very high when the patterns are different. A certain threshold value decides whether the vein pattern is authentic or not.

FAR	FRR		
	Conventional method	our Method	
		Global matching	Global and local matching
1%	2.06%	0.148%	0.148%
0.1%	7.67%	0.738%	0.738%
0.01%	15.3%	1.17%	1.03%
0.001%	18.9%	1.92%	1.03%
0%	22.7%	2.51%	1.03%

a.

FAR	FRR		
	Conventional method	our Method	
		Global matching	Global and local matching
1%	0%	0 %	0%
0.1%	0.16%	0 %	0%
0.01%	0.57%	0 %	0%
0.001%	0.72%	0 %	0%
0%	1.0%	0 %	0%

b.

Table 1. Performance comparison between a method according to the invention derived from US patent 6993160 and another method, in terms of the FAR and the FRR. a. results when registered images for both template and verification purposes where captured only once b. results when registered images for both template and verification purposes where captured three times, and the best result was selected in the process. Obtained from [81], figure 16.

The local pattern-matching algorithm is used when the ratio is too close to this predetermined threshold value. In this algorithm, one image is divided in *m* sub regions, and all the individual sub regions are shifted over the second image, whereby the number of pixels having the same luminous intensity in both images is counted for the area of the sub region. The location with the greatest number of matched pixels is regarded as the matching region, which is restricted to a predetermined logical area in both images, so that impossible matching regions do not occur. Eventually, for all m sub regions a corresponding matching region is found, which can be expressed in the deviation in location and number of mismatching pixels. This information on m matching regions is plotted on a plane. If these points are densely concentrated, it means a close correlation between two images and a high matching score or, conversely, if they are sparse, almost no correlation is found, and thus the matching score is low.

Reliability - reliability tests are done with 678 subjects using the finger vein authentication method described in this patent and by another method. This latter method uniformly filters the acquired image to emphasize the vein pattern, then two-dimensional convolution calculation is applied to a registered template and the image, and the sharpness of the peak in the short axis direction of the finger is evaluated to match the vein patterns. Results in terms of FAR and FRR of collation of every combination between registered template and authentic or not-authentic vein pattern are shown in table 1. Table 1a shows results when the images are only captured once, and table 1b shows the results when the image for both template and authentication purpose is the best image selected out of three captured images. The results show a very accurate performance of the present invention compared to the alternative method, especially when several images are taken.

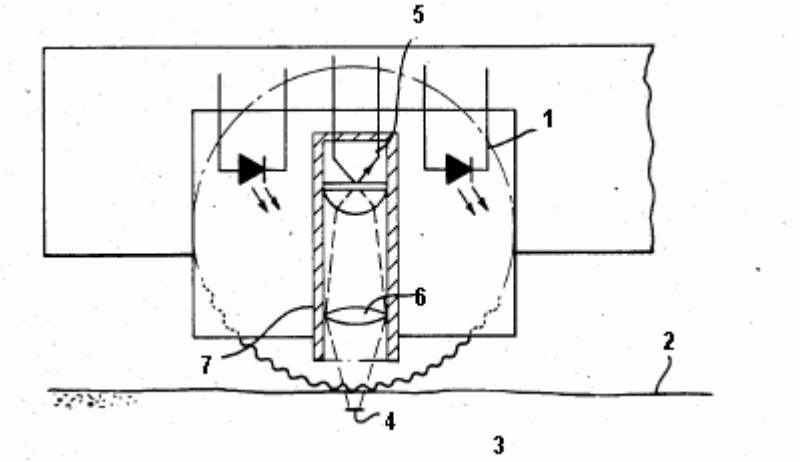


Figure 25. One element of the scanning device: 1. infrared radiating diode, 2. skin, 3. subcutaneous region, 4. blood vessel, 5. photosensitive pin diode, 6. lens, 7. aperture stop. . Obtained [109], figure 2.

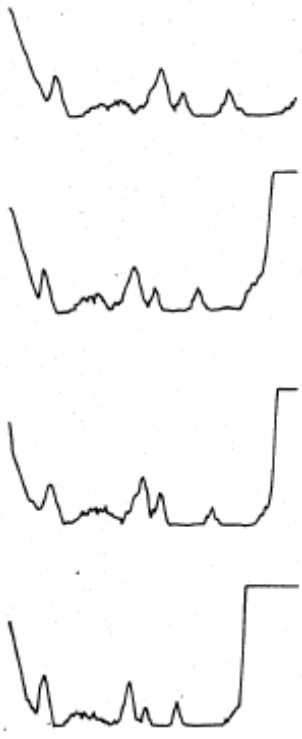


Figure 26. Example of output signals prior to digitisation of several scans of an individual wrist. Obtained from [109], figure 4.

3.1.4 Veins in wrist

Although often mentioned in the same enumeration as hand or finger vein pattern extracting devices for identification purposes, wrist vein pattern identification systems are hard to find and so far, no commercial application has been found. The patent described below [109] regards to a general apparatus for identification of individuals using the position of subcutaneous blood vessels, at any non-specific part of the body. However, the patent does mention specifically the wrist as a suitable region for detecting blood vessels, and is therefore mentioned in this section although it can also apply to other vein patterns.

US patent 4699149 'Apparatus for the identification of individuals' - 1997
Inventor: Joseph Rice

The identification of individuals in this patent is not based on comparison of a vein pattern image, but rather on comparison of a parameter, for example measurement of the reflection of incident radiation. Comparison of the measured pattern parameter with the parameter of a predetermined pattern provides identification of the individual. The apparatus consists of a radiation source, means for detecting radiation, transducer means for generating a signal and means for comparison of this signal.

Parameter measurement – The parameter used for comparison is the amount of radiation reflected by the tissue containing the vein pattern that is scanned. In figure 25 one element of the scanning device is shown. The skin is substantially transparent to radiation from infrared radiating diodes. The infrared light penetrates the skin and illuminates the subcutaneous region. The radiation is reflected by subcutaneous blood vessels and is received by a photosensitive pin diode, which is sensitive to differences in intensity of the reflected radiation. A lens and a tubular aperture stop limit the area from which radiation is conceived. A typical output signal prior to digitisation is shown in figure 26.

Region determination – The signals in Figure 26 show a series of peaks which are characteristic of a particular individual and correspond to the pattern of veins beneath the surface of the skin. Thus, if the scanning device is constricted to follow a predetermined path, the output will represent a pattern which can be recorded and correlated with an earlier produced pattern representation of the same path.

Signal processing - The total scanning device contains a plurality of in-line scanning elements. The output signals from the parallel pin diodes are fed to a multiple amplifier and subsequently to an AD-converter. Then, the parallel outputs are converted to four bit words. By using a detector with several transducers, a matrix of readings can be obtained. These are stored as a 2-dimensional array of words in a memory section.

Matching of vein feature- A transformation circuit performs rotational transforms on the array, to take account of the fact that the verification scan may not have been exactly parallel to the original calibration scan. A correlation circuit compares the scan signal with the calibration signal. The output of this circuit is fed to an indicator when a desired level of match is attained.

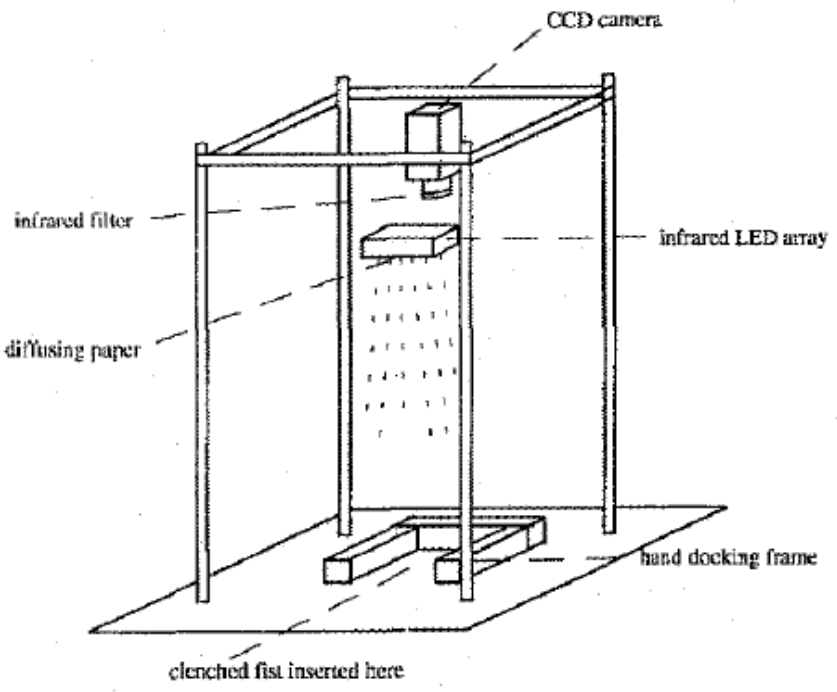


Figure 27. Schematic of the imaging unit. Obtained from [54], figure 5

Figure 28. Determination of ROI or working domain. Left: Attenuate noise, enhance contrast. Centre: separate foreground from background. Right: Obtain working domain after erosion. Obtained from [54] figure 6abc.

3.2 Scientific Literature

3.2.1 Veins in back of hand

J.M. Cross and C.L. Smith (1995) Edith Cowan University, Western Australia [54]

At the Australian institute of Security and Applied Technology research has been undertaken by Cross and Smith to use the subcutaneous vascular network of the back of the hand as a unique personal biometric for identification.

Image capturing – To capture a clear vein pattern by thermographic imaging with a CCD camera, the back of the hand was irradiated with a NIR cold source (880 nm ±25 nm) and the CCD was equipped with a not-ideal off-the-shelf IR filter, designed to transmit wavelengths greater than 900 nm, but with a tail of transmittance down to about 750 nm (shown in figure 13). Figure 27 is a sketch of the imaging unit. The hand should be placed in the U-shaped docking frame as a clenched fist. The set-up is covered with minimal reflecting material. The IR source can be manually dimmed.

Region determination – First noise is attenuated and contrast is enhanced, then the morphological gradient is used to separate the foreground (hand) from the background. After applying erosion, the working domain of the hand is defined, which is the region of interest, see figure 28.

Image processing – The illumination on a curved hand is not uniform which gives a shiny image. Therefore the brightness surface is estimated and subtracted leaving only the vein pattern. Then a morphological thresholding algorithm separates the vein pattern from the background and a binary alternating filter is used to remove threshold artefacts and to fill in small holes. The image process is shown in figure 29 a, b c and d. After this step the image is ready for registration, but this requires corrections for variations in position of the hand. This is done by obtaining a reference axis, defined by the midpoint of the last row (wrist) and the centroid of the working domain. Registration involves translating this position vector to the centre of the image buffer, and then rotating it so that is it perpendicular to the horizontal. Although this is shown to be a robust method, vein signatures still exhibit some horizontal positional noise. This should be accounted for in the matching process.

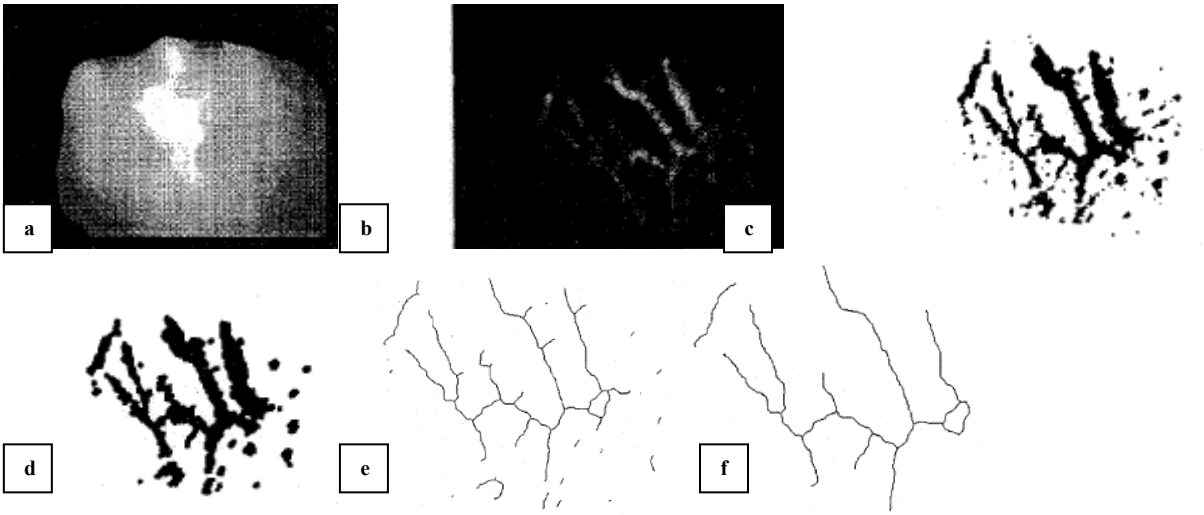


Figure 29. Segmentation of the vein pattern (image processing). A. Estimate of the brightness surface; B. after subtraction of brightness surface, background and vein pattern remain; C. after morphological thresholding algorithm; D. after binary alternating filter; E. medial axis presentation of vein pattern after thinning algorithm and post-thinning; F. after pruning. Obtained from [54], figure 6 efgh, 8 and 9.

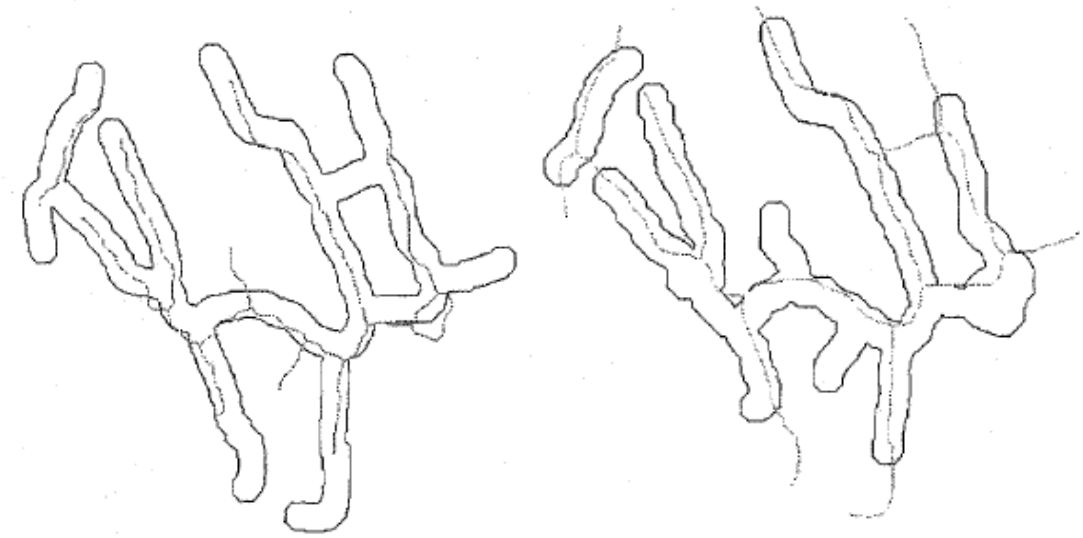


Figure 30. Forward and reverse matching of a library and test image of the same hand. Left. Forward matching: The library image is dilated and matched with the test image; the outcome is an 83% forward match. Right. Reverse matching: now the test image is dilated and matched with the library image; the outcome is a 75% reverse match. This results in a positive identification. Obtained from [54], figure 14.

Vein feature extraction – The vein features are represented by extracting the medial axis of the veins. A thinning algorithm is applied, including a single post-thinning pass, leaving a single pixel medial axis pattern of the vein pattern. Finally, a pruning algorithm retains the dominant veins and eliminates possible artefacts to obtain the vein pattern ready for matching. The vein pattern extraction steps are shown in figure 29 e and f.

Vein feature matching – For vein pattern matching the medial axis representations of the reference and test image obtained from the previous steps are compared using constrained sequential correlation, a variation on traditional correlation methods for template matching. The reference image is dilated and the test image is superimposed on this reference buffer. Horizontally it can shift ±30 pixels, until the highest match percentage between the two images is found. This is the value of *forward* similarity between the test and reference image. Next, the test image is dilated and the correlation procedure is repeated giving the *reverse* similarity value between the test and reference image. Both the forward and reverse similarities must be high to have a match. In figure 30 an example of a forward and reverse match is shown, which makes the difference between a diluted and a thinned vein pattern clear.

Reliability - A test was done with 20 adults (3 male, 17 female; Caucasian, Indian and Oriental). Of all individual 5 images were captured, and of 2 individuals this was also done several weeks earlier. The last three images were used to create the reference image: the oldest image was processed (including dilating) and stored in the library. The next image was superimposed as optimal as possible, and the union of this translated and the library image was taken and, after processing, replaced the former library image. This was repeated once with the last image, so that the union of all three images created the reference image.

The first and second images were individually matched with each of the library images. By nature of its construction, a library image contains more information than any single image. Hence the minimal acceptable percentage of a forward match should be higher than for a reverse match. A threshold percentage of 75% and 60% for forward and reverse matching respectively, constitutes a FRR of 7.5% and a FAR of 0% based on these 20 subjects.

In this test, problems appeared with an error in vertically registering the templates and images, due to some freedom to move the hand in the docking frame (see figure 27). Another problem arises with the horizontal shift of ±30 pixels that allows obtaining high matching values between two vein patterns of two *different* hands.

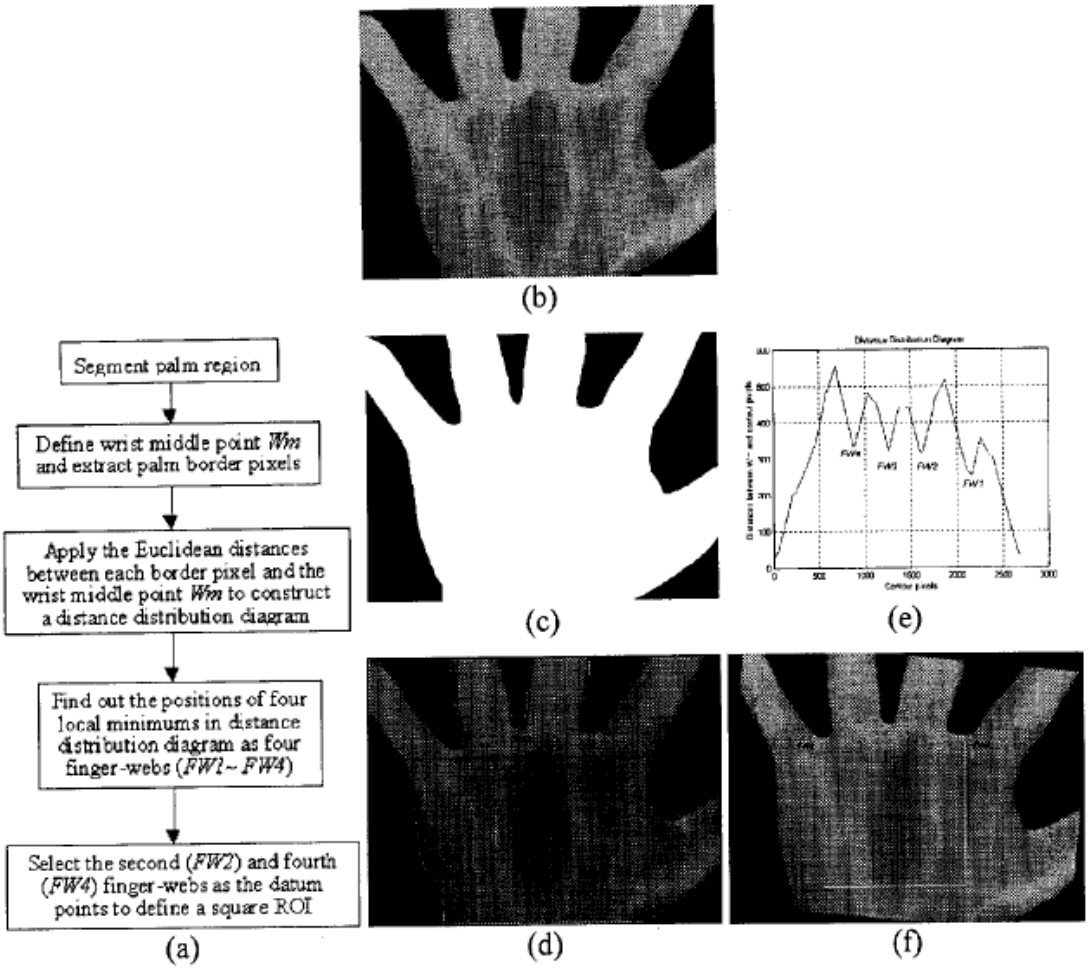


Fig. 31 (a) Flowchart of how to determine the ROI (b) Original thermal image (c). Image after segmentation and binarization (d) the palm border pixels are extracted by the inner border tracing algorithm (e) Calculated Euclidean distances between the wrist centre point and the border pixels displayed in a distance distribution diagram, showing obviously the four local minima corresponding to the finger webs. (f) A square ROI is defined by locating and rotating it using the second and fourth finger web. Obtained from [67].

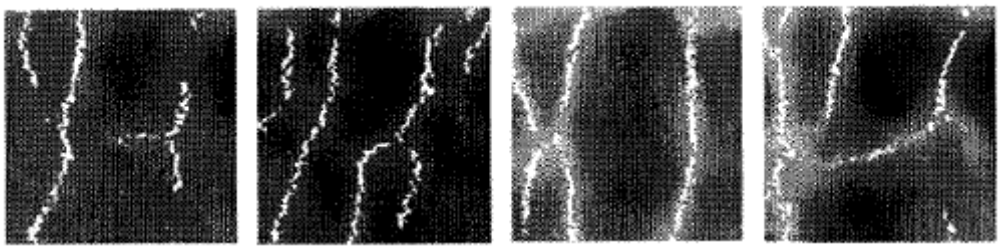


Figure 32. Feature point images superimposed on the ROIs of the thermal images captured from four different hands. Obtained from [67]figure 6a1 t/m d1.

C.-L. Lin and K.-C. Fan (2004) National Central University, Taiwan [67]

A recent study in Taiwan on hand vein pattern imaging for identification, developed in response to other techniques that are constraint by lighting conditions, a reliable and robust system that relies on the vein patterns in thermal images of the back of the hand taken under all lighting conditions, including total darkness.

Image capturing - The method is different from other methods in that it makes use of infrared light that naturally emanates from the hand, without making use of an additional infrared beam to illuminate the hand (comparable to PosID's energy mapping of the fingertip). The used IR camera was sensitive to IR radiation with wavelengths between 3.4 – 5 μm (3400 – 5000 nm), thereby absolutely independent on visible light and capable of capturing images in the dark. The analog signal from the camera is digitized by a frame grabber into greyscale images.

Image processing – The only image processing step is median filtering of the thermal image to remove noise. In this method this is done before region determination.

Region determination – The procedure for ROI determination is shown in figure 31, and is shortly as follows: determine the threshold for segmentation of the palm region, binarize the image and find the palm border using an inner border tracing algorithm, then locate the centre point of the wrist at the botton margin of the image. Next, compute the Euclidian distance between each border pixel and the wrist centre point to construct a distance distribution diagram. Apply wavelet transformation to find the four local minima of the diagram which are the four finger webs. Finally, select the second and fourth finger web as data point to define a square ROI, by rotating the palm so that the second and fourth finger webs are located on the horizon.

Vein feature extraction – In thermal images, the grey value of the veins is lighter than that of the surrounding skin under normal conditions. Using this knowledge, a basic tool for watershed transformation in order to extract the feature points of the vein pattern (FPVP) is developed, based on the region maximum method. The resulting feature points are stored in a feature point image (FPI). In figure 32 the FPI is superimposed on the corresponding original thermal image.

Vein pattern matching – The FPI only consist of the FPVPs. Based on the Fourier law, the FPVP locations, grey values of FPVPs, and the distance between the FPVPs determine the temperature gradient and the gradient direction. These properties are selected as features and put in a feature vector. The method for selection of the ROI cannot ensure that it is always in the same position. To resolve this problem, multi resolution analysis is applied to decompose the FPI into multiscale FPIs. Effectively this means that the effects of ROI displacement can be reduced to a more acceptable degree in low-resolution images. To prevent that FPVPs get lost while down-sampling the FPI with a multi resolution filter, three filters have been developed (a moment, mean and counter filter) to process the original FPI and to generate multi resolution representations in which each feature point possesses information about the number, location, intensity, gradient, and gradient direction of the FPVPs, as well as information about neighbouring FPVPs. The multiple features are weighted and a positive

Boolean function (PBF) is used to integrate the multi resolution representations of the palm-dorsum thermal images generated by multi resolution analysis. The PBF integrating function for vein pattern verification in combination with a trained threshold, results in a near-to-minimum error rate in verification.

Reliability - In order to verify the validity of the proposed approach, 960 IR images of the dorsal surface of the hand are collected (32 persons, 30 IR images per person). For each dorsal surface of the hand in the database, 5 images are used as template samples, 5 images as training samples to design so-called positive Boolean function, 5 images as training samples to select a near-to-optimal threshold, and the other 15 images as testing samples to verify the performance of the system. The experiments result in FRR = 1.5% and FAR = 3.5%.

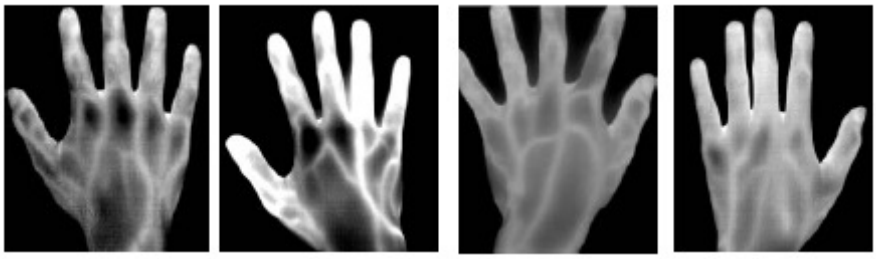


Figure 33. Thermal images of the back of the hands in normal office environment. Obtained from [1], figure 2.

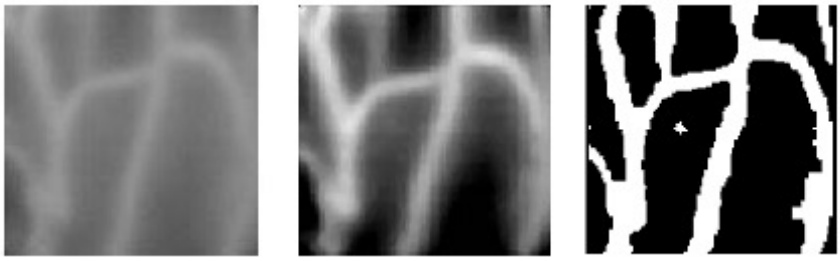


Figure 34. Successive steps from original image (left), image after normalization (centre) and after local thresholding (right). Obtained from [1], figure 4.

L.W. Wang and G. Leedham (2005) Nanyang Technology University, Singapore [1]

The School of Computer Engineering of the Nanyang Technology University presents a verification system using the thermal-imaged vein pattern in the back of the hand.

Image capturing – Image capturing is based on the higher temperature of human superficial veins compared with the surrounding tissue. Therefore, the vein pattern can be captured from natural emanating light using a thermal camera. Figure 33 shows some of the thermal images collected from different people, in which the vein pattern appears brighter and is now visually distinguishable.

Region determination - The technique for locating the ROI is similar to Lin and Fan (see page 64) and based on landmarks on the hand to locate a rectangular ROI.

Image processing – A 5 × 5 median filter was used to remove speckling noise and a Gaussian shaped low-pass filter was used to suppress the effects of high frequency noise in the image, followed by a normalization method.

Vein pattern extraction – A locally adaptive thresholding algorithm was utilized to segment the vein patterns from the background. Figure 34 shows the successive stages of the image during image processing and pattern segmentation. The vein features are represented by extracting the vein skeleton. A thinning algorithm is used to show the skeleton, and subsequently it is 'pruned'. A well preserved vein pattern is successfully extracted, see figure 35.

Figure 35. Left: skeleton after thinning of vein pattern. Right: skeleton after pruning. Obtained from [1], figure 5.

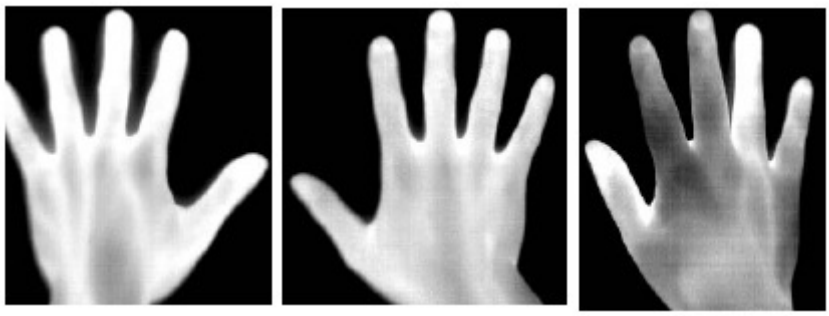


Figure 36. Thermal images of the back of the hands in a tropical environment. Obtained from [1], figure 3.

Vein pattern matching – Vein pattern matching is done by measuring the line segment Hausdorff distance between a pair of veins. Hausdorff distance is the maximum distance of a set to the nearest point in the other set. It is defined as [110]:

For two sets of points $A = a_1,..., a_n$ *and* $B = b_1,...,b_n$

$$H(A, B) = \max(h(A, B), h(B, A)) \quad [1]$$

where

$$h(A, B) = \max_{a \in A} \min_{b \in B} \| a\ b \| \quad [2]$$

Modified Hausdorff distance (MHD):

$$h_{\mathrm{mod}}(A, B) = \frac{1}{|A|} \sum_{a \in A} \min_{b \in B} \|a - b\| \quad [3]$$

In this way, spatial information of an image is obtained, but it lacks structural information when it comes to comparing the shape of curves. The distance between two curved line segments can be measured, using the *line segment* Hausdorff distance (LHD), a method proposed for face matching [111]. This method calculates a vector indicating the angle distance, parallel distance and perpendicular distance between two line segments. The vein pattern is divided in a number of curve segments, sampled by a few points on the curve. Using these sample points as endpoints, a set of line segments representing the shape of the pattern is obtained. The LHD can be calculated with equation [1] in combination with equation [3], using the vector distance and the length of the line segment as additional parameters. The LHD represents the similarity between two vein patterns.

Reliability - The hand vein pattern verification system is tested on a vein pattern database consisting 108 images from 12 people (9 on each person). Three images where randomly selected for each person as template images. For verification, three LHDs are computed for an incoming hand vein pattern with the three template images. The average Hausdorff distance value is calculated, and is regarded as the similarity measure between the incoming vein pattern and the template images. The lower the distance value, the higher the probability the vein pattern belongs to the authentic person. In this experiment, a threshold value of 9.0 resulted in a FAR and a FRR of 0% for all images.

It should be noted thought, that vein patterns where captured in a controlled manner, in a normal office with ambient temperature around 20°C and low humidity. In real life applications, the surrounding conditions are unknown. The thermal images of figure 36 for example are taken in a tropical environment and the quality of the vein patterns is reduced. Consequently, a decrease in accuracy can be expected.

Y. Ding, D. Zhuang and K. Wang (2005) Harbin Engineering University, China [112]

In this study, conventional and new methods are explored for the image processing stage and vein pattern matching stage in hand vein recognition procedures. Image processing includes threshold segmentation and thinning of the vein pattern.

Threshold segmentation - Poor segmentation was found using conventional single threshold or multi-threshold segmentation methods; therefore a new segmentation method is proposed: the threshold image method. Good segmentation is essential to obtain an effective binary image with sufficient information. The principle of the algorithm is as follows: for every pixel in the original image f(x,y) one grey scale value T is calculated using the N surrounding pixels (N = (2k -1)*(2k-1)-1, and a value of k = 5 is used in this paper). T is the average gray scale value in an n×n template and this value is given to the center pixel. A bitmap T(x,y) is initialized with zeros. Starting with the left bottom of f(x,y), the first grey scale value is calculated and given to T_0. The center pixel defines the location of T_0 in T(x,y). In this paper, a template of 31×31 is used, therefore T(16,16) = T_0. (note: the value k = 5 and template size 31×31 do not seem to agree in this paper). The template is shifted one pixel to the right and T(16,17) = T_1 is calculated. In this way the whole threshold image T(x,y) is calculated, with an n-pixels wide outer frame consisting of zeros. Next, the original and the threshold image are compared pixel by pixel and binarized according to:

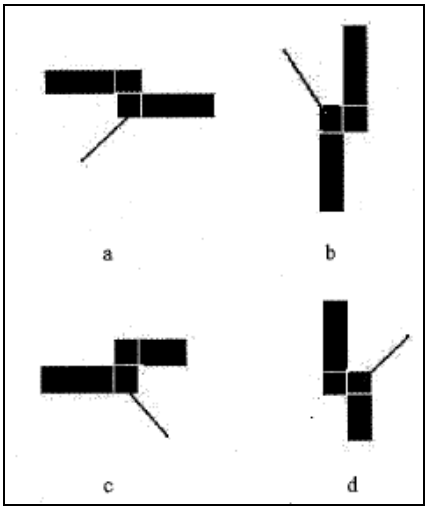
$$\begin{cases} f(x,y) = 0 & f(x,y) \geq T(x,y) \\ f(x,y) = 255 & f(x,y) < T(x,y) \end{cases}$$

The image is further processed by median filtering to eliminate burrs and to make the borderline smooth.

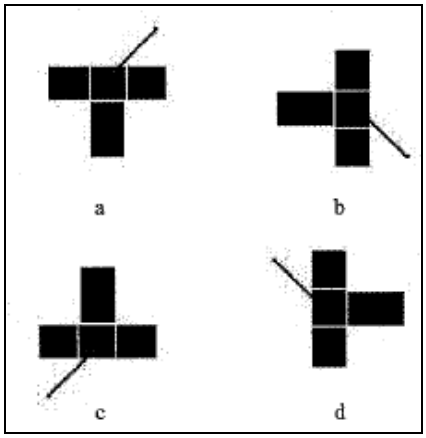
Thinning algorithm - Accurate thinning of the vein pattern is important when the feature extracting is based on endpoints and crossing points of the veins. The conventional thinning algorithm is as follows: mark the target points 1 (pixel value 255), the background points 0 (pixel value 0). The target points in whose 8-neighborhood there is at least one background point are defined as boundary points. Then, consider the 8-neighborhood points (p_2, p_3, … p_9) centered by the boundary point (p_1). If p_2 satisfies the following conditions, then delete p_1:

1) $2 \leq N(p_1) \leq 6$;
2) $S(p_1)=1$;
3) $p_2 * p_4 * p_6 = 0$;
4) $p_4 * p_6 * p_8 = 0$;

Where $N(p_1)$ is the number of nonzero neighbor points and $S(p_1)$ is the number of times the point value changes from 0 to 1 in the order of p_2, p_3, … p_9. After all boundary points have been checked out, the process repeats until none of the pixel points can be deleted. With this thinning



1.



2.

Figure 37. Examples of un-single pixel points in the image after the conventional thinning algorithm of the first kind (1) and the second kind (2). The improved thinning algorithm will delete the pixels indicated with the black line. Obtained from [112].

A. **B.** **C.** **D.**

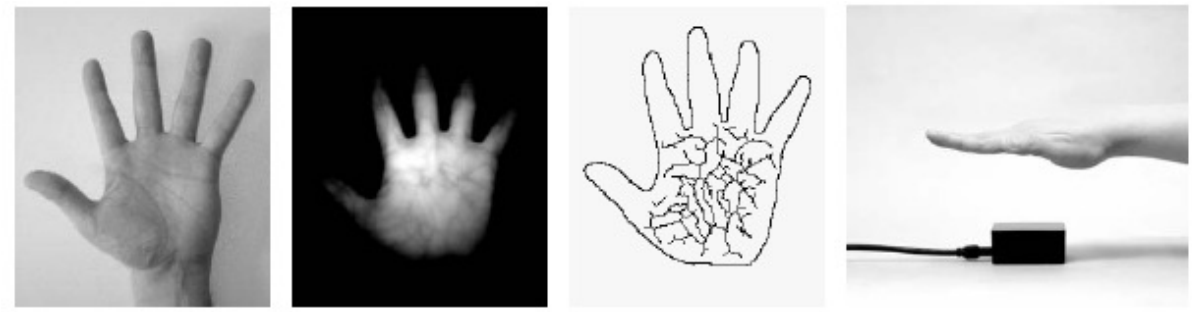
Figure 38. The different steps in image processing: A. The original image, B. Image after threshold segmentation, C. Image after median filtering, D. Image after thinning. Obtained from [112]

algorithm, connected points of lines, turning points and T type branching are coherent with the original image. The problem is that not always a thin line of maximal one-pixel wide is obtained which makes feature extraction based on end points and crossing points troublesome. This paper improves the conventional thinning algorithm by adding a template algorithm to get rid of the un-single pixel points. The un-single pixels points of the first and second kind are shown in figure 37. The pixels indicated by the line satisfy the conditions of one of the template algorithms and are deleted. In figure 38 the results are shown of the three steps in image processing, threshold segmentation, filtering and the thinning process.

Vein feature extraction and matching - The end points and crossing points are given a letter A, …, Z in the captured image and a, …, z in the image in the database. Two methods are used for feature extraction and matching. In the Tsinghua University method A is compared to a, and the displacement discrepancy is calculated and the image is corrected for this discrepancy. The coincidence ratio *r* is calculated between the corrected and the original image and if *r* is more than 80%, the matching is successful. Else, go on from b to z. If not successful, take B as starting position, analogy till Z until matching is successful (or not).

In the new method of Harbin University all end points and crossing points are counted. Then calculate distances between the end points and between the crossing points and arrange them according to size. In general, there will be more than 100 distances calculated. A matching method using these distances in the captured and database image is then used to match the vein patterns.

Reliability - The two matching schemes are based on extracting feature points, where Tsinghua uses the method of coordinate matching and Harbin the method of distance matching. Both have tested the reliability, Tsinghua with 13 and Harbin with 48 subjects. From all subjects 5 images of one hand were captured, and matched: different images from the same hand and different images from different hands. The pass ratio for two images of the same hand was 95.4% and 99.1% for Tsinghua and Harbin respectively. The mistaken identifying ratio was 0% for both experiments. Therefore, the Harbin research group concludes to have improved the matching scheme.



A. B. C. D.

Figure 39. A. Visible ray image B. Infrared ray image C. Extracted vein pattern D. Palm vein sensor Obtained from[102]..

3.2.2 Veins in palm of hand

M. Watanabe et al. (2005) Fujitsu laboratories, Japan [102]

In Proceedings of the Biometric Consortium Conference a paper from the Fujitsu laboratories provides little additional information about the technique. The palm vein sensor captures contactless an infrared ray image of the palm of the hand. The NIR absorption properties of deoxidized haemoglobin in the vein vessels make them show up as dark lines. The strength of illumination is controlled by the sensor. The vein authentication software translates the black lines into a blood vessel pattern of the palm, see figure 39. The software then matches the translated vein pattern with a pre-registered template pattern, while correcting for position and orientation of the palm by a pattern matching method.

Reliability - Also fujitsu laboratories have performed a reliability experiment on their palm vein authentication technology. A total of 140.000 palms from 70.000 individuals were tested in the following condition: three subsequent scans are taken of each palm of the individual for registration, and then one final scan is permitted to confirm authentication. The individuals where very diverse in both age, background, nationality and activity. The results confirmed a FAR of 0.00008% and a FRR of 0.01%. (These numbers are extremely low; in the discussion an independent biometric testing round is discussed with more credible numbers.)

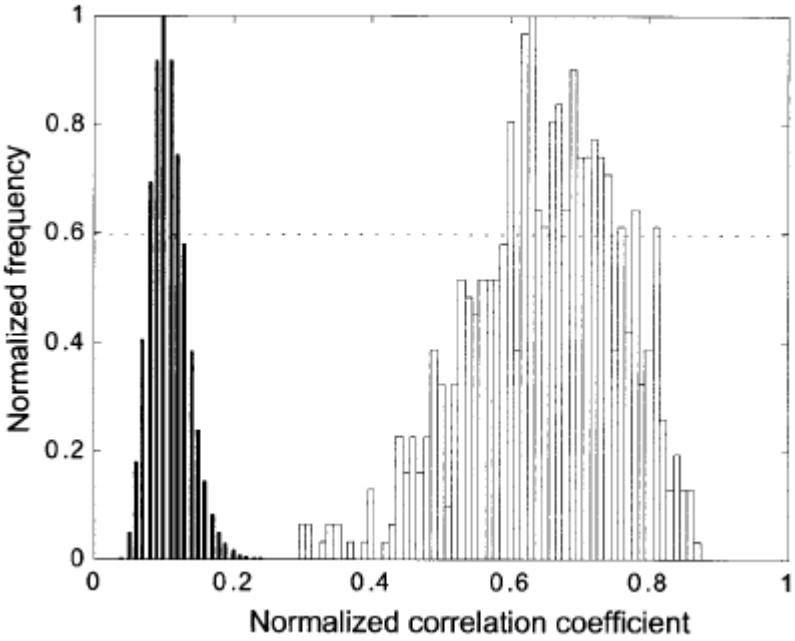


Figure 40. Histograms of the normalized correlation coefficient between two images of the 678 individuals. White bars denote the results from the two images of each individual, black bars denote the results from two different individuals. Obtained from [83].

3.2.3 Veins in finger

M. Kono et al. (2002) Hitachi Ltd., Japan [83]

Image capturing - The experimental set-up consisted of an array of near-infrared LEDs (810 nm) illuminating the dorsal (upper or back) side of a finger, and the transmitted light was captured by an infrared-sensitive CCD camera. In this way, the palm side of the finger vein pattern was acquired on a 640 × 480 pixel gray-scale still image. The intensity of the LEDs could manually be adjusted to correct for finger thickness.

ROI determination and image processing - The first step is filtering the image: the average of each pixel value and its eight surrounding neighbours replaces its original value. This process reduces background noise. Tracking of the shape of the finger is done by edge detection. The fingertip is cut out and again low-pass filtered to obtain a background profile, with a filter that replaces the intensity of a pixel with the average of its original intensity and a predetermined number of neighbour pixels (optimized M × M array). By subtracting the obtained background profile from the original captured image an enhanced finger vein pattern can be seen. The last step was rotational correction as described in the patent of Hitachi [81].

Vein feature extraction – An image of an enhanced finger vein pattern was obtained by subtracting the background profile from the captured image (see previous step)

Vein feature matching - The matching of the two vein features was evaluated based on a correlation coefficient between the two images. Using (inverse) two-dimensional fast Fourier transformation (FFT) of the signals and a normalisation algorithm, a normalized cross correlation coefficient was obtained. The value of this correlation coefficient determined an authorized individual.

Reliability - The sampled group consisted of 678 volunteers (479 males and 199 females): employees coming from the same research laboratory. Most volunteers where aged between 20 and 40 years. Of all volunteers two vein patterns where imaged of their left little fingers, one as the reference image and the other was used as the image to be tested.

Results for identification with a low-pass filter with M = 25 and image size 512 × 512 pixels are shown in figure 40. White bars denote the results from each individual, and black bars denote the results from two different individuals. Because there is no overlap between the different colors, a threshold value for the correlation coefficient can be found that perfectly identifies all individuals.

For different low-pass filter sizes, and image data sizes the FAR and FRR where obtained as a function of the threshold value for the cross correlation coefficient. A value M = 25, provided high accuracy and fast processing. Perfect identification was achieved until the image data size was reduced up to approximately 10^3 pixels. FARs for larger groups are predicted to be $3.5 * 10^{-5}$% at image size of 128 × 128 pixels, and 0.043% at an image size of 32 ×32 pixels, at a fixed FFR of 0.1%.

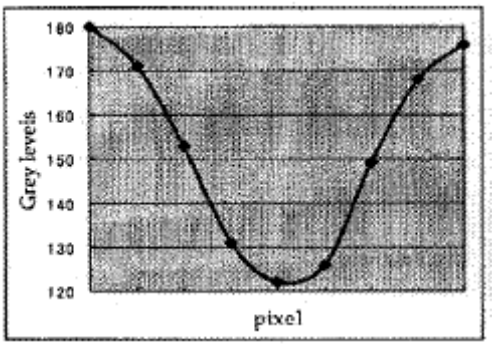


Figure 41. Cross-sectional brightness profile of a vein. Obtained from [82] figure 3a.

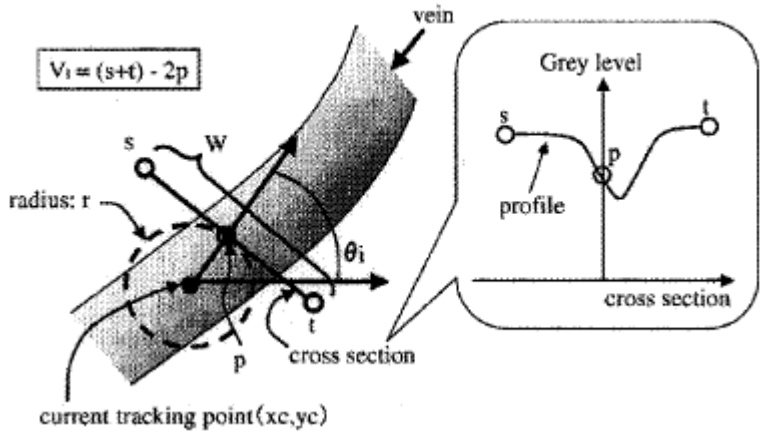


Figure 42. Process of dark-line detection. Obtained from [82]., figure 4.

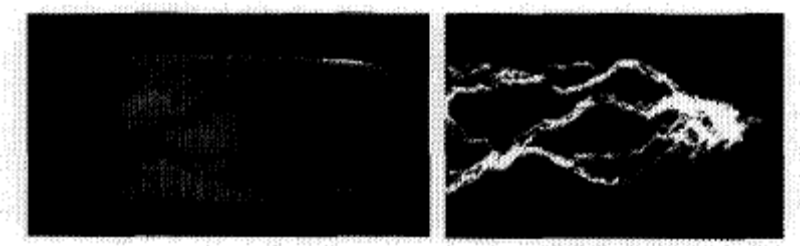


Figure 43. Effectiveness of finger vein pattern extraction. Left: original infrared image. Right: Value distribution in locus space. Obtained from [82]., figure 5.

***N. Miura et al. (2004) Hitachi Ltd., Japan** [82]*

ROI determination/image processing – Two-dimensional normalization is performed to correct for the location and angle of the finger.

Vein feature extraction – As partially stated in US patent 6993160 (page 50) [81], the line tracking method starts at various random positions in the image, from which pixel by pixel tracking along a dark line is executed or, when these dark lines don't exist, is interrupted. The method is as follows. The dept of the cross-sectional profile is checked around the random chosen starting point, now called 'current tracking point'. A cross-sectional brightness profile of a vein appears as a valley as is shown in figure 41. Therefore, the surrounding pixels of a current tracking point are checked to be lying in a valley. An example of a current tracking point (xc, yc) is shown in figure 42. A neighbouring pixel *p* lies in a valley, as is seen by cross-sectional profile *s-p-t*. Therefore, the current tracking point is on a dark line. The direction of the dark line can be detected by checking the depth of the valley with varying angle θ_i. The pixel closest to the deepest point of the valley will become the next current tracking point. If the valley is not detectable in any direction θ_i, the current tracking point is not on a dark line and a fresh tracking operation starts at another position. To restrict tracking to small global curvatures, only one of eight neighbouring pictures can become the next current tracking point.

The tracking starts at several evenly spread positions on the image. The current tracking point may track a region of noise by chance. Statistically, however, the dark lines are increasingly tracked more often with repeated operations (N). This makes the line tracking a robust method for vein feature extraction, while it is not needed to start from every single pixel in the image. Experiments have determined that N = 3000 is the lower limit for sufficient feature extraction. The number of times that each pixel has become the current locus space is count and makes up a matrix so-called the 'locus space', the same size of the original image. The positions with high values in the locus space, where tracked frequently in the line-tracking procedure and have high probabilities of being the positions of veins. Therefore, the paths of finger veins are obtained as chains of high-value positions in the locus space. Figure 43 shows the result of this process, on the left is the infrared image from with the pattern on the right is produced as the distribution of values in the locus space. Higher values are shown as brighter pixels.

Matching of vein pattern – A template matching method is used to match two vein features, consisting of three steps. The first step is labelling or binarization of the locus space. Pixels with smaller values than a certain threshold are labelled background (0), and the other pixels are labelled as parts of the vein region (255). In the second step the locus space is reduced to one third of its original size in both dimensions, and the pixels are given the average value of the 3×3 pixels. Then, all pixels are labelled again where pixels in the range 0 to 85 are labelled 0 (background), pixels in the range 86 to 170 are labelled 128 (ambiguous regions) and pixel values in the range 171 to 255 are labelled 255

(veins). The third step is matching of the data. This is done by calculating a mismatch value N_m, which reflects the difference between the registered and input data, and dividing this value by the total

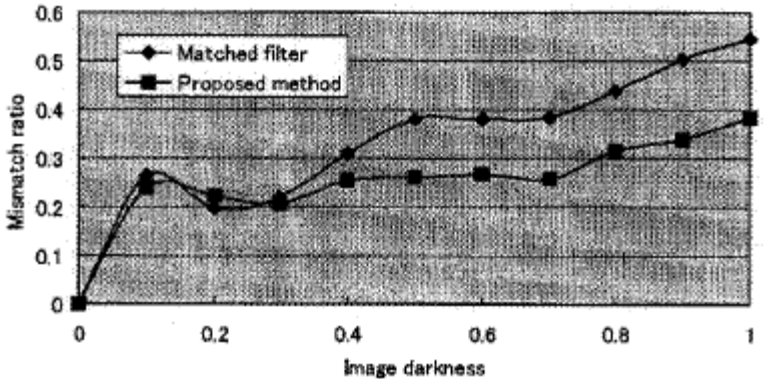


Figure 44. Robustness against fluctuations in light intensity fluctuations for two matching methods. Obtained from [82], figure 13.

number of pixels that are classified as belonging to the vein region in the two data sets gives the mismatch ratio R_m. The average time for feature extraction was 460 ms.

Reliability - Also the reliability of the vein feature extraction method based on line tracking is investigated. Compared to manual vein feature extraction by experts, this matching method obtained a mismatch ratio of 33%, while a conventional method based on matched filtering obtained a mismatch ratio of 44% in the same study. The robustness against fluctuations in light intensity levels was also tested and compared to the conventional method. As the images became darker, the mismatch ratio increased for both methods, see figure 44. The proposed method maintained a lower mismatch ratio, and is suggested to be more robust against LED light intensity fluctuation. To test the performance for identification with the proposed algorithms, again the finger images of the 678 employees were tested. This time the equal error rate (EER) was 0.145%, when the threshold value for the mismatch ratio R_m was set at 37.6%.

3.3 Discussion

The answer on the second research question 'how do biometric devices that utilize the hand vein pattern work' is in detail given in sections 3.1 and 3.2. In general, there are 5 stages to distinguish in the process of biometric verification using the hand vein system: image capturing, ROI determination, vein feature extraction and vein feature matching. There are similarities and differences in these stages for different companies or studies on hand vein pattern verification. In table 2 an overview is given of all verification methods described, so that differences in the stages can be seen more clearly. This discussion will continue with giving some remarks on the essential differences between the verification methods for each stage and on the reliability of the methods.

	Image capturing	ROI determination	Image processing	Vein feature extraction	Vein feature matching
BACK	**OF HAND**				
Clayden, BTG – 1998 [87]	IR-light, video camera + IR filters, handgrip	--	Weighing convolution to enhance contrast of longitudinal vessels	Convert pattern to series of vectors approx. center vessel	1. Superimpose, ratio coinciding pixels 2. total length vectors 3. other
Choi, BK systems – 2001 [30]	IR-light, CCD camera, IR filter, with/without handgrip	Binarize, largest rectangular area white pixels = hand	High-pass filter, histogram-based binarization, median filter	Thinning algorithm, branching characteristics	Superimpose reference (PIN) points, orientation correction, correlation value
Cross and Smith – 1995 [54]	IR-light 880 nm, CCD camera, IR filter, docking frame	Morphological gradient separation fore/ background, erosion	Brightness subtraction, morphological thresholding algorithm, remove artifacts + rotational correction	Thinning + pruning algorithm: medial vein axis representation	Superimpose + correlation: forward + reverse similariy of dilated test/reference image
Fan and Lin – 2004 [67]	Natural radiation, IR camera (3.4-5μm)	Binarize, Euclidean distance center wrist – border pixels, use 2nd and 4th fingerweb to obtain square	Median filtering	Watershed transformation, extract feature points (FP), create feature point image	Moment, mean and counter filter: multi resolution representation of FPs, PBF integration, verification threshold
Wang and Leedham – 2005 [1]	Natural radiation, IR camera	Similar to Lin and Fan: based on landmarks on hand	Median filter, Gaussian low-pass filter, normalization	Thinning + pruning algorithm: skeleton of vein pattern	Line segment Hausdorff distance: vector of angle, ⊥ and ‖ distance gives similarity two patterns
Ding et al. – 2005 [112]	--	--	Segmentation via threshold image method, binarization	Thinning algorithm, assign endpoints and crossing points A- Z (ref) and a-z (test)	Coordinate matching or distance matching between assigned points

Table 2, (this page and the next). Overview of the different stages in the hand vein pattern recognition process for all methods described in chapter 2.1 and 2.2

	Image capturing	ROI determination	Image processing	Vein feature extraction	Vein feature matching
FINGER					
Nagasaka, Hitachi – 2005 [80]	IR-light 810nm, CCD camera *opposite* side finger as light, filter, feedback to light intensity no contact	Finger positioned by cavity and pressing 'on-switch'	--	--	--
Miura, Hitachi – 2006 [81]	IR-light, CCD camera *opposite* side finger as light, filter, no contact	Pixel tracking to outline finger, rotational correction, size normalization	--	Repeated pixel tracking for blood vessels, label pixels; no/likely blood(1/2), uncertain (3), background(4)	Global matching algorithm: mismatch ratio. Close to threshold? > Local matching algortihm
Willmore, PosID, 1994 [31]	natural radiation (7μm) detection by IRCCD element, image processor	Fingertip placed on predetermined region	Pixel energies > scalar values, enhancement, normalization	Vein features imaged as IR energy pattern, no extraction	Software to compare scalar values to reference scalar values
Kono, Hitachi – 2002 [83]	IR-light 810nm, CCD camera *opposite* side finger as light, filter, feedback to light intensity no contact	Low-pass filter, finger edge detection, cut out finger, rotational correction	Subtract background profile (obtained with low-pass filter) from original profile	--	Inverse 2D FFT + normalization algorithm gives normalized cross correlation coefficient
Miura, Hitachi – 2004 [82]	IR-light 810 nm, CCD camera *opposite* side finger as light, filter, no contact	Location and rotational correction, 2D normalization	--	Repeated pixel tracking using cross-sectional brightness profile, create locus space matrix	Labeling of locus space (0 or 255), spatial reduction and re-labeling (0, 128 or 255), calculate mismatch ratio
PALM					
Watanabe, Fujitsu – 2005 [102]	IR-light, 'palm vein sensor', feedback to light intensity, no contact	--	--	Algorithm: translate black lines to vessel pattern	Algorithm: Position + orientation correction, matching with template
WRIST					
Rice – 1987 [109]	IR-light, photosensitive pin diodes, output signal (image = peak pattern)	Scanning device follows predetermined path	Output of parallel diodes digitized and stored in 2D array	--	Rotational correction on array, correlation circuit

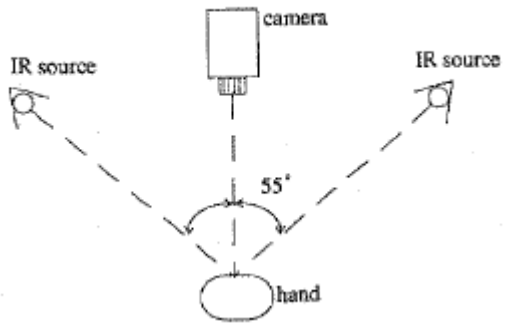


figure 45. Ideal lighting angle for imaging the back of a hand. Obtained from [54], figure 16.

3.3.1 Image capturing

A vein image is essentially made by capturing of mid- or near- infrared radiation by a photosensitive device, which generates electronic signals that are converted into an image or a peak diagram. The most essential difference in the image capturing stage is capturing the natural emanating MIR radiation or capturing the reflected and scattered NIR radiation. I will refer to the first method as 'thermal imaging' and to the second method as 'reflective imaging'.

Good quality of the image is essential, because high-quality images retain detailed information of biometric features. Consequently, more information upon which verification is based is present in the images, which improves reliability [67]. Factors that influence the quality of thermal images are ambient temperatures, both cold and hot. As was seen in figure 36 (page 67) thermal images of the back of a hand in a tropical outside environment (30-34 °C and >80% humidity) have a low quality [1], which makes it hard to extract a vein pattern. This is due to a low contrast in temperature between veins and surrounding tissue. In cold weather veins constrict and also become less clear. This also holds for the quality of reflective imaging [82].

Another factor that influences the quality of reflection images is the lighting condition [67]. Sufficient lighting with near IR light sources and proper use of filters are essential. Some methods use a feedback system to adjust the intensity of the IR lights for optimal illumination to prevent over- and underexposure. This is an important improvement for the quality of the images [80, 83, 102]. Another factor for image quality is the position of the light in relation to the hand. A single IR source induces surface shadows and specular reflection. It is suggested that a convex surface, such as the back of a hand, should be optimally lit using a lighting angle of 55° as shown in figure 45 [54]. An advantage of thermal imaging is that it is independent of lighting conditions and can be used in total absence of light [67].

Both imaging methods produce images with a reduced and obscured vein pattern when the subject has a relatively thick layer of subcutaneous fat [54, 67]. This results in nearly homogeneous grey values and lack of high contrast regions. Smith and Cross [54] suggest a study to determine the optimal band of the NIR range for imaging these deeper subcutaneous veins. They had used a 880nm source, which is, according to figure 14 (page 35), a region of deepest penetration into the skin. Considering this, it is probably not possible to obtain a deeper penetration using different light sources. Other factors that affect the distinctiveness of the vein pattern are the degree of venous engorgement, the condition of the vein walls, and the nearness of the vein to the surface [67]. These factors are in turn influenced by for example diseases that induce deterioration of veins and environmental temperature, physical activity or alcohol intake, which reduce dilation or constriction of the peripheral veins. A last issue is the amount of hair on the hand of the user: clumping of hair is also responsible for low image quality [54].

Other essential differences in the imaging stage are the position of the imaging device in relation to the light source and hand. In thermal imaging the sensor will capture mid IR light

emanating from the same side of the hand or finger as the sensor and no additional light sources are needed. Reflective imaging of the finger veins by Hitachi is done by positioning the NIR sources on the opposite side of the finger as the camera. The image consists of light that has travelled through the fingertip without being absorbed by the veins or tissue. Methods that image the palm, wrist or back of the hand position their light sources and camera on the same side of the hand, thereby capturing light that has penetrated the skin and is scattered or reflected back out of the same side.

In section 2.5.3 it is noted how different opinions on penetration depth of NIR light into tissue are stated in literature. Distances range from a 'few millimetres' to up to 8 centimetres, (with very sensitive equipment). Since it is possible to capture NIR radiation opposite to the fingertip, a sufficient amount will at least travel this distance of around 0.5-2 cm's. Light that enters the back or palm of the hand will travel around the same distance in the skin before it is reflected back to the camera. The amount of diffusion of the photons due to scattering resulting in an image with smooth gradients is probably more or less similar for both methods. The wavelength of the NIR sources was sometimes given; 880 nm [54] and 810 nm [102]. 880 nm will give a slightly deeper penetration [74, 93] and 810nm is closer to the isobestic wavelength (figure 10) where deoxy- and oxyhemoglobin have a similar extinction coefficient.

One remark on signal capturing by Rice [109] should be made. The patent says that 'the radiation is reflected by subcutaneous blood vessels and received by photosensitive pin diode'. Some radiation will indeed be reflected by the blood vessels, but most radiation will be reflected by the surrounding tissue and rather be *absorbed* by haemoglobin inside the blood vessels.

3.3.2 ROI determination

Verification is based on comparison of features of vein patterns extracted in the same region from two or more different images. The region to be extracted, the ROI, is therefore important to be fixed in the same position in different images to ensure stability of the principal extracted vein features, and thus accurate and reliable verification. There are several ways to stabilize the ROI. The finger or hand can physically be guided to a selected position by a docking frame [54], cavity to insert the finger [80, 81] or other form of restricted area to present the biometric feature [30, 31, 87, 109]. In this way, the primary captured image is of the same region each time, although some positional variation can be expected. This should be accounted for at the vein feature matching stage, where some shifting of the feature image should be allowed. Another issue with physically guiding the biometric feature is hygiene: a handgrip that is touched by all users is not very clean. A cavity can restrict movement, and without any physical contact it is more hygienic than a grip. Some companies provide devices with or without a handgrip [30] or make the contact surfaces of antibacterial material [80].

Another way to determine the ROI is to use information on the image after capturing. One can select reference points such as finger webs and the wrist [1, 67], or define the outline of the hand or finger using foreground-background properties [30, 54, 81, 83]. Then rotate the image until the reference features are on standardized positions. Sometimes size normalization is part of this process as well [81, 82]. The goal of pre- and/or post-imaging ROI determination is to reduce the displacement of the ROI to acceptable range. In the vein feature matching process often more shifting and scaling is applied. Several methods use both pre- and post-imaging ROI determination and additionally allow for adaptations in the matching process.

All corrections for position that have just been mentioned are two dimensional corrections. Three dimensional rotation of the finger degrades identification accuracy because two dimensional images are used in the systems [82]. The third dimension in movement (angle of the hand/finger) can not (yet) be corrected for, it can only be minimized by placement restrictions at the pre-imaging stage.

3.3.3 Image processing.

The image that is acquired contains much of information unnecessary for identification, such as background noise, irregular shades due to muscle and bones in the finger and intensity fluctuations [82]. The aim of image processing is to enhance the wanted vein pattern and reduce this unwanted information. Useful digital image processing techniques are abundant. In sections 3.1 and 3.2 many have been described. An in-depth review on these techniques is beyond the scope of this thesis, but some remarks are made below.

In some methods, image processing is an accumulation of several filters and algorithms and seems to be overkill. Choi [30] for example, uses a high-pass filter to enhance contrast, followed by histogram based binarization followed by median filtering to remove noise. Wang and Leedham [1] both median and low pass filter their image, for double noise reduction. Methods that manipulate the original image relatively much continue with rather simple vein feature extraction methods or methods that rely on a simple (black/white) vein image. These methods often derive step by step a representation of the vein skeleton, starting from the original image [1, 30, 54, 83, 87, 112]. Other methods don't change the original image much [67, 80-82, 109]. They don't segment or binarized the images so that the images still contain smooth gradients. Consequently, their vein feature extraction methods are more complex and robust against images with noise and gradients. Often they extract features or label pixels to obtain a new image, containing only the extracted information.

While after vein imaging and ROI determination the images obtained according to the different companies and studies showed many similarities, after the image processing stage the different methods dissociate more from each other, although a few common trends exist. The next steps, vein feature extraction and matching, continue with the processed images on the different routes towards verification.

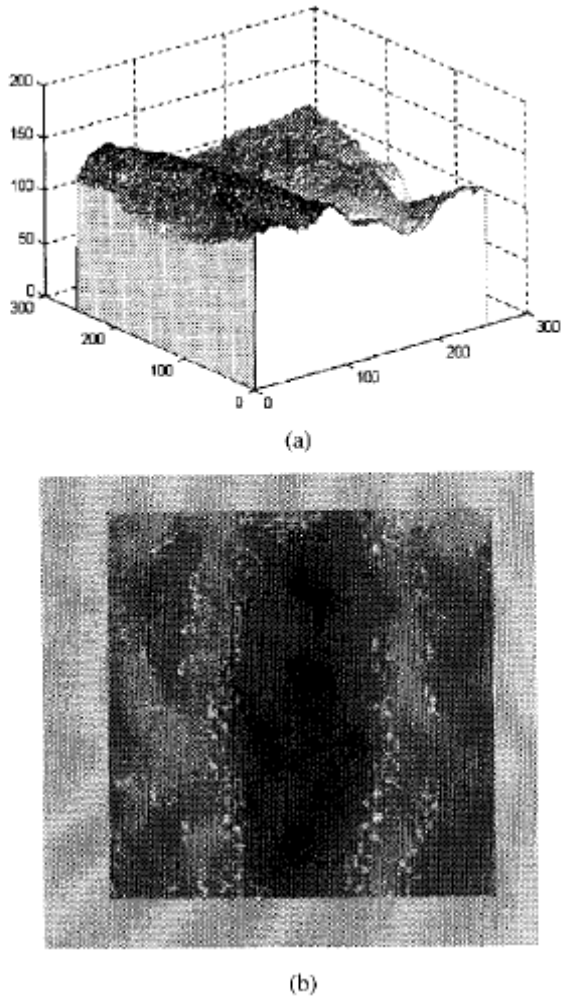


Figure 46 a) the temperature distribution shows a smooth varying temperature change of thermal images of the hand. b) Feature points (white dots) extracted by wavelet transformation (edge detection) superimposed on the corresponding ROI show that they are located at the edges of the vein patterns and are unstable. Obtained from figure 7 [67].

3.3.4 Vein feature extraction

The goal of vein feature extraction is to obtain an image containing only the vein structure, or a representation thereof. A representation of the characteristics of a vein pattern is seen in Choi [30], who applied a thinning algorithm and then computed the branching characteristics to represent the features of the vein pattern in a table. Also Ding et al.[112] use the threshold image method, binarize and apply a thinning algorithm, followed by a representation of the vein pattern by coordinates of end and crossing points.

Methods that retain the full vein structure, by representing its skeleton or medial axis are Clayden [87], who approximated the vein centers with a series of (longitudinal) vectors, and Smith and Cross [54] who applied a morphological thresholding algorithm to separate the veins from the background and consequently applied a thinning and pruning algorithm, and used the remaining skeleton for matching. One of the common trends thus seen is thinning of the vein pattern, also used by Wang and Leedham [1] who also followed with pruning.

Another trend is line tracking. Miura et al. [81, 82], evaluated this for finger vein pattern extraction. Conventional methods for extracting line-shaped features from images, such as the connection of emphasized edge lines for line extraction or ridge line following, are not suitable because they take much computational cost or respectively need an image with clear ridges, which is not the case for finger vein images. Moreover, because transmittance of light varies with the thickness of the finger, irregular shading and noise are present in the captured images. The aim of the vein feature extraction method based on line tracking in this study is to be robust against these factors and perform a fast identification. They used repeated pixel tracking, based on the cross-sectional brightness profile. The frequency of tracking is put in a locus space matrix to categorize pixels. As the parts of the veins are tracked over and over again in the repeated operations, they are increasingly emphasized. Although noise may also be tracked, this will be to a lesser extent [82].

Lin and Fan [67] discuss the use of an edge detector. The grey level of thermal image changes smoothly from a high to a low temperature. The temperature gradient of the hand also changes smoothly, and consequently the greyscale image contains smooth gradients (see figure 46). As a result, the familiar edge detectors based on gradient magnitudes, cannot effectively extract features from the images. In figure 46b it is shown that the feature points extracted with edge detectors are located at the edges of veins and not at their actual locations. To overcome these problems, Lin and Fan developed a basic tool for watershed transformation to extract feature points. Now the feature points represent the vein pattern uniform distributed over the veins (figure 32, page 63). The smooth gradient is not only seen in thermal images, but also occurs in images obtained with reflection, due to the diffuse reflection of tissue and the path length of the radiation in the tissue (section 2.5.3, page 36). Edge detectors, as well as ridge detectors, are therefore not suitable for vein feature extraction.

Segmentation of the vein pattern from the background encounters five general types of segmentation errors [54]:

1. *mismeasured attributes*: noise can induce quantitative measurement errors in the segmented image. For example, the length of a vein might appear longer in different images of the same hand.
2. *missing objects*: if an object is not clearly visible due to glance, shadows or occlusion it will not be represented in the segmented image
3. *false objects:* large marks or shadows appear as feature objects in the segmented image
4. *fragmented objects (ovesegmentation):* noise can induce fake edges and fragment one object into several regions in the segmented image
5. *merged objects (undersegmentation):* noise can induce blurred edges resulting in two or more objects merged together as one region in the segmented image

Because vein images usually contain a lot of noise due to the complex structure of the tissue, bones and skin surface, vein feature extraction methods should be robust enough to overcome errors. In addition, the quality of the images after image processing should be as high as possible, but not excessively manipulated.

3.3.5 Vein feature matching

In this stage, the template image already stored in the database is recalled and compared to the test image for verification. This can be a one-to-one match or a database search (one-to-many), which are essentially many one-to-one matches until a match is found. It is important that the template image is a high-quality image, captured under standardized conditions [54]. The temperature of the hand and the amount of physical action prior to capturing the template image should be constant. This can, for example, require that the individual squeezes a rubber ball several times prior to image capturing, so that the vessels are dilated [54]. In addition, the template image can be an average of several images, 3 [1, 54] or 5 [67], captured for matching. Consequently it contains more detail than a single test image. Other methods use only one image as a template [83].

Simple pixel by pixel comparison of two digital images of a vein pattern is not sufficient because of two main reasons: 1. the subcutaneous blood vessels have some freedom to move within the soft tissue they are embedded in; the shape of the hand (stretched fingers or clenched fist) will influence the stretching of the skin and underlying veins, and 2. the diameters of the veins may vary as a result of weather circumstances or physical activity [54]. Moreover, several IR images of a single hand, both raw and processed, exhibit marked variability due to the complex structure of the tissue, bones and skin surface and physiological circumstances of the veins. These factors collectively diminish the accuracy of correlation and sequential matching which is the classical approach for matching images [54].

On the other hand Miura et al. [82] reject structural matching, because structural matching requires additional extraction of features points such as line endings and bifurcations and since a finger-vein pattern has few of these points, template matching based on comparison of pixel values is more appropriate for finger-vein pattern matching.

Examples of structural matching are found in Choi [30], who compares branching characteristics of the test and template image (number of branches and connections between branching points). All other methods use some kind of template matching and correlation method, although different gradations of advanced algorithms are used.

In all methods the threshold value for matching similarity decides whether a positive match occurred. This value should be high enough to prevent false positive matches, but low enough to allow for the variability seen in several images of one single hand, due to the complex process of capturing a vein image. A short discussion on the performance of the hand vein pattern verification methods is therefore the topic of the next section.

	subjects	# test images	# match attempts	FAR	FRR	FTE
Cross and Smith – 1995 [54]	20	2	40 genuine attempts 760 impostor attempts	0%	7.5%	0%, but in new trial 1 out of 34 subjects failed
Wang and Leedham – 2005 [1]	12	6	72 genuine attempts 792 impostor attempts	0%	0%	0%
Tsinghya university [112]	13	5 (*and* reference image)	260 genuine attempts 3120 impostor attempts	0%	4.6%	0%
Harbin university [112]	48	5 (*and* reference image)	960 genuine attempts 45120 impostor attempts	0%	0.8%	0%
Watanabe - 2005 [102]	70.000	1	140000 genuine attempts 1.96E10 impostor attempts	0.00008%	0.01%	0%
Kono – 2002 [83]	678	1	678 genuine attempts 459006 impostor attempts	0.043%	0.1%	0%
Miura – 2006 [81]	678	1	678 genuine attempts 459006 impostor attempts	1%	0%	0%
Miura – 2004 [82]	678	1	678 genuine attempts 459006 impostor attempts	0.145%	0.145%	0%
Lin and Fan – 2004 [67]	32	15	480 genuine attempts 14880 impostor attempts	3.5%	1.5%	'a few'

Table 3. Overview of the performance experiments performed for some of the methods described in section 3.1 and 3.2.

$$FRR = \frac{NFF}{NEVA} \qquad [2]$$

Where *FRR* is the false rejection rate
NFR is the number of false rejections
NEVA is the number of enrollee verification attempts

$$FAR = \frac{NFA}{NIVA} \qquad [3]$$

Where *FAR* is the false acceptance rate
NFA is the number of false acceptances
NIVA is the number of impostor verification attempts

3.3.6 Performance

The performance of a biometric system is essential to determine whether the system has a potential to be applied in real life situations. Performance can be measured by three key performance metrics:

- FAR, the probability that an unauthorized person is accepted as an authorized person
- FRR, the probability that an authorized person is rejected as an unauthorized person
- FTE, the probability that a given user will be unable to enrol in a biometric system due to an insufficiently distinctive biometric sample.

To estimate the performance of a biometric system all three metrics must be evaluated, as reliance on one or two metrics without the third can be highly misleading. If manufacturers, for example, provide only the FAR, it is possible that the system with the lower FAR has got an unacceptable high FRR. Changing settings, such as the matching threshold, can influence each of the three metrics. Increasing the threshold will make the system less accessible to impostors, but also the probability that legitimate users will be rejected increases. Such an adjustable threshold makes is hard to compare different systems, because there is no reasonable way to decide if a system with a higher FAR and a lower FRR performs better than a system with a lower FAR and a higher FRR value. Decreasing the FTE means allowing more subjects to enrol successfully despite the fact that they exhibit low-quality biometric samples will also increase the FRR of the system. The equal error rate (EER) of a system can be used to give a threshold independent performance measure. The lower the EER is, the better is the system's performance, as the total error rate which is the sum of the FAR and the FRR at the point of the EER decreases.

Several manufacturers or researchers tested the performance of hand vein pattern recognition systems. A brief overview of the results is given in table 3. To interpret the numbers in table 3 it is important to put them in context. The standard of the International Biometric Group (IBG) [113] is shown in table 4. The IBG uses other metrics for accuracy comparison: the False Match Rate (FMR) and the False Non-Match Rate (FNMR). These are defined as:

$$FMR = \frac{imposter\_attempts\_that\_generate\_comparison\_score\_above\_threshold}{total\_impostor\_attempts} \quad [4]$$

$$FNMR = \frac{genuine\_attempts\_that\_generate\_comparison\_score\_below\_threshold}{total\_genuine\_attempts} \quad [5]$$

	Level 4	Level 3	Level 2	Level 1
Usability Metrics				
Failure to enrol rate (FTE)	<1.00 %	<2.50%	<5.00%	<8.00%
Average Enrollment Transaction Duration (Seconds)	<30	<60	<90	<120
Transactional Failure to Acquire Rate (T-FTA)	<1.00%	<2.00%	<4.00%	<6.00%
Average Recognition Attempt Duration (Seconds)	<3	<5	<10	<20
Accuracy Metrics				
False Match Rate (FMR)	<0.05 %	<0.20%	<0.75%	<1.50%
False Non-Match Rate (FNMR)	<1.00 %	<2.50%	<5.00%	<10.00%
Transactional False Match Rate (T-FMR)	<0.15%	<0.50%	<2.00%	<4.00%
Transactional False Non-Match Rate (T-FNMR)	<0.50%	<1.50%	<3.50%	<7.50%

Table 4. Selection of standards of the International Biometric Group for classifying the performance of biometric systems. Source: international biometric group [114].

To compare the FAR and FRR to the FMR and FNMR the following formulas can be used [115]:

$$FAR = FMR * (1 - FTA) \quad [6]$$

$$FRR = FTA + FNMR*(1-FTA) \quad [7]$$

Here, the FTA means Failure to Acquire and is defined as the proportion of verification or identification attempts for which the system fails to capture or locate a signal of sufficient quality. The difference with FTE is thus that the FTA occurs when the person is already enrolled, but the system fails to capture the biometric feature during verification. The FAR and FRR, including this FTA in the calculation, are usually reported by the biometric manufacturers and studies (see table 3). However, without knowing the FTA one cannot compare the different performance metrics and the FTA is never reported in the studies. Assuming the FTA to be zero in the incorporated studies is reasonable, because the FTA is not expected to deviate much from the FTE. Making this assumption, only the method of Lin and Fan [67] fails to meet the level 1 criteria for FMR and is not qualified according to these standards. All other methods meet level 1 to level 4 criteria for accuracy.

Some other remarks on table 3 should be made. First of all, in general these studies only reported the FAR and the FRR, except Miura et al. [82] who reported the EER. This makes it hard to compare the results more quantitatively than with the IBG standards, because no threshold independent performance comparisons can be made.

The FTE of 0% might mean that failures to enrol have been excluded from the experiment, although this was never reported. In addition the subjects might not be representative for the general public. Most 'failure to enrol cases' where due to a thick layer of subcutaneous fat [54, 67], and these people might not be present among the subjects. In support of the lack of representing the entire population, in Kono et al. [83] it is said that 'the genetic and age variations in this group of subjects (678 subjects) are much smaller than the entire human population. Further study is needed to test its accuracy in a large group with a large genetic and age variation.'

Most studies in table 3 did not include large numbers of subjects. Therefore, the estimated error rates are less reliable. Cross and Smith [54] state they need a more detailed study, using images from more than a 100 people, to more reliable estimate the FRR and the FAR and to optimize the match parameters.

Another remark can be made on the study of Miura et al. [82]. They found a mismatch ratio of 33% with their new method, compared to a mismatch ratio of 44% using a conventional method. The mismatch ratio is calculated by comparing a manual vein feature extraction done by experts, to the results obtained with the automated methods. This ratio cannot be compared to other studies because they did not report such mismatch ratios. However, the question rises whether 33% mismatch of an automated system is such a good performance. Insight into the reasons why the automated system performs a lot worse than a human eye can provide improvements for the automated system.

A bias in table 3 occurs when more test images of the same hand are taken and used as test images. In this way, the FAR is estimated based on several impostor attempts of the same hand (only the images are taken at different times) and this tends to estimate the FAR lower than when in reality many different people use the system. The number of subjects should thus always be taken into account when looking at table 3.

The experiments where all performed with little time difference between capturing images for enrolment and capturing images for verification. Most subjects performed enrolment and subsequently submitted the biometric feature for verification. It has been shown that over time, many biometric systems are prone to incorrectly rejecting a substantial percentage of users. Verifying a user immediately after enrolment is not highly challenging to biometric systems. 'However, after six weeks, testing shows that some systems' error rates increase tenfold.'[113] Only Cross and Smith [54] have tested two subjects again after several weeks. This implies that the performance metrics in table 3 will become higher when the methods are applied in real world situations, where it is likely that enrolment and verification will occur with substantial time differences.

A last comment to make is that usability comparison of the incorporated methods is not possible because most of the usability metrics of table 4 are not reported.

The most important remark that should be made on the comparison of all the methods of table 3 using the performance metrics reported in scientific studies, patents or company reports is that they are all calculated using different test data and test protocols. This makes drawing hard conclusions on their performance impossible. Table 3 should only be used as an indication for comparison. Ideally system performance parameters are calculated using an infinite and representative test set, which of course is not possible under real world conditions. To get comparable results it is therefore necessary that the metrics that are compared are calculated on the same test data using the same test protocol. The IBG performs 'comparative biometric testing rounds' in which these two test conditions are fulfilled for the biometric devices attaining the test round. In September 2006 the Round 6 Public Report became available [115], in which both Fujitsu and Hitachi subjected their vascular recognition technologies to the comparison test. This reliable performance test is a very good tool for comparison of these two methods.

Comparative Biometric Testing [115]

The IBG evaluates full biometric systems in their comparative biometric testing round 6, consisting of acquisition devices, sample capture software, enrolment software, and comparison software. Data collection occurred in a controlled, indoor office environment. 650 subjects where involved, of which 476 conducted two visits and 174 conducted one visit. During the first visit enrolment and recognitions transactions were performed; during the second visit only recognition transaction were performed to test the performance metrics with a time difference of at least a few days (up to a few weeks) to resemble real world demands on the systems. All subjects were given the same training and guidance. For each subject, two instances were acquired. For Fujitsu PalmSecure system these were the right and the left palm and for Hitachi UB Reader the right index and right middle finger. Fujitsu was tested at three thresholds: Low Security, Default, and High Security. All together, ~90.000 genuine comparisons and ~116million impostor comparisons were executed.

Attempt vs. transaction level calculations [115]

Acquisition and accuracy calculations can be presented in *attempt* and *transaction* levels. Attempt-level accuracy is based on results from each comparison, thereby measuring accuracy without consideration of a multi-attempt decision policy. The FMR is measured at an attempt level: the proportion of impostor attempts that generate a comparison score above a given threshold. The attempt-level FNMR is the proportion of genuine attempts that generate a comparison score below a given threshold.

Transactional error rates on the other hand, are calculated taking into account that multiple match attempts are permitted, which is consistent with the use of biometrics in many applications. Consequently, transactional genuine error rates (T-FNMR) are lower than attempt-level genuine error rates, because a test subject is more likely to match when given multiple attempts. For the same reason, transactional impostor error rates (T-FMR) are higher than attempt-level impostor error rates (see also the standards in table 4).

The set-up of the experiment in the biometric comparison test round resulted in a generation of six comparison scores, based on comparison of each recognition sample against each enrolment sample. Transactional accuracy is based on the strongest comparison score generated within a transaction, i.e. the best-of-six-score. .

FMR, FNMR and T-FNMR, T-FMR do not include acquisition failures. Attempt-level as well as transactional-level accuracy metrics are thorough in evaluating system performance. Transactional-level metrics however, reflect the real world situation for operational systems better.

	Fujitsu		Hitachi	
Zero instances enrolled (FTE)	1	0.08%	1	0.08%
Only one instance enrolled	20	1.55%	6	0.47%
Two instances enrolled	1269	98.37%	1277	99.45%
Total transactions	1290	100.00%	1284	100.00%

Table 5. Enrollment Rates for biometric vein recognition systems of Fujitsu and Hitachi, adapted from [115]..

	Fujitsu		Hitachi	
	Enrolment transaction duration	Recognition Attempt duration	Enrolment transaction duration	Recognition Attempt duration
Min (seconds)	32.6		17.9	
Median (seconds)	61.7	2.13	33.3	1.23
Mean (seconds)	66.8	2.14	38.4	1.77

Table 6. Enrolment transaction duration and Recognition attempt duration for biometric vein recognition systems of Fujitsu and Hitachi, adapted from [115].

	Fujitsu		Hitachi	
Zero instances acquired (**T-FTA**)	5	0.15%	2	0.06%
Only one instance acquired	6	0.18%	15	0.45%
Two instances acquired	3343	99.67%	3334	99.49%
Total transactions	3354	100.00%	3351	100.00%

Table 7. Transactional Acquisition Rates for biometric vein recognition systems of Fujitsu and Hitachi, adapted from [115].

Ennrolment and recognition results [115]

The results for failure to enrol rates (FTE) are shown in table 5. The report states that Hitachi and Fujitsu achieved FTE rates exceptionally low for this type of testing. Hitachi was able to enrol both the middle and index finger in all but 7 enrolment transactions.

The results for enrolment transaction duration and recognition attempt duration are shown in table 6. Enrolment transaction duration includes time required for the test person to align himself with the acquisition device, the time needed for al presentations needed for template generation to enrol, the time between enrolling the first and second instance (e.g. left and right) and the generation of the enrolment template. Recognition attempt duration includes time for the test person to align himself with the acquisition device, time for the device to locate the instance, and time for the software to validate the quality of the sample. It is clear that Hitachi performs faster that Fujitsu. It depends on the application whether time constraints are important. Application software and interaction between test subject and sensor will also impact enrolment duration.

Acquisition and Accuracy Results [115]

The transactional failure to acquire rate (T-FTA) is shown in table 7. Per definition, the T-FTA is calculated using the number of recognition transactions in which no instance is successfully acquired. The T-FTA was universally low according to the report; each system acquired one or more sample in over 99.5% of transactions.

The accuracy metrics are measured for same-day attempts (performed in visit 1) and for different-day attempts (visit 2 tested against the template created at visit 1). This also holds for same-day and different-day transactions, where the strongest comparison scores are used. The resulting same-day and different-day FMR, FMNR, T-FMR and T-FMNR accuracy results are shown in table 8 and table 9. The results for different-day transactional metrics are the most relevant ones, because most devices allow multiple attempts, and have to perform comparisons for biometrics captured at different days.

Table 8 and 9 appear different for Hitachi and Fujitsu. This is due to the practice to evaluate systems based on their genuine error rates at specific impostor error rates. A system can for example be configured to provide 0.10% or 0.01% FMR, to ensure the likelihood for a false match is of 1 in 1000 or 1 in 10.000 respectively. Therefore, the IBG examined the genuine error rates at these specific impostor rates as shown in table 8. However, Fujitsu does not generate matching scores, but matching *decisions* (match or non-match) and the genuine error rates can thus not be calculated at impostor error rates of precisely 0.10% or 0.01%. The scores for Fujitsu are represented in a different manner in table 9, but comparison between the two tables can still be done.

Hitachi	Attempt level (FNMR)		Transactional (T-FNMR)	
	Same-day	Different-Day	Same-Day	Different-Day
Genuine Error Rate fixed at 0.10% FMR/T-FMR	0.77%	3.02%	0.34%	**1.94%**
Genuine Error Rate fixed at 0.01% FMR/T-FMR	1.26%	4.72%	0.68%	**2.77%**

Table 8. Attempt level and transactional accuracy results for the biometric vein recognition systems of Hitachi, adapted from [115].

Fujitsu	Attempt level				Transactional			
	Same day		Different Day		Same Day		Different Day	
	FNMR	FMR	FNMR	FMR	T-FNMR	T-FMR	T-FNMR	T-FMR
Low security	3.13%	0.0380%	6.17%	0.0395%	0.22%	0.1766%	0.33%	0.1831%
Default	4.23%	0.0118%	8.52%	0.0135%	0.57%	0.0559%	**0.69%**	**0.0629%**
High Security	5.64%	0.0018%	11.86%	0.0007%	0.87%	0.0091%	1.42%	0.0042%

Table 9. Attempt level and transactional accuracy results for the biometric vein recognition systems of Fujitsui, adapted from [115].

Based on table 4, Hitachi's system would perform according to the level 2 accuracy standard and Fujitus's system would perform according to level 3 accuracy standards, and thus slightly better. Hitachi clearly performs a lot better on the same-day than on different-day accuracy metrics. Also Fujitsu performs better on same-day comparisons, but its different-day T-FNMR of 0.69% is a very good achievement, compared to other systems with a corresponding T-FMR. Fujitsu's attempt-level FNMR is relatively high.

Another way to visualize accuracy performance for biometric systems is with detection error trade-off (DET) curves. DET curves plot error pairs (e.g. FNMR and FMR) across a range of values. The accuracy improves towards the bottom-left corner of the graph. In figure 47 and figure 48 (next page) the DETs show error rates across the following ranges: FNMR and T-FNMR: 100% to 0.01%. FMR and T-FMR: 100% to 0.0001%. DET curves provide a tool for identifying at which point (threshold) one wants to operate the system (e.g. at 0.01% FMR). In Round 6 of Biometric Comparison Testing a third system, IrisGuard H-100 for iris recognition, was included. IrisGuard and Hitachi systems obtain output score values, which can be evaluated at different thresholds, while Fujitsu generates decisions which can only be evaluated at three thresholds. Therefore Fujitsu's DET curve consists only of three measure points at these thresholds. Figure 47 and 48 show attempt-level and transactional DETs for the three systems.

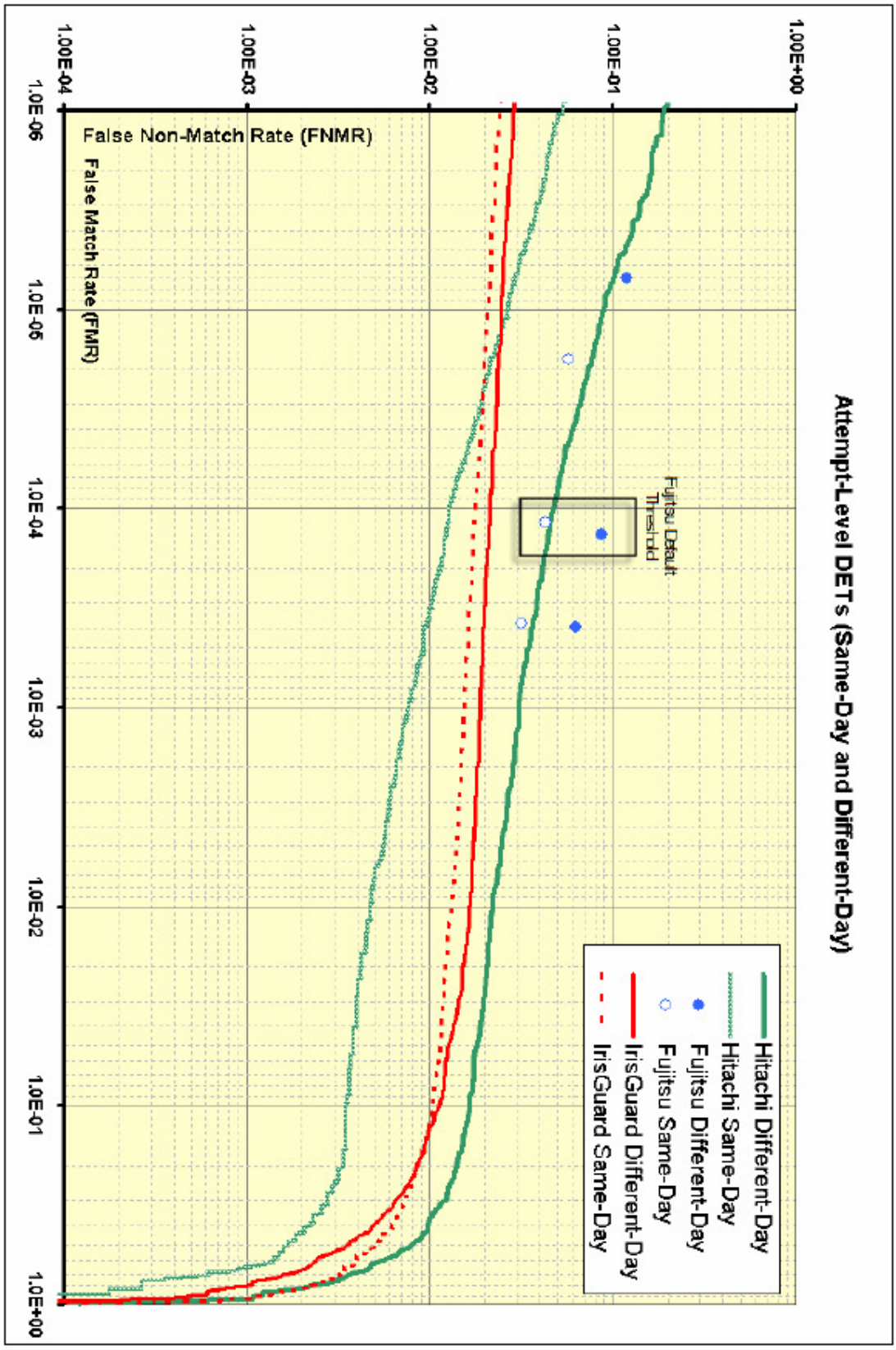


Figure 47. Attempt-level DET curves for Fujitsu, Hitachi and IrisGuard biometric systems. Obtained from [115].

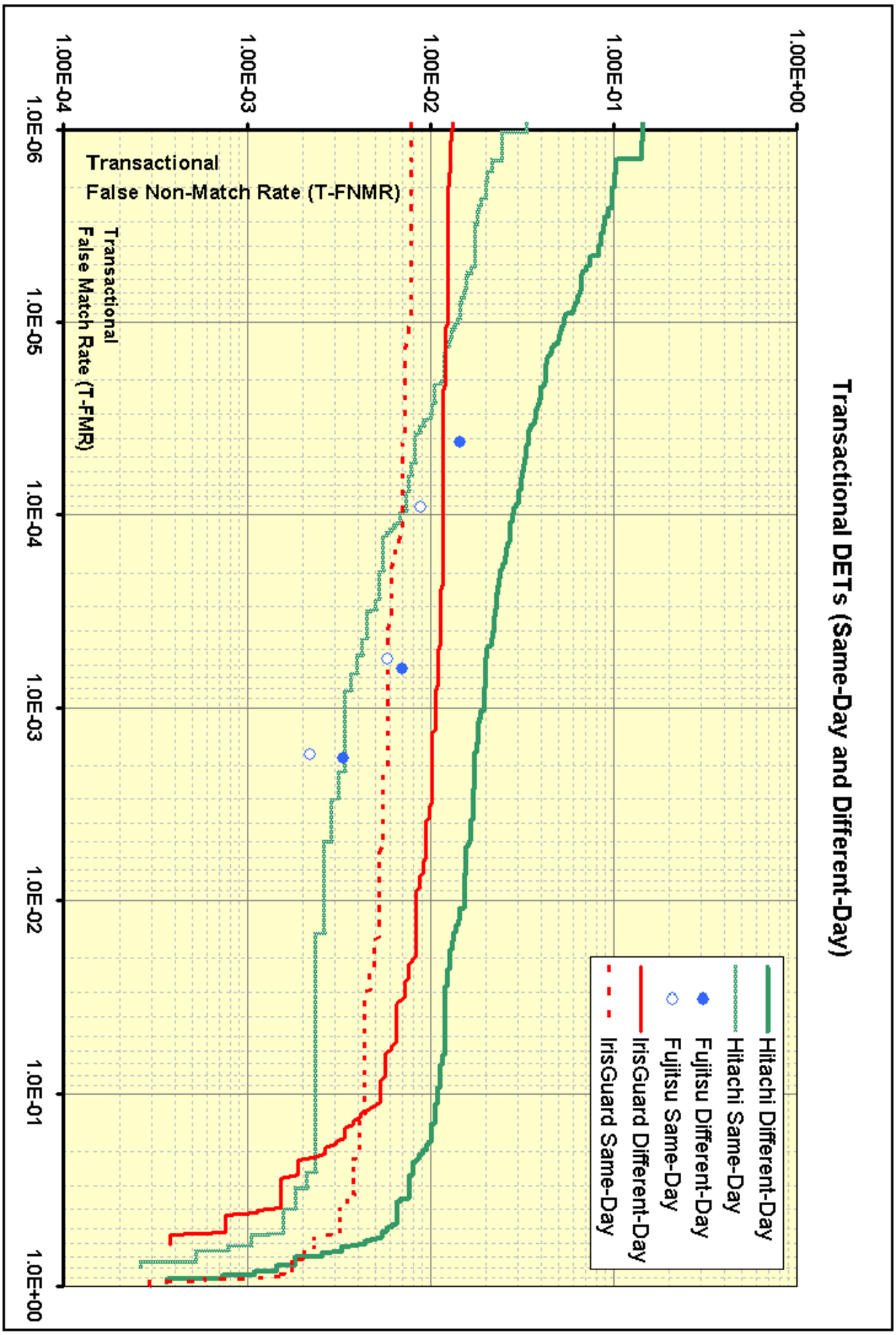


Figure 48. Transactional DET curves for Fujitsu, Hitachi and IrisGuard biometric systems. Obtained from [115].

The overall result of to IBG's Public Report is that all three systems 'can be considered very high-performing systems for the types of applications that CBT (Comparative Biometric Tests) models.' They were surprised by the low failure to enrol and acquire rates generated by particularly the vascular recognition systems, even at the attempt-level. Also the short durations of the systems processes, especially of Hitachi, were marked as very positive for usability.
'In sum, vascular recognition appears to be a very serious competitor to fingerprint, hand geometry, and certain iris recognition systems used in large-scale 1:1 access control, logical access and customer ID applications. The systems provided a strong combination of usability and accuracy.'

Performance challenging

The Comparative Biometric Testing, Round 6 [115] was the first independent comparison study done for vascular recognition systems. The positive result is a nice accomplishment for these two systems. However, some remarks should be made to put the results into perspective. As has been shown by Wang and Leedham [1], vascular images captured in an office environment obtain high quality compared to images captured in less constant environmental settings, such as an outdoor (tropical) environment. All performance studies so far, have been conducted in office or laboratory environments, including the IBG Test Report. In real life situations it is likely that people will use the systems outside, or coming from outside environments indoors. Performance test in such variable conditions should also be performed, to investigate the usability and accuracy of vascular recognitions systems.

Another remark is that all match attempts have been made with real, biological, living hands of people with goodwill who did not try to challenge the system. The question is how the systems are equipped to distinct between real and fake hands, and protect themselves against attacks from real impostors. In Chapter 4 on Liveness Detection more information regarding this threat is given and vascular recognition systems are evaluated in this respect. For now it is important to keep in mind that the performance studies described so far, have not dealt with real impostor threats.

3.3.7 Speed

Two criteria for usability performance put forward by the IBG are duration of enrolment transaction and duration of recognition attempt duration [115]. Fast algorithms, simple processes and good processors can therefore also influence the performance of a system. The method of Ding et al. [112] for example, encounters speed problems in the part of threshold segmentation. Indeed the developed algorithm looks rather cumbrous. Several studies are focused on improving the speed of the authentication process by improving algorithms [84, 116].

One example is the development of an application specific processor (ASP) and algorithm for vein pattern extraction, by BK systems in cooperation with the Department of Electronics Engineering of Korea University [84]. It can replace the conventional vein-pattern-extracting algorithm that inevitable includes a high-priced digital signal processor (DSP) used in biometric identification systems. In the conventional algorithm floating-point operators are needed for the Gaussian low-pass and high-pass filtering processes in a real-time process. The proposed algorithm follows the same steps as the conventional algorithm, except that both coefficients for the Gaussian low pass filter and the low pass filter are designed to have 7-tap CSD (canonical signed digit) codes at the maximum. It is said that, CSD code is an effective code for designing a FIR (finite impulse response) filter without a multiplier. The general CSD code is equal to,

$$W_j = \sum_{i=1}^{M_j} S_i 2^{-i} \qquad [8]$$

where j = 1, 2, …, 121, $S_i \in$ {-1, 0, 1} and M is an integer. Instead of using a 3 x 3 spatial Gaussian low pass filter repeatedly, an 11 x 11 spatial Gaussian low-pass filter is applied. Also, for the normalization, the fast decimation method is used. A fast data processing capability is reached using the proposed algorithm of 150 ms/person.

The accuracy and usability aspects of the vein pattern verification systems influence their performance, from qualitative image capturing till fast verification, as has been described so far. The next step is assessing their performance when being challenged by an impostor, as can be expected for security systems. The next chapter deals with this.

4 LIFENESS DETECTION

To illustrate the concept of liveness detection I would like to start with an example from [117]: At certain places in Africa it was custom to identify people entitled to social benefits by their fingerprints. After verification they were directly given their money. One day two young people came in, heavily supporting an old man in between them. When they arrived at the front desk, they had to help the man by raising his arm and pressing his finger on the ink and paper, and explained 'he is very lazy'. Because of the rather unnatural and uncoordinated movements of the man, the employee behind the desk became suspicious. End of the story: the man turned out to be dead. Before this attentive employer caught this couple red-handed, they had successfully obtained money from several other dead claimants.

Liveness detection is the capability of a biometric system to check whether the biometric sample presented for verification or identification is alive or not. It should also be able to check whether the biometric feature being captured belongs to the authorized person who is present at the time of capture. When a system fails at this point, it is said to be 'spoofed' by the perpetrator: he/she can, for example, gain access to a secured system by presenting fake biometric features (fake artefacts) that belong to an authorized person. Or, as in the example, presenting original biometric features that belong to a dead body and are therefore non-acceptable.

There are four scenarios possible as a consequence of the susceptibility of biometric systems to spoofing [19, 118]:

- fake artefacts may be mounted against existing enrolments in order to gain access to a protected facility or system
- fake artefacts being used to associate the authentic owner of the biometric feature with an unauthorized event.
- fake artefacts may enrol in the system and subsequently be shared across multiple individuals, thereby undermining the integrity of the entire system
- the inability of the system to defend against attacks with fake artefacts gives authorized users the possibility to repudiate transactions associated with their enrolment, and claim that they are done by perpetrators.

Given these unwanted scenarios – especially because biometric control systems are often used in essential processes in society; like bank and network security, border control or access to private properties – a proper incorporation of liveness detection in biometric systems is very important.

In the example above, the liveness detector was a person supervising, who was able to recognize a non-living biometric feature. But well organized, hardly visible spoofing of biometric features is very hard to detect by the human eye. Moreover, most biometric systems are supposed to be fully automated to exclude the need for an employee. Many manufacturers claim that liveness detection is incorporated in their systems. But striking results have been reported on how easily biometric technologies are susceptible to attacks in which fake fingerprints, static facial images or video clips, and static iris images can be used successfully as biometric samples. Methods of attack include fashioning fingerprints from gelatine or silicon (see figure 48), superimposing iris images atop human eyes, even breathing on a fingerprint sensor [4, 21, 23, 113, 119, 120]

This chapter contains a general description of liveness detection, followed by liveness detection techniques that can be applied to hand vein pattern biometric systems. These techniques are already used in hand vein systems; are derived from fingerprint verification systems; or are proposed as new, potential liveness detection techniques. Directly after each technique description a method to fool this technique is suggested. The chapter ends with a section on additional methods to prevent spoofing, on other attacks at biometric systems and finally a discussion on this chapter.

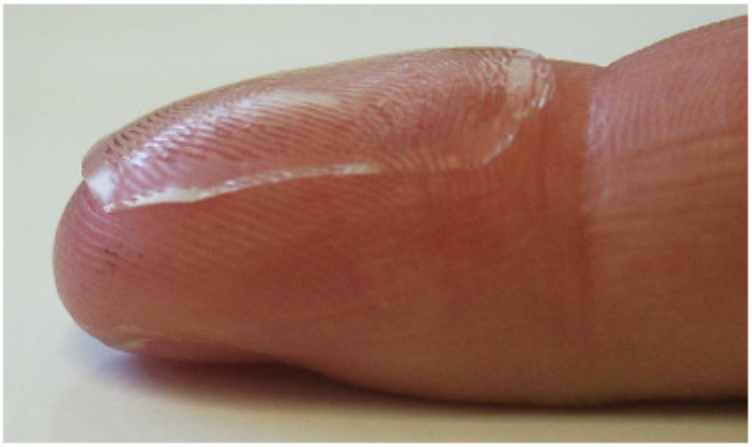


Figure 48. A fingertip with a wafer-thin gelatine fingerprint on top of it. Obtained from [4] figure 7.4

4.1 Principles of liveness detection

When considering liveness detection, one should also consider the concept of non-liveness detection. Looking at the mechanisms nowadays however, often the theory of liveness detection is addressed: one or more qualities of a biometric sample are consistent with the qualities associated with live biometric samples. Therefore a biometric system is designed to process data that falls within a certain set of parameters (often with margins) and to not process data that falls beyond the margins of these parameters. In 'IT-language' this decision process can be described as

```
if data = live, perform acquisition and extraction;
```

rather than

```
if data = not live, do not perform acquisition and extraction;
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This means that the tendency towards liveness detection as opposed to non-liveness detection in biometric systems gives individuals that want to spoof the system the simpler task of mimicking characteristics of a live sample, than circumventing non-liveness detection methods. Although a fake biometric sample can have a number of non-live characteristics, as long as it possesses the feature characteristics that represent liveness, it can defeat the system. In fact, it is stated by [19] that '*any liveness detection method can and will be defeated*'.

The check for liveness can be performed at the acquisition stage (capturing raw data) or at the processing stage (obtaining features from raw data). All methods of liveness detection fall within three broad categories [117]:

1. methods that look at the intrinsic properties of a living body

   E.g. weight, density and elasticity, (physical properties), capacitance, permittivity and resistance (electrical properties), colour and opacity (visual properties), reflectance and absorbance (optical properties), and the analysis of bodily fluids for contents such as blood constituents, oxygen or DNA.

2. methods that analyze involuntary signals generated by a living body

   E.g. pulse, blood pressure, heat, thermal gradients, corpuscular blood flow (plesythmographic) signals, skin exudation, transpiration of gases, body odor, perspiration, electrical signals generated by the heart (ECG), brain wave (EEG).

3. methods that measure a bodily response to a stimulus – a challenge-response method. It can look for either voluntary (behaviorial) or involuntary (reflexive) responses.

   E.g. voluntary; the user provides a logical response to a prompt generated by the system. The stimulus can be tactile, visual or auditory in nature. ("touch A if the plate is hot, touch B when the plate is cold", or tasks like smiling or blinking)
   Involuntary; user's body automatically provides the response with a physiological change or reaction to a stimulus (electrical response for muscles, pupil reflex, knee reflex)

Lifeness detection is generally implemented in the system in one of the following three ways: it can capture signs of life from liveness information inherent to the biometric feature; from additional processing of data already captured by the biometric reader; and third from the acquisition of life signs by using additional hardware [22].

Additional hardware has got the disadvantage that it is bulky, expensive and it might be easy to spoof when it is possible to present the fake artefact to the identification hardware, while another living biometric sample is presented to the liveness detector. Successful liveness detection can already happen when a fake biometric sample is mounted on a living person. Examples of life signs captured by additional hardware are blood pressure, oxygen content or challenge-response actions.

The second approach - an algorithm for liveness detection to process data that is already captured by the biometric device - does not have these disadvantages, but it can be difficult to accomplish liveness detection without obtaining more data with additional hardware. One example in the fingerprint field is measuring perspiration over time as both a life sign and a way to image the unique ridges and valleys of a fingerprint [121]. The limitation is that the liveness detector should be effective in both dry and sweaty environments, and this wide range of the parameter 'perspiration' makes it easy to be included using an artificial fingerprint.

Biometric features that inherently contain liveness information are for example keystroke patterns [122], gait [123], ECG [124] body odor and facial thermograms [22]. These systems require a living person in order to measure the biometric feature and are therefore least susceptible to spoofing. These biometric technologies are not yet as developed as other biometric modalities (fingerprint, iris recognition). Some regard hand vein biometrics as belonging to this category as well [22], but this is not in agreement with practical results of the method. This is explained in the next section where more information is provided on liveness detection with regard to vein pattern recognition systems.

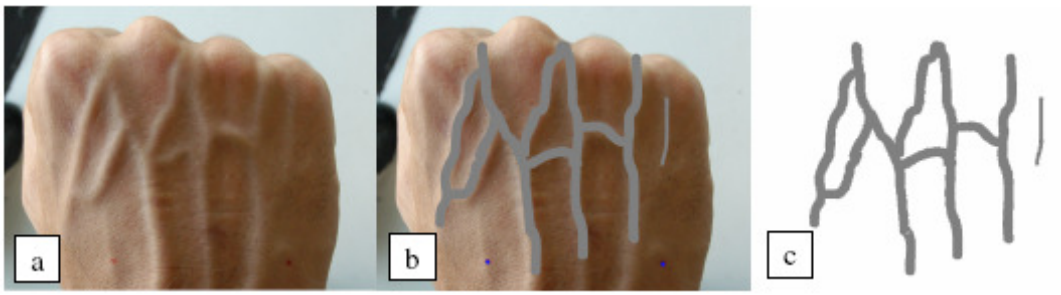

Fig. 49 How to obtain a hand vein pattern using a digital camera. a) Image of the back of the hand shot in daylight using a common digital photo camera. b) visible veins are traced to obtain only the hand vein pattern shown in c) the hand vein pattern ready for printing. Obtained from [11] figure 5.24

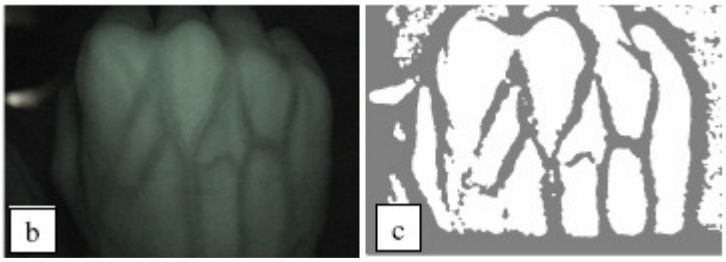

Figure 50. How to obtain a hand vein pattern using a night camera. b) Using a handycam with nightshot function this image of the hand was taken in the dark c) two-color vascular pattern extracted from the image in b) using image processing techniques. Obtained from [11] figure 5.25

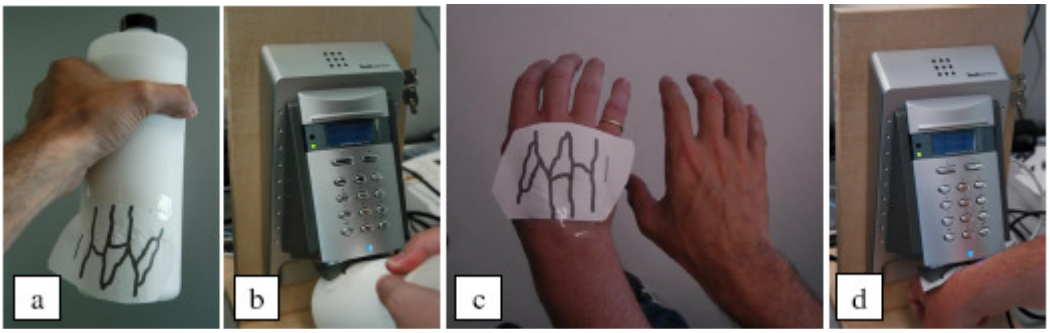

Figure 51. The ink copy of the obtained vein pattern mounted on a bottle (a) and on a hand (c) has shown to be an effective spoof and is verified as authorized user by the device (b + d). In b) the original hand (right) is shown next to the copy of the vein pattern (left). In this experiment the lifeness detection was turned 'off'. Obtained from [11] figure 5.27

4.2 Liveness detection in hand vein pattern recognition systems

4.2.1 Challenging the systems

Liveness is not inherent to a hand vein pattern in the present commercial systems that use this biometric feature. Recently, it has been shown to enrol a fake artefact in a hand vein pattern recognition system or match fake vein patterns with live vein patterns in a very easy way [11]. In figures 49 and 50 it is shown how vascular patterns can be obtained with cameras or night cameras and then simply mounted on a hand or a bottle to be identified as the vascular pattern of the biological owner of the pattern (figure 51). This study examined the TechSphere VP-II device (section 3.1.1 page 42).

To recapitulate; most methods for obtaining the vascular pattern are based on illuminating the hand, finger or palm with a near-IR source, and capture the reflected light with near IR optical sensors (section 2.3.2 page 24). The different absorption properties of blood and tissue in this wavelength region enable the system to visualize the locations of veins where there is more absorption of light than at non-vein regions (section 2.3.3 page 24). When the absorption and scattering properties of flowing blood and living tissue would be too complex to imitate and satisfy the devices that capture these properties, then liveness detection would be inherent to the system. In practice however, the IR-absorption-based hand vein imaging methods do not require that the presented hand is actually living or that the blood is flowing. And concluding from the positive spoofing results with simple ink-copied vein patterns (figure 51), it is not even required to present a vascular pattern containing hemoglobin. In an informal test setting, documented in appendix A, similar results were obtained with a commercial system (Fujitsu, secton 3.1.2 page 46) that utilizes the vascular pattern in the palm of the hand.

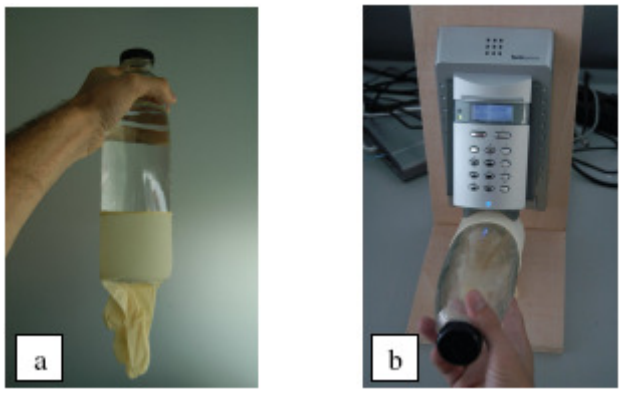

Figure 52. a) Latex glove on bottle (without a vein pattern) b) the latex glove identified, with liveness detection 'on'. Obtained from [11] figure 5.26

Enrolment liveness detection	Verification liveness detection	Enrol vascular pattern copy, verify with same	Enrol vascular pattern copy, verify with live vascular pattern	Enrol live pattern, verify with vascular pattern copy	Enrol latex glove on bottle, verify with same
Off	Off	successful	successful	successful	successful
On	Off				successful
Off	On		successful		successful
On	On				successful

Table 10. Results of a study on spoofing of vein pattern recognition biometrics for different liveness detection settings of the biometric device. Obtained from [11] table 5.16

4.2.2 Applied liveness detection?

The results [11] mentioned in the section above are striking and illustrate the need for liveness detection in vascular pattern recognition systems. In addition, this same study did *not* successfully fool the biometric device when the liveness detection setting was turned 'on': all attempts of enrolling a vascular pattern paper copy or matching a paper copy with a template pattern failed. This indicates the importance of liveness detection for this biometric system. On the website of TechSphere information on the prevention of entry of non-biometric information is as follows: "The capability to sense the user's temperature pattern is another VP-II™ s outstanding feature as a biometric system. The system performs a comparative analysis on the temperature distribution attributes, blocking the possibility of the registration of a non-organic entity." [95]. Where this liveness detection apparently worked against attacks of paper copies of vascular patterns, it did not for a third attempt in the same study [11]. Here, an unmodified latex examination glove atop of a bottle, without any vein pattern on it, could enroll in the system and was subsequently verified by the system, with liveness detection 'on' in both enrolment and verification. This is illustrated in figure 52. All results of this study are presented in table 10.

The company Fujitsu claims that liveness detection is incorporated in their product PalmSecure™ because 'The device captures a vein pattern only if haemoglobin is actively flowing through a user's veins', although the means by which this is done are not explained [125].

In the patent of Clayden used by Luminetx it is stated that 'by viewing the vein pattern through a pair of filters having different transmission characteristics, it is possible to differentiate between veins and arteries, which have different relative contents of oxy-haemoglobin and carboxy-haemoglobin. This may be used as a basis for enhanced recognition tests or simply to verify that the hand is still attached and vital." [87]

Another patent [109] states: 'The location of blood vessels may be detected by differential temperature measurement. Alternatively, movement or the presence of blood can be detected by techniques such as nuclear magnetic resonance or acoustic monitoring of the pulse.'

4.2.3 Thermal imaging

On pages 48, 64 and 66 three biometric devices are covered that work essentially different from most commercial vein pattern imaging methods. These methods capture the naturally emanating infrared light from the hand as opposed to scanning the hand with an IR-beam and capturing the reflected light. Vascular regions emit IR-light with a higher intensity than non-vascular regions. Therefore, a thermal image shows the pattern of the veins. For these methods, the biometric feature is a thermal image from the hand which indeed inherently contains liveness information; a dead hand or a paper copy will not emit IR-light.

4.2.4 Methods for liveness detection

In the hand vein pattern biometric systems this passive thermal imaging is not common used. Most companies make use of the active scanning technique, where *additional* liveness detection should be an essential part of the system to improve reliability. Some companies (TechSphere, Fujitsu, Luminetx) claim that they incorporate liveness detection. Information on their liveness detectors however is minimal. And abnormal enrolments, as shown with the white glove experiment [11], are yet to be explained if TechSphere actually uses a temperature liveness detector.

Therefore, in the next sections several methods for liveness detection will be presented. They are subdivided into the three categories based on: intrinsic properties, involuntary signals and bodily responses [22]. Applicable methods for vein pattern biometrics which have been studied for fingerprint or other biometric technologies will be discussed in addition to the methods already used in hand vein pattern recognition and several proposed methods from the medical field. These can be applicable to hand vein pattern recognition systems as well.

4.3 Intrinsic Properties

Living human bodies exhibit intrinsic properties (parameters) that can be measured by liveness detectors. A positive measurement result indicates that the parameter under investigation corresponds to the range of this parameter found for a living body. The main problem is that for some parameters other materials also exhibit these 'liveness cues'. The intrinsic properties can be measured inherent to the biometric feature, by adding software and by using additional hardware.

4.3.1 Liveness inherent to biometric feature

a) Spectrographic signature (near infrared region)

Living tissue under infrared illumination has a characteristic spectral signature, due to the different absorption properties of the components of living tissue (section 2.3.3 page 24). As a means for liveness detection in iris scans it is suggested to compare the fractions of light reflected in 650nm – 1100nm bands (tissue optical window) to reveal these characteristics and verify the liveness of the presented eye [126, 127].

Of course, this suggestion for *liveness detection* in iris scans is the basis of the *biometric detection* in the vein pattern imaging biometric technique. This means that the spectrographic signature of the hand used for imaging of the veins is also a liveness detector and thus inherent to the biometric sample. Then of course, the question remains, why is this not the case in practice? As shown before, without additional liveness detection the hand vein biometric systems can easily be fooled.

This possible liveness detection method in iris scanning is only mentioned in [126, 127], without providing information about the exact method, which makes it difficult to answer the question. Most probably the vein imaging biometric methods are not selective enough to capture specific wavelength dependent spectral properties of tissue, fat, blood and pigment. Commercial available LEDs used for biometrics according to [128] are for vein imaging: 780 nm and 870 nm LEDs; for iris imaging 810 nm and for finger imaging 660 nm. Their half width is approximately 35 nm. Hitachi [80] makes use of 810 nm light and in [54] 880 nm is reported. Most filters to prevent visible light entering the CCD imaging apparatus are commercially off-the-shelf longpass filters.

So what happens is that a spectrally broad scanning beam of NIR light illuminates the hand. This light will be partially absorbed, scattered or reflected depending on the underlying material. The (diffuse) reflected light is captured by the CCD, whereby the shorter wavelengths will be reduced by the filter, but most filters allow wavelengths down to 650 nm to pass. In this wavelength region, (deoxy) haemoglobin is one of the main absorbing proteins when imaging a hand. But when imaging an ink pattern in this wavelength region, the ink will also be the main

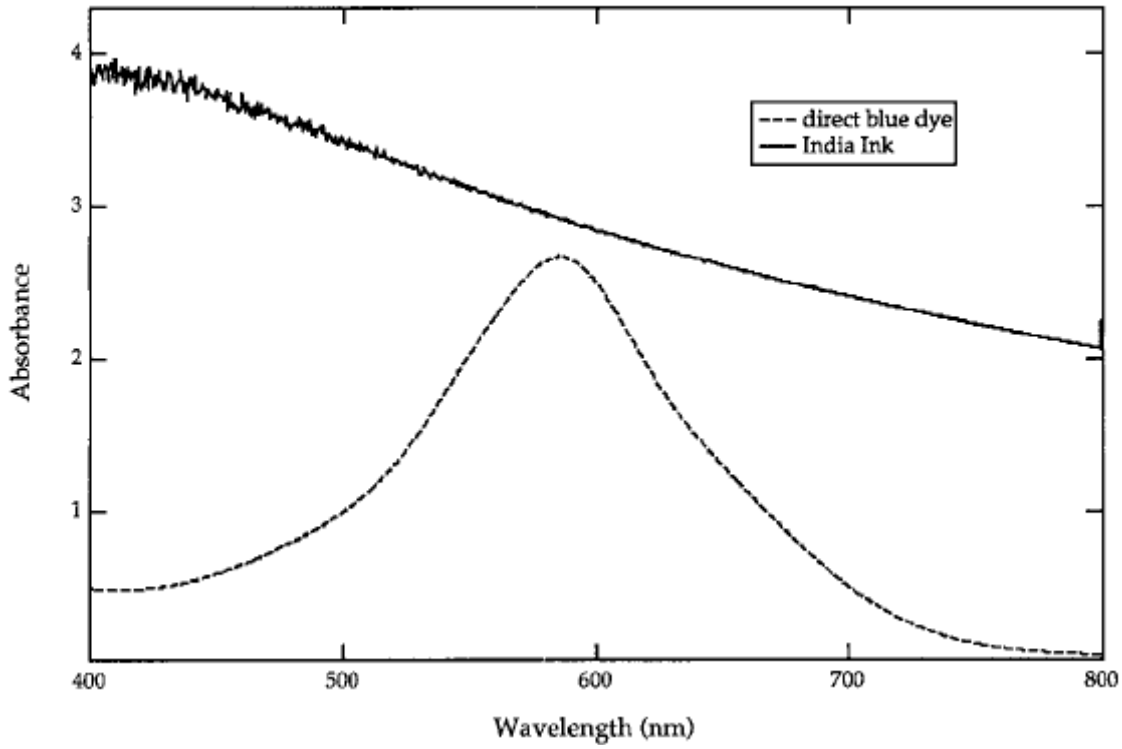

Figure 53. Absorption spectra of India ink and blue dye. Obtained from [129] figure 5.

absorbing component compared to e.g. white paper. This can be seen in figure 53: India ink absorbs everywhere in this spectrum and a blue dye absorbs up to 800 nm. Herein lays the essence of the problem: other materials than veins share similar absorption and scattering properties in this wavelength area.

When looking at the absorption spectra of the main components of blood (fig. 10), they are of course different and more complex than the spectrum shown in figure 53. But because of the non-selective illumination and detection of NIR light by the devices, this doesn't matter for obtaining an image. Therefore, these devices can be spoofed by a vein pattern produced by ink on paper.

A solution to this problem might be to make use of several selective band pass filters and light sources at different wavelength and to calculate the absorption *ratio* for these different wavelengths to make better use of the specific absorption properties of (deoxy) haemoglobin along the NIR spectrum. Arteries (HbO_2) will for example absorb more at 900 nm compared to 700 nm, while veins (Hb) have opposite absorption properties. A similar approach has been proposed in the patent of Clayden, utilized by Lumintex [87]. Disadvantages are the costs of these expensive filters and the fact that the hand should be kept very still while several images are made using each filter.

4.3.2 Using extra hardware

a) Comparative Analysis

Comparing several images taken at different wavelengths of the same hand vein pattern, as described in the last paragraph of the former section, should be categorized as using extra hardware: adding filters and/or light sources, including additional algorithms to obtain the liveness characteristics. These characteristics are the specific absorption properties of (de)oxyhaemoglobin at certain wavelengths, which are harder to imitate with fraudulent materials. Main disadvantages are the costs and the practical implementation of this method.

a) Electric resistance

Electric resistance is a measure of the degree to which an object opposes the passage of an electric current [5]. This can also be done for the skin; by passing a weak current through the skin and measuring the electricity flow. In galvanometers, for example, this is measured over time as a function of emotion: electric resistance depends on the humidity of the skin which increases during sweating. Some people have a dry skin, while others produce a considerable amount of sweat. To get an acceptable FRR, the acceptance range in electric resistance is wide. Therefore, it is easy to spoof this method. The method is used so far in fingerprint biometrics, and spoofed by simply putting some saliva on a silicon fingerprint [21]. In addition, this liveness detection method requires contact with

the sensor, while from a hygiene point of view one of the advantages of the hand vein biometric technique is, that no contact is needed.

b) Relative dielectric constant

Another liveness detection method found in the fingerprint field is the relative dielectric constant (RDC). The RDC of a material is the ratio of the amount of stored electrical energy when a potential is applied, relative to the permittivity in vacuum. It is also called relative permittivity [5]. The RDC of the skin can also be measured as a property of liveness of the skin. As with electric resistance, the RDC depends on the humidity of the skin. Spoofing of this liveness detection method again is not difficult, because other commonly available materials have a RDC value within the acceptance range of the RDC of the skin [21]. Another disadvantage of this liveness detection method is that contact with the sensor is required.

c) Temperature

A living human body keeps itself warm; the temperature at the epidermis is in normal conditions 26-30°C. A temperature sensor can be incorporated in the device that measures whether the epidermis' temperature is 'alive' [21, 130]. The same problems arrive here: the margins are rather broad and physical contact is required. Moreover, the skin that touches the temperature sensor can be real, while the 'veins' are fake.

The company TechSphere states to not only measure *one* temperature, but the liveness detector measures the *thermal gradient* of the hand. The system then compares this temperature distribution to the thermal pattern of a 'living hand' to block the registration of a non-organic entity [95]. It is never said how this works exactly, but the enrolment of a Latex-glove [11] seems to undermine the reliability of the liveness detector.

d) Oxygen content

Another intrinsic property of a living human body is the oxygen content of blood. Since 1983 a non-invasive method of monitoring the oxygenation of a patient's blood is used in hospitals, namely *pulse oximetry*. The simple application makes it possible to use in a biometric device [130]. It works as following: a sensor is placed on a relatively thin (translucent) part of the patient's body, usually a fingertip or earlobe. On the other side of the finger a pair of small LED's is placed and red and infrared light is passed from one side to the other. The light is partly absorbed by haemoglobin, by amounts which differ depending on whether it is saturated or not saturated with oxygen (HbO_2 vs. Hb, see figure 10). By calculating the absorption at the two wavelengths the processor can compute the proportion of haemoglobin which is oxygenated. The computer within the oximeter is capable of distinguishing pulsatile flow from other more static signals to display only the arterial flow and factor

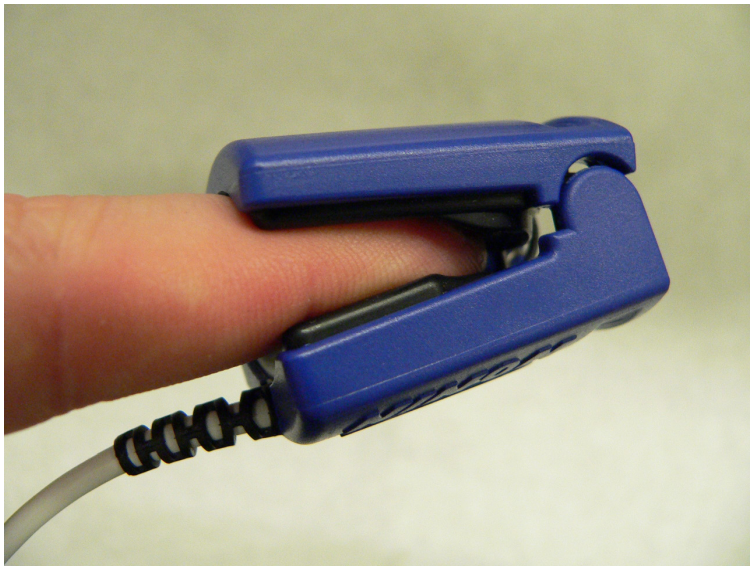

Figure 54. Example of a pulse oximeter, typically used through the fingernail. Obtained from[5].

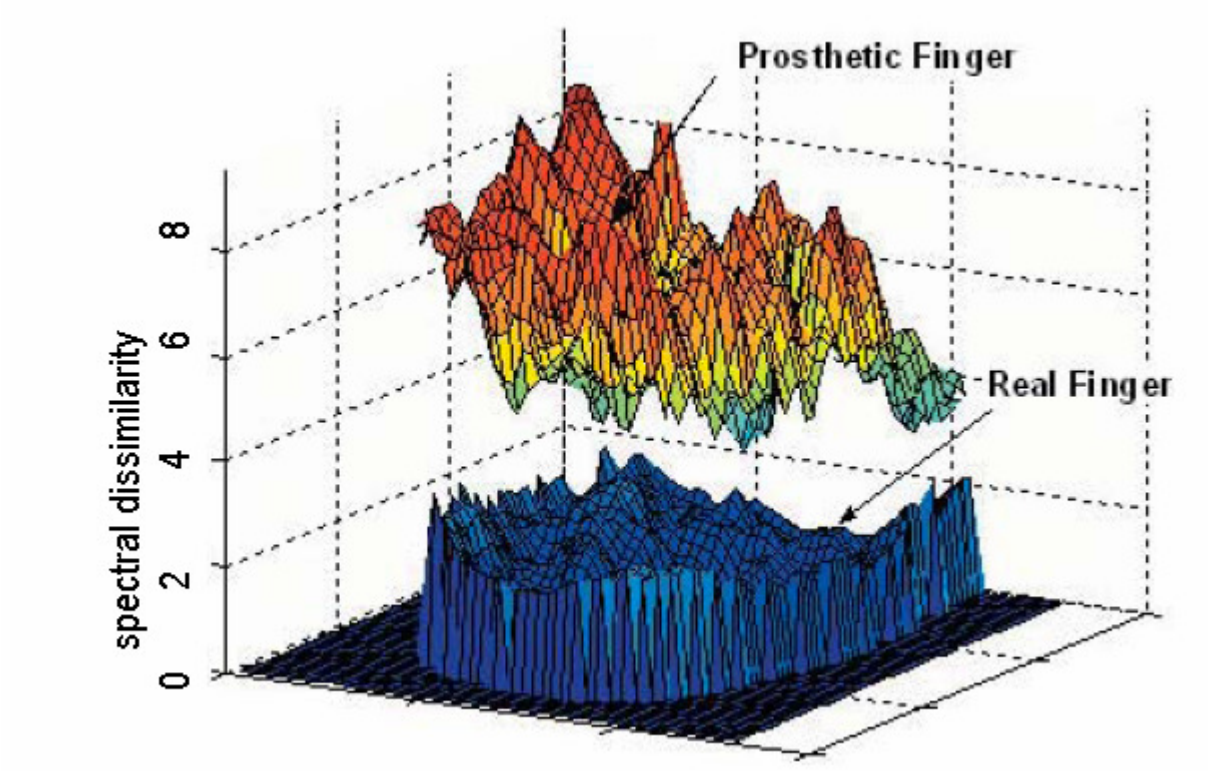

Figure 55 Spectral differences with respect to a living finger for a second measurement of the finger and a well-matched spoof. Obtained from [131] figure 6.

out venous blood, skin, bone, muscle, fat, and even fingernail polish. Therefore, the oximeter is dependent on pulsatile flow and it will not function if there is none [5, 132, 133]. An example of a medically used oximeter is shown in figure 54.

Acceptable normal ranges of percentage oxidized hemoglobin are from 95 to 100 percent. Falsely low readings may be caused by hypo perfusion of the extremity being used for monitoring (due to the part being cold or from vasoconstriction due to the use of vessel narrowing agents); or by incorrect sensor application; highly calloused skin; and movement.

These last issues can be a problem in the use in biometric devices outside or with moving or calloused hands. Advantage is that this method is dependent on both pulse and absorption, thus actually measuring two features of liveness. A disadvantage again is that physical contact is required and although these liveness cues are hard to simulate, it is easy to spoof the biometric detector while the liveness detector measures the pulse and oxygen features of a living unauthorized person [22].

e) Spectrographic signature (near infrared and visual region)

The company Lumidigm, specialized in fingerprint biometric systems, makes use of a multispectral imager to verify liveness characteristics in a fingerprint [131]. The system consists of multiple illumination wavelengths for imaging, in addition to regular total internal reflection imaging to obtain the fingerprint features. Two out of three anti-spoofing methods they developed which can be applied to vein imaging will be discussed in this section, while the third falls in the category discussed in section [response x.x].

1. Principal Component Analysis

Lumidigm has developed a small and rugged spectral sensor using solid-state optical components operating in the visible and very NIR spectral region (400-940nm) that accurately measures diffusely reflected skin spectra. This non-imaging spectroscopic method uses spectral metrics determined from the enrolment sample and compares those to the same metrics calculated from the test sample. The developed algorithm creates a model using Principal Component Analysis (PCA) during the enrolment process. This model is compared to the test image using the Mahalanobis distance. A threshold criterion is used to verify similarity. According to the authors the models created from enrolment spectra, even when using the small number of wavelengths available in this system, are effective for detecting sample materials that are not living skin, provided that the enrolment occurs in a supervised, secure manner [131].

2. Chromatic Texture

This spoof detection method compares the power spectra from the enrolment and test images to determine if the test image is a spoof. A power spectrum is a diagram of wavelength versus reflected intensity. Power spectra of non-humane materials have different optical properties than human skin, resulting in a deviation from ‘normal’ optical signal. The same holds for dismembered tissue [118]. In figure 55 Lumidigm shows how much spectra differ between a prosthetic and a real

finger. The algorithm determines the frequency content ('texture') generated by the different colours for each enrolled person and then compares the texture of a test image to the enrolled texture. A reliable liveness check is the result, provided that the enrolment occurs in a supervised, secure manner [131].

The two anti-spoofing methods both use optical properties of the skin in the infrared and visible wavelength (red, blue and green) region as a liveness detector. Not much technical information is provided. It is said before that infrared optical properties are not measured selective enough to be able to detect liveness, and it is to be expected that several materials have optical properties in the visible wavelengths which are very similar to the human skin. Though optical signature liveness detection might be more reliable in this method because PCA and texture *models* are created of the liveness characteristics of the individual and enrolment is supervised. Lumidigm proposes the use of these two methods together as being very robust, but test results are yet statistically non-significant [131].

4.4 Involuntary signals

Living human bodies also give off signals that can be measured by liveness detectors. Signals are natural bodily features that have to be captured by a sensor. A positive measurement result indicates that the parameter under investigation corresponds to the range of the signal found for a living body. The involuntary signals can be measured inherent to the biometric feature and by using additional hardware. Ways to spoof such a feature are mentioned at the end of each subsection.

4.4.1 Liveness inherent to biometric feature

a) Thermal radiation

Liveness detection based on involuntary signals inherent to the biometric feature occurs only in the methods that obtain a thermal image of the hand or finger for extracting a unique biometric sample. The involuntary signal here is the radiation emanating from the hand in the mid-infrared region (section 2.3.1 page 22). Capturing this signal results in a thermal image, from which a vein pattern is extracted. It is rather difficult to spoof this lifeness detection method that is inherent to the biometric feature. However, this method requires rather expensive detectors. One could consider that e.g. a network of heat emanating wires in the shape of a hand vein pattern could spoof this kind of device.

4.4.2 Additional hardware

a) Blood volume pulse

The measurement of the pulse is proposed as a fingerprint lifeness detector [130, 134]. This can be done with one LED in the following way, also known as photoplethysmography: reflected or transmitted light from the red LED (600 - 700nm) is stored in subsequent intensity samples from the photodetector. With pulsating flow there is a consequent variation in the light received by the detector at the skin surface, due to scattering and absorption by the pulsating volume of blood under the skin. The pulsatile component (a.c.) of the signal reflects changing blood pulse volume due to the pumping of the heart, while the steady component (d.c.) is related to the relative vascularisation of the tissue [135]. To obtain the pulse frequency and volume change the signal is further processed. In [134] the samples are first scaled and next bandpass-filtered to remove noise below approximately 0.3 Hz and above 3.3 Hz; these frequencies correspond to 20 and 200 heartbeats per minute. These frequencies can also be set differently. The resulting signal is then processed to determine its frequency and amplitude. The results are then compared by the microprocessor as to whether or not the frequency and amplitude values of the signal fall within minimum and maximum levels that are consistent with

blood flow in a live human. Thus, by measuring the variation in transmitted or reflected red light, the method determines if the object being scanned exhibits characteristics of blood flow consistent with that of a live human. By adding an extra LED in the infrared region and obtaining samples with both LEDS, this embodiment also determines if an extra flashing light source has been used to fool the device, or whether the fake sample is artificially moved to mimic a pulse [134]. This works essentially the same as the pulse oximeter, but without the oxygenation measurement.

A disadvantage again is that physical contact is required to avoid contamination with ambient light and although this liveness cue is hard to simulate (with the double LED combination), it is easy to spoof the biometric detector while the liveness detector measures the pulse and oxygen features of a living unauthorized person [22]. Another disadvantage is the large variability in pulse rates and the time needed to correctly obtain a pulse; a person with a pulse of 40 beats per minute will have to hold his finger on the sensor for at least 4 seconds [4].

b) Blood pressure

Another proposed liveness detector is measuring blood pressure [130]. The well-known auscultatory method with a doctor listening through the stethoscope is of course not suitable, but more methods have become available. However each method has its practical disadvantages [136], and are not convenient for biometrics [4, 21]. And again, physical contact is needed and the blood pressure can be obtained from a real sample, while the biometric is a spoof.

c) Perspiration

Measuring perspiration as a liveness detector is proposed for fingerprint scanners [137]. The underlying hypothesis is that live fingers demonstrate a specific changing moisture pattern due to perspiration. A fingertip with moist skin on a capacitance sensor will result in a higher capacitance than a dry finger, and a changing moisture pattern influences the capacitance over time. By placing the fingertip on the sensor for 5 seconds, the system can verify whether the finger shows perspiration over time within the margins of a living finger.

Because the (finger) vein pattern is not so closely related to the skin surface as the fingerprint, again it is possible to present a living area of skin to the perspiration liveness detector, while the vein pattern is a spoof. And physical contact is required.

d) ECG

The electrical activity of the heart over time is measured with an electrocardiograph and visualized in an electrocardiogram (ECG). Measuring the ECG has also been proposed as a liveness cue [130]. The time needed, practical disadvantages [4], the separation of the liveness cue from the actual biometric feature, and the need for physical contact make this a weak competitor for liveness detection on this moment.

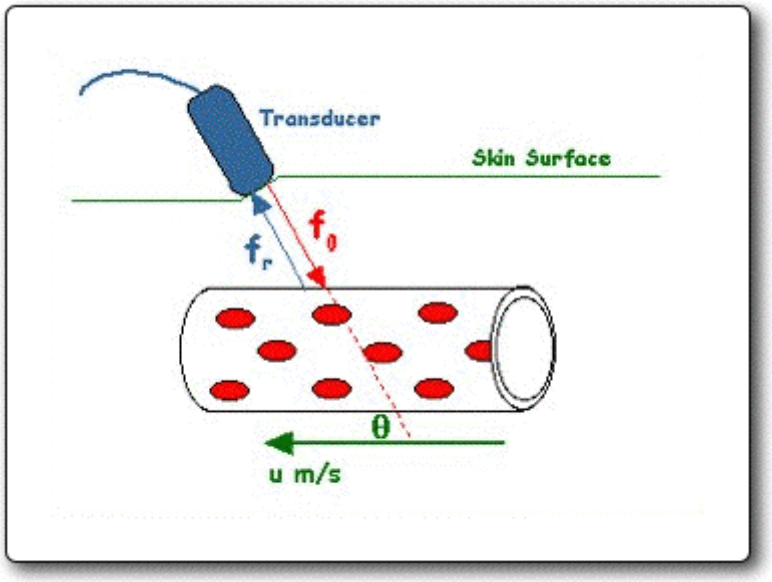

Figure 56. Illustration of blood flow detection using the Doppler Effect with ultrasound waves. F_0 is the frequency of the ultrasound emitted by the transducer, , F_r is the frequency produced by the reflectors (blood cells). Obtained from [138].

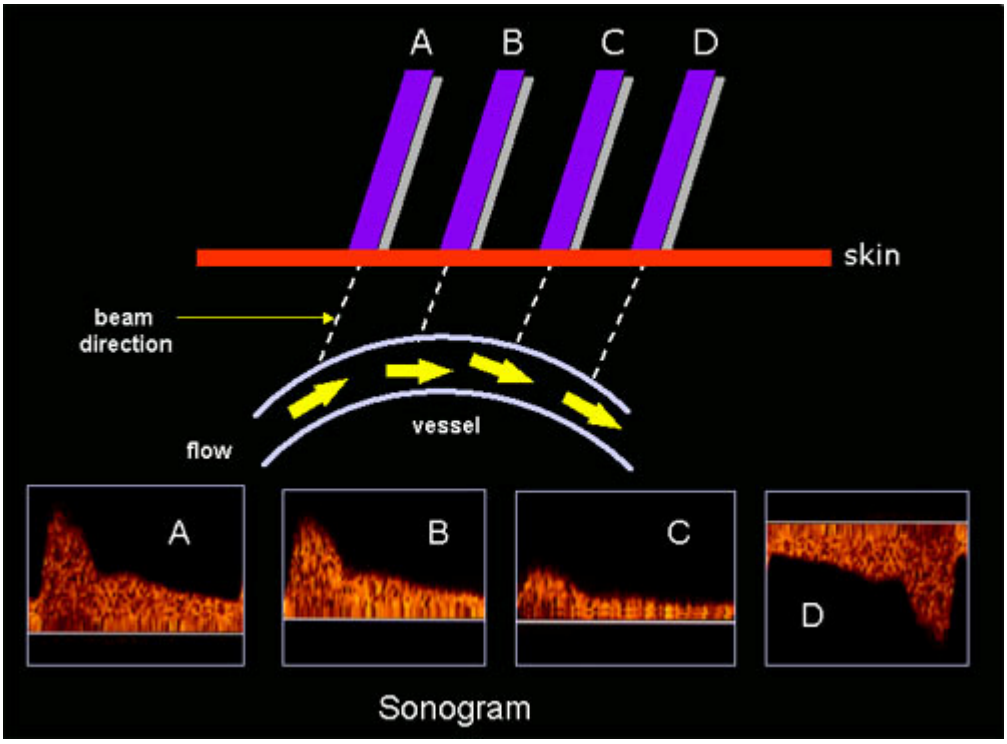

Figure 57. The effect of the Doppler angle in the sonogram. A higher signal is obtained if the beam is aligned more to the direction of the flow, as is shown in figures A) to C), where the beam is perpendicular to the flow and the signal very poor. In D) the flow is away from the beam resulting in a negative signal. Obtained from [139], figure 3.

The following three methods are derived from the medical field. Although this is not seen in practice, these methods can possibly be used as a liveness detector in vein pattern biometrics.

e) Blood flow velocity

Doppler ultrasound

The Doppler Effect in general is the change in frequency produced by the scattering of waves by a moving object. Using ultrasound waves in human tissue, the Doppler shift ∂f is given by:

$$\partial f = 2\frac{f v_s \cos\theta}{v_t} \qquad [9]$$

Where *f* is the frequency of the ultrasound source, v_s is the velocity of the source which causes the Doppler shift (in this case the moving blood cells), $\cos\theta$ is the beam-vessel angle v_t is the speed of sound in tissue [140]. The principle of blood flow measurement is shown in figure 56. The shift in frequency received by the detector gives information on the velocity of moving blood (with known beam-vessel angle), and can be a liveness cue. Any moving object however, will produce a Doppler shift. Amplitudes and frequency shifts have specific ranges regarding blood flow and therefore with the use of proper filters only signals within this range can be used as a liveness detector. Typically the transmitted frequency used for medical purposes is 2-8 MHz. In arteries blood flow velocities up to 5 - 6 m/s are present producing Doppler shift frequencies up to about 20 KHz [140]. In the finger flows of 24-50 cm/sec are measured depending on the environmental temperature [141]. A lower blood flow velocity results in a lower frequency shift, which makes it harder to detect [142]. The transmitted and reflected sound beam are (electronically) mixed together to form an interference pattern and beats are produced. The beat frequency is equal to the Doppler shift [143].

The wide range and low flow velocity in the finger make it easier to simulate active flow by moving the fake biometric sample. Another problem is the angle of incidence between the ultrasound beam and the flow direction; the more parallel the beam the more accurate the frequency shift, see figure 57. Also, one has to know the angle to calculate the exact flow. However, for liveness detection the exact blood flow velocity is not the aim, but rather the verification of a moving source with a velocity and amplitude that falls within the boundaries of human blood flow. As long as the angle θ is not zero, but rather large (for the hand this means parallel to the skin) a Doppler shift can be detected. With continuous wave detection also the pulse can be extracted from the flow curve.

A practical disadvantage is that the transducer should touch the skin, because at any boundary between different media the ultrasound beam is partially transmitted and partially reflected, depending on the difference in impedance of the two media which is large for air and tissue, but small for blood and tissue [144]. Another disadvantage is that the measurement of the blood flow and the vein pattern imaging rely on different principles, thus a living hand can be presented to the liveness detector while the vein image is taken of a spoof.

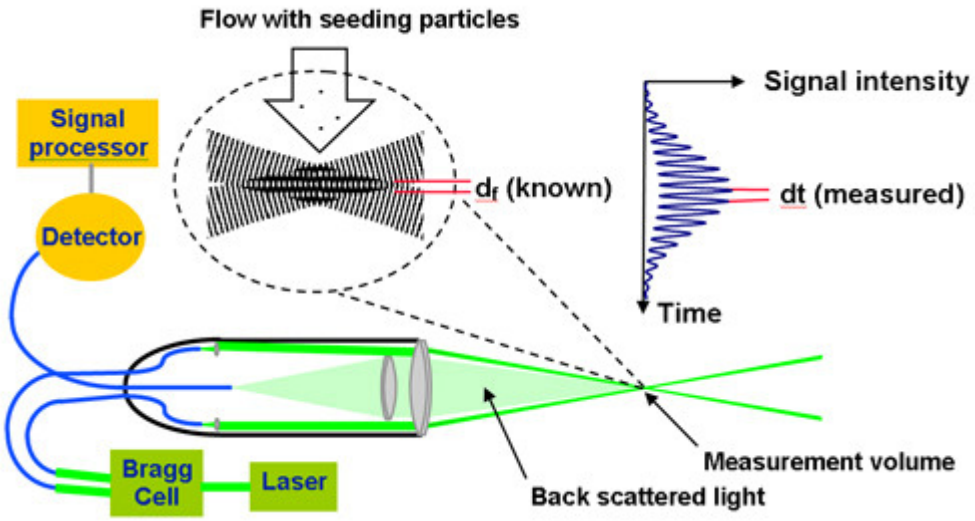

Figure 58. The general principle of a laser Doppler anemometer, obtained from [145] figure 1.

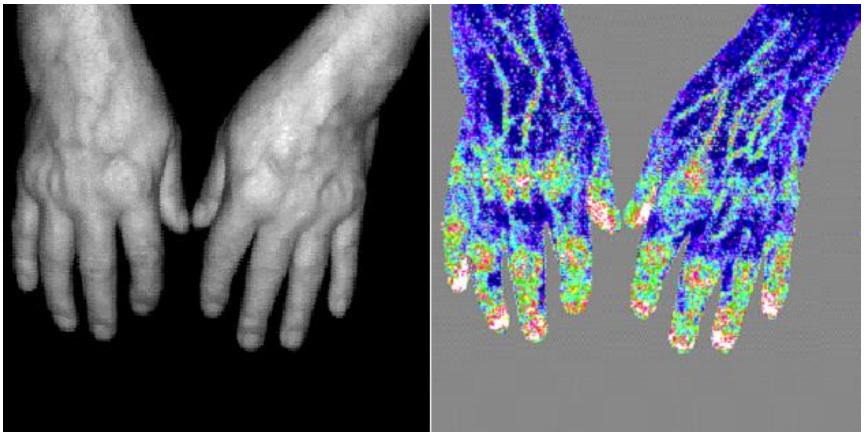

Figure 59. Laser Doppler perfusion images of arthritic hands, Obtained from [146]

Laser Doppler flowmetry

On the same principle as ultrasound flow measurement lays the laser Doppler flowmetry (also known as anemometry or perfusion) technique: the Doppler effect. In this technique the Doppler shift is detected in light waves that are scattered by moving blood cells. Formula 9 can be applied for light as well, v_t is the speed of light in tissue, which is the speed of light c ($3.00 * 10^8$ m/s). The light source is a monochromatic laser beam, which is split in a probe and reference beam. Then, the shifted and unshifted light is allowed to interfere on the surface of a sensitive photo detector, a beat frequency will be produced, the detectable component of which is equal to the Doppler shift. The general principle is shown in figure 58. Typical frequency shifts detected by a laser-Doppler perfusion monitor using a wavelength of 780 nm in the microcirculation range from 0–20 kHz [147]. This makes the laser Doppler flowmetry technique a better performer for low flow velocities. In [148] an infrared (850 nm) laser diode is used and speeds of 67 cm/s are accurately measured. Moreover, no contact is needed between the sensor and the skin [149]. In figure 59, results are shown of laser Doppler flowmetry when used 2-dimensionally to obtain a flow image. In this way, the vein pattern can also be made visible (due to arthritis the vein pattern has a low quality).

The costs and complex alignment of this liveness detector are the main disadvantages, although 'a low-cost, non-invasive, completely contained hand held laser Doppler flowmeter' is available [150]. Regardless of particle size, shape, conductivity or chemical composition, the particles will scatter light and therefore, any other material (such as a spoof) that is moving can result in a Doppler shift of the reflected light. As with the former method, the measurement of the blood flow and the vein pattern imaging rely on different principles, which makes passing the liveness detector while simultaneously presenting a spoof possible

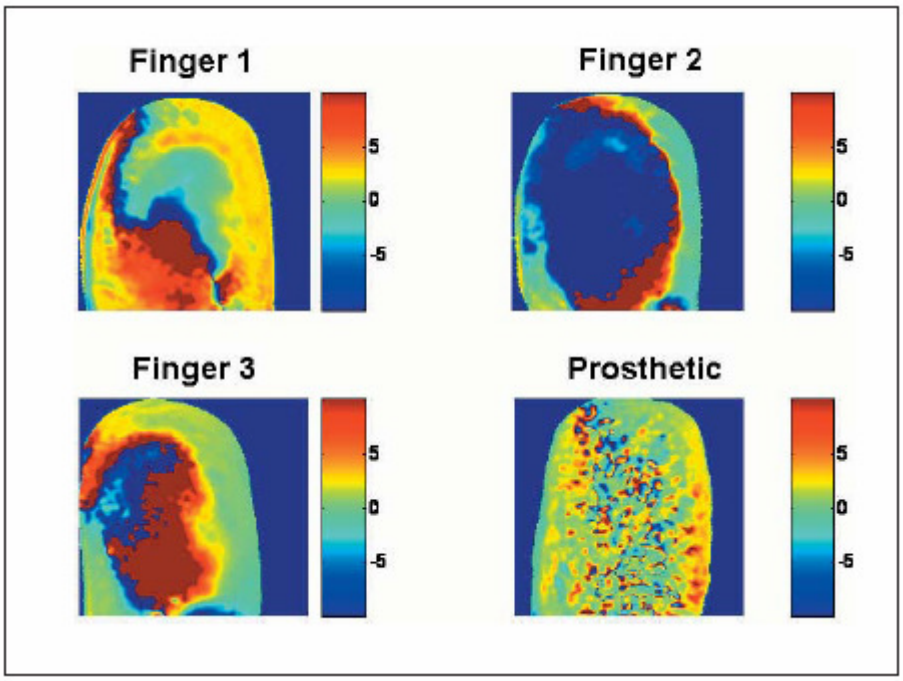

Figure 60. Images of blanching detection in live fingers and a prosthetic finger. Obtained from [131] figure 9.

4.5 Bodily response

The last category of liveness detectors are the methods that measure a bodily response to a stimulus; a challenge-response method. It can measure either voluntary (behavioural) or involuntary (reflexive) responses. The bodily responses can be measured by using an additional algorithm and by using additional hardware. Ways to spoof the system are mentioned at the end of each subsection

4.5.1 Using additional algorithm

a) Nonlinear deformation

Deformation of the skin of a fingertip when pressed hard against a surface compared to a less rigid contact is proposed as a cue for liveness in fingerprint biometrics. A living skin should exhibit nonlinear distortions, while thick artificial fake fingerprints are supposed to give rigid transformations [4]. The same can hold for the hand vein pattern; because the veins are embedded in soft tissue small movements of the veins are likely when the hand is put into different configurations (e.g. flexing or stretching). These distortions are probably also nonlinear, while for example a paper hand or balloon will deform in ways that are not characteristic for living tissue and veins. This liveness cue can be measured with the same equipment; only adjustment of software is needed to compare two images taken from different configurations of the hand. It is a form of a voluntary bodily response.

Not much is known about this method; therefore no valid statement can be made on the properties of nonlinear deformations of the veins, or the ability of algorithms to verify authenticity and liveness while the hand vein pattern is nonlinearly changed.

4.5.2 Additional hardware

a) Logical response

Examples of logical responses to prompts generated by the system are little tasks like '*touch A if the plate is hot, touch B when the plate is cold'* will be appropriate in verifying whether the person standing in front of the device is alive or not, but can not at all verify whether the presented biometric feature is belonging to this living person. Therefore this liveness detector is very easy to circumvent.

b) Blanching

The third liveness detection method of the company Ludigim [131] is a form of a bodily response: the user is asked to press his finger against a hard surface. When a finger is in contact with a hard surface, blanching occurs which is specific to a live finger. This blanching is primarily due to changes in pooling of blood and therefore it can be measured in especially the red, and to a smaller extent in the green wavelength region. To detect blanching, a series of images are taken using the red and green wavelength LED's of the mulitspectral system and the ratio of the differences of the green

and the red intensities is calculated. This ratio is a measure of blanching. As shown in figure 60, live fingers show large blood pooling regions, while the prosthetic finger shows a distinct, mottled pattern. When blanching can also be measured with an infrared LED already used to capture the vein pattern, only adjustment of the software is needed for this liveness detection method.

This anti-spoofing method has got the primary disadvantage that contact with some hard surface is needed. Second, it can only be used for finger vein biometric methods; for the convex and concave shapes of the back and palm of the hand it will be complex to image blanching. Moreover, the blanching verification and vein imaging should happen simultaneously otherwise it is easy to replace the non-live biometric sample with a living finger in the liveness verification step. An essential problem now is that the veins will be hard to visualize due to the blanching and the biometric vein pattern itself will change as a function of pressure. Therefore, verification will be very complex and this method is not useful for vein imaging methods.

c) Hot/cold stimulus

An involuntary bodily response that is closely related to the hand vein pattern itself is the response of veins to hot or cold environments. For energy saving purposes veins dilate in warm environments, while they contract in cold environments. Veins in two different images taken under different temperatures should therefore differ in diameter. This can be measured with an additional algorithm and some cooling or heating system.

The disadvantages are obvious: inconvenience for the users; a long liveness verification time is needed because the reaction of the veins is not immediate; and the resolution of the images should improve a lot before the differences are detectable and significant. Due to the distance that photons travel in tissue which makes their path diffuse (section 2.5.3 page 36), it is probably impossible to obtain images that are accurate enough for this liveness detection.

4.6 Other methods to limit spoofing

4.6.1 Combination of multiple methods

The combination of multiple biometrics [19, 151] as well as a combination of several liveness detection methods [130] will make it harder for an intruder to trespass the system. The intruder has to obtain several biometric features of the same authorized person or simulate several liveness cues on the same time. In this way, a lot of possible spoofs fall outside the range of one of the different methods, while they could have been included if only one such method was used [151]. Although this might seem obvious, in practice combining multiple biometrics in one system is rather difficult, due to environmental, cost or equipment limitations [19].

4.6.2 Multiple entrees

Another way to limit spoofing is to take several images of the same vein pattern and requiring each of these to be identified and verified correctly [4]. For a paper copy of a hand vein pattern or other spoof, this might be harder to achieve than a real authorized biometric sample. However, for an authorized person this will increase the FRR and the verification time, and therefore increases the inconvenience for ordinary users of the system.

4.6.3 Multiple templates

When users enrol multiple templates to the system, for example both left and right hand for the hand vein pattern or all ten fingers for the finger vein pattern, the system can randomly ask for a specific biometric feature and the intruder has to get hold of all of them to trespass the system. Such a system may also require two different vein patterns before verifying authenticity [19].

4.6.4 Combination with other authenticity cues

Another proposed method against spoofing is the use of ‘multi-factor authentication’ [19]: using biometrics in combination with smart cards, tokens or passwords. This reduces the convenience, and perhaps also the idea of biometrics ‘being the key yourself’ but it will increase the security of the system. An impostor would need both the biometric sample and the token or secret in order to defeat the system.

4.6.5 Supervising

This chapter started with an example of an attentive employer as a liveness detector. In fact, supervision during enrolment, verification and identification will increase the security of biometric systems. Some spoofs however, are that small or lifelike that it is very difficult for a supervisor to detect it. Especially because supervision is a human task, prone to human mistakes or lack of concentration due to the monotonous job [4].

4.7 More spoofing risks

Besides tricking a biometric system with the aid of an artificially created fake biometric feature that is presented to the regular sensor technology of the system, there are two additional approaches possible to fool a biometric system: via the USB port and via the data base.

4.7.1 Attack via USB port

Regarding the approach attack the system via the Universal Serial Bus (USB), the system is also fooled by artificial data, but this data is purely electronic [120, 152]. One can get hold of reference data with, for instance, the aid of a sniffer program listening on the USB port. USB ports, as is implicated in the name, are invented for convenient swapping of devices hooked up to a computer while a computer is running. This allows potential assailants to exchange the biometric scanner for a deceptive device of their own. By presenting the 'stolen' data to the USB port, the system's regular sensor system is bypassed, a procedure commonly known as a replay attack [120].

Two examples of eavesdropping tools are mentioned by [120]. The first is a filter drive like 'USB Snoop' for Windows; this tool is free to download on the internet [153]. It interposes itself between the driver of the USB adapter and the actual device driver. All data that is being exchanged between Windows and the device driver is written in a log file of USB Snoop itself. This log file is available for the impostor to extract the data and re-submit it at any wanted time to the USB port to fool the system. The second example is based on a hardware analyzer, which eavesdrops on the USB cable directly and is virtually invisible. It records all transmitted data through the cable, and can be made available to the impostor to filter out the relevant biometric data.

This study reports a successful attack at a fingerprint biometric device, ID Mouse by Siemens: 'with the aid of data packets gathered by eavesdropping and some lines of Perl script we were able to reconstruct complete fingerprints' [120]. Their device was capable of impersonating towards the target PC the previously removed biometric scanner: the device could respond with answers identical to those of the actual fingerprint scanner and then at the right moment play back the stored biometric data. [152] also recognizes the fact that USB devices (like PalmSecure) can be spoofed via these kinds of attacks.

4.7.2 Attack via data base

This approach is based at the data base directly. An example is the following: 'the hypothetical case that a former bank employee who years after leaving his firm decides to bring down to life the at one time surreptitiously created data set 'Mr. Miller's eleventh finger' with the intention of generously taking care of his retirement needs' [120]. To do this, an impostor needs to have administrator rights, and the data sets should have no separate protection by the system. In that case, the forger can reactivate this created login at any later moment in time.

4.8 Discussion

True stories, like in the introduction of this chapter about the dead man in South Africa, but also movie images of people being killed to obtain their eyes or fingers, have resulted in a certain gore factor on the biometric industry [152]. A security system that decreases a user's personal security is not so popular. Although killing to obtain a person's biometric feature is a rather farfetched thought, *copying* someone's biometric feature is a more significant threat to biometric systems.

However it must be said that the easiness with which you leave your fingerprints behind on cups, door handles or other surfaces does not apply to your hand vein pattern. It is relatively hidden beneath your skin, and does not leave surface traces. To copy somebody's vein pattern one must have access to the hands to draw (when the veins are quite superficial) or photograph the veins with for example a (night) camera (see figures 49 and 50). Although possible, it would be rather hard to obtain a detailed vein pattern without permission. This fact in itself makes the hand vein pattern biometry less susceptible to be misused by impostors.

When impostors can have access to the database the threats are different. In this case hand vein pattern templates can get stolen, or the impostor can create a fake account (section 4.7.2). Another threat is attacking the USB port directly (section 4.7.1). All these scenarios require certain concerns for the biometric industry to secure their systems.

Liveness detection is an option to secure a system against spoof biometrics. In the last chapter many different ways to incorporate lifeness detection have been described. However, also ways to circumvent the liveness detection are described for almost every method. Some main remarks on the described methods can be made.

4.8.1 Liveness detection related to biometric verification

First of all, the biometric verification and the liveness detection are often not closely related which makes it easy to present a fake biometric sample to the biometric sensor, while presenting the liveness cues to the liveness detector. Ideally, the two systems work on the same time on the same object, with the same detection technique. This is the case in for example thermal imaging (4.4.1a) and some spectrographic methods (4.3.2a). In the first method, thermal radiation (MIR) is captured to image the vein pattern *and* to obtain the liveness cue. In the second method NIR (and red) light and proper filters are used to capture the vein pattern *and* to obtain the liveness cue: specific absorption properties of (de)oxygenated haemoglobin. In theory, another method that falls into this category is the laser Doppler flowmetry when this technique is used to image the vein pattern based on flow velocities (see figure 59), besides detecting liveness. Also the blood volume pulse liveness detection method (Section 4.4.2a) could be adapted into a configuration where reflection of near IR light is measured

over time to capture both the vein pattern and simultaneously the pulsatile change in blood volume. These methods have their disadvantages as well; mostly cost, complex implementation, and contamination with ambient light.

In a large number of the described methods the liveness detector makes use of radiation: spectrographic signatures, oxygen content, blood pulse, blood flow, blanching and nonlinear deformation, are all based on some interaction of light with the living body. Because vein imaging is also based on capturing radiation, these methods are closely related to the biometric feature itself, although not in an inherent way. Proper filters, light sources and sensors have to be used to make spoofing more complex (costs), and in most cases physical contact is needed to prevent ambient light to interfere.

4.8.2 Other threats

The two threats based on attacks via USB ports and databases belong to a different category. Attacks via the USB port are not as science-fiction as they seem, in fact programmes and drivers have already been developed. However, filter drivers are also quite easy to detect and require administration rights to be installed [120]. But then again, programmers will probably always find ways around this. A way to prevent attacks like this is to incorporate a so called challenge-response procedure, in which the biometric device and the application mutually authenticate one another and thereafter exclusively communicate with each other in an encrypted fashion [120]. Again, this adaptation of the biometric devices will trigger new impostor attempts to circumvent the new security measures, and so on.

To prevent false enrolments in the database the simple solution is to handle your database with care: check regularly for data sets that have not been used long, or are not registered and update your database frequently. Though this will probably not prevent some ingenious ways which impostors will create to contaminate a database of enrolled biometric features.

4.8.3 Critical Issues

Several methods that have been proposed for liveness detection sound rather solid. However, most of the research into liveness detection is still in its infancy, especially for the relatively new hand vein pattern biometric. The methods are simply not good enough to rely on for full protection against impostors. The results shown before [11] demonstrate this clearly. This is in contrast with the aims of the producers of the biometric devices. The biggest problem arising here is the feeling of safety, while the threats are not recognized. Especially because biometrics are used in network security this can cause serious damage, for both the user and the build-up status of biometrics in general [19]. In the introduction of this chapter four unwanted scenarios have been discussed that are possible when biometric systems are defeated.

A reason for the weakness of liveness detection is the 'black-box' treatment of the biometric industry: '*most vendors fall back on the need to retain a competitive advantage in holding secret their liveness detection methods'* [19]. The controversy is however, that when complex systems are available for review, this triggers revocation and reissuance processes that reinforce system integrity. Critical functions of the system will improve by the willingness to accept and use criticism, an approach which most powerful cryptographic systems are already familiar with. The biometrics closed design is unlikely to be a long-term solution for building secure, reliable and effective systems. In contrary to what vendors might feel (secrecy as their greatest protection against impostors), the systems will benefit from an open approach to third party inspection, analysis, criticism and improvement [19]. Accepting this will give potential users the possibility to assess whether the system is suitable for their particular purposes [11].

Another important issue in evaluating liveness detection is the development of vendor-independent testing of robustness of these methods against spoof attacks [4, 22, 118]. [11] is one example, but more effort is needed. Lifeness detection will be at the cost of user convenience, hardware prices or matching accuracy [118]. The relation of performance tests to lifeness detection will be further discussed in the final chapter (Chapter 5).

It is important to keep in mind that spoofing techniques will always be evolving, and countermeasures are only temporary. Therefore research and development will always be necessary, as well as proper evaluation of the systems. And even with flawless liveness detection, people can still be forced or drugged to present their biometric feature. Liveness detection is only a means to *minimize* the effectiveness of artificial or simulated biometric samples. It is never a guarantee that the biometric sample belongs to the authentic live human being. '*If man can make it, man can break it.'*[117].

5 Final discussion and conclusion

The core question of this thesis *'How suitable is the hand vein pattern as a biometric feature*?' resulted in literature research of many articles, websites and patents. The three sub questions that shaped the former three chapters will for clarity be repeated:

1) How unique and time-invariant is the hand vein pattern and how can we perceive it?
2) How does the vein pattern biometric identification technology work?
3) How can the systems defend themselves against impostor attacks?

5.1 On the sub questions

How unique and time-invariant is the hand vein pattern and how can we perceive it?

No statistical certainty can be given on the uniqueness of each hand vein pattern, unlike, for example DNA profile frequencies. For DNA-profiles a scientific based model calculates the frequency of a profile in the population based on the frequencies of each single independent allele (varying element in DNA) in that profile [154]. For hand vein patterns no such scientific model exists to quantitatively support the uniqueness of the pattern. However, it has been shown that, despite the universal aim for optimal blood supply to the body, a very high variety in branching parameters is found for the vascular tree of different organisms. According to [91] the arteries, that are located on the palm side of the hand relatively deep under the surface, show less variation among persons than the vein structure, located more superficial at the back side of the hand. But due to the low number of hand vein patterns that have been investigated no harsh conclusion can be made on the uniqueness of each hand vein pattern.

Another property of the hand vein pattern, compared to e.g. a fingerprint pattern, is the relative simplicity of the pattern itself. In figure 1 it is seen that only a few bigger veins are present in the hand, this fact can reduce the uniqueness of a pattern. In addition, the 'uniqueness in practice' depends on the sensitivity of the devices to pick up small differences. Consequently it depends on the image capturing technique (how many veins can the device capture) and on the matching method (how much information of the vein pattern does the device retain for matching).

The non-time-invariance of the hand vein pattern is clear when looking at the growth and reduction of the human body as a whole, resulting in growth and reduction of the vascular structure [1, 67]. In adult life these are minor changes and probably insignificant for the hand vein pattern. For children this is different. Again the consequences for vein pattern verification are dependent on the method of matching: bifurcations and intersections of veins (the structure) are determined in the early stages of life, and matching based on structure will therefore not suffer from human growth [1]. Matching methods based on template matching on the other hand will not be robust against growth of

the vein pattern. This can be solved by a regular update of the template when identification of infants is concerned.

Changes in the vessel diameter are quite common: naturally due to cold (smaller diameter) or warm (larger diameter) temperatures, alcohol intake, or physical activity. In some diseases thickening or thinning of the vessel wall or silting up of the vessels can result in an extended reduction in blood flow which makes the vessels less or not visible on images. In cold weather and for poor vessel conditions the variance in the visibility of the veins can induce errors in verification [1, 54]. Artificial changes of the vein pattern can be made surgically. According to two Dutch surgeons the veins can easily be moved a few millimetres, removed, tied up or seared (in which case new veins will evolve or existing small veins will expand), or be removed and reconnected to other veins [90, 91]. Surgically it is thus possible nowadays to interfere with the vein pattern identification system. In the future when angiogenetic therapy is more developed, this treatment might also influence the hand vein pattern. Artificial changes in the vein pattern can be made on purpose (fraudulent) or can be a side effect of surgery or therapy.

Two ways of vein imaging are used by the biometric industry and biometric research: thermal imaging and reflective imaging with NIR light. Thermal imaging relies on the fact that veins emit more mid-infrared radiation than the surrounding tissue. Reflective imaging relies on the fact that in the tissue optical window, (de)oxyhaemoglobin the main absorber of radiation is, while the other tissue components reflect the NIR radiation. The absorption coefficient of both forms of haemoglobin is wavelength dependent, except for the isobestic wavelength (805nm) where the absorption coefficient is equal. Most imaging techniques use NIR light with wavelengths around the isobestic wavelength. In figure 10 the absorption coefficient curves of deoxy- and oxyhaemoglobin show that oxyhaemoglobin absorbs more at wavelengths beyond 805nm, while deoxyhaemoglobin absorbs more at shorter wavelengths. When taking this into account it could be interesting to use wavelengths shorter than 805nm for images of the back of the hand where the veins are situated which carry more deoxyhaemoglobin than oxyhaemoglobin, and using wavelengths longer than 805nm for the palm region of the hand, where the arteries are located.

The penetration depth of NIR radiation depends on wavelength, mean blood fractional volume, blood oxygen saturation, and other specific tissue properties. When using the same device with the same light source, there will always be a slight difference in reflected radiation between different times of imaging. The devices have to be robust against this kind of variations, while on the same time sensitive enough to pick up the differences belonging to different vein patterns. In addition, due to the principle of scattering, the reflected light will be diffuse and thus reducing the sharpness of the images. The influence of variation due to penetration depth and scattering should quantitatively be assessed in large-scale studies. So far, despite this kind of inaccuracy the selectivity of the devices is said to be quite good, of course according to the biometric industry itself [24, 25, 94] and IBG's Comparative Biometric Test [115].

Three biometric experts have been asked to compare the properties of different biometric technologies. The properties universality, uniqueness, permanence and collectability of the hand vein pattern as a biometric are according to the perception of the biometric experts 'medium' compared to other biometrics technologies [16].

How does the vein pattern biometric identification technology work?

The veins are perceived with reflected NIR or emitted MIR radiation and optical sensors (CCD, CMOS, thermal camera). The sensors generate an image where the veins are visible either as dark regions (NIR) or light regions (MIR). How smoother the gradients in grey values in the images, the less visible are the veins. Circumstances in which this happens considerably are hot or cold weather conditions, physical activity or alcohol intake, a thick layer of subcutaneous fat, clumping of hair or poor condition of the veins [54, 67]. Due to a smooth temperature gradient in tissue (MIR images) and due to scattering (NIR images) the vein images will always possess a gradient between veins and surrounding tissue, even in ideal circumstances.

The next step is to define the region where the biometric feature of interest is present. Ideally this region should be exactly the same each time to make straightforward comparisons. This can be pre-imaging by guiding the hand into a fixed position and/or post-imaging by extracting the ROI from the image with algorithms. An issue here is that the vein pattern actually is a 3-dimensional structure, but imaged 2-dimensionally. Due to possible variations of the hand position in 3 dimensions, positional correction is never 100% proof; therefore some shifting has to be allowed in the pattern matching stage.

The transformation from the original image to a representation of the vein pattern can be done in many ways, through many different algorithms. A judgment on the quality of each method is not easily given. A few general ways to do this are with filtering, thresholding and thinning or with pixel tracking algorithms. Difficulties are to obtain only the vein pattern and neglect noise, which is present in the hand due to bones, tissue and irregular shading. Median filtering can reduce noise; subsequent contrast enhancing and thresholding algorithms to obtain a binary image will visualize the vein pattern and the background only. With thinning and pruning algorithms a skeleton presentation of the vein pattern can be obtained. Line tracking needs less filtering of the image, because the lighter pixels belonging to the veins are more likely to be tracked and labelled as a vein than noise. A matrix image containing the labels of the pixels represents the vein pattern. Due to the smooth gradient in grey values between tissue and veins that is naturally present in vein images, vein extraction with edge detectors is not applicable. However, an adapted form of edge detecting is used [67].

The main concern is to neglect noise, while maintaining as much information on the actual vein pattern as possible without manipulating the pictures too much. For example Choi [30] represents the vein patterns in a table with branching characteristics and coordinates of some reference points of

the veins for comparison. The question is, whether enough information is present in this table to maintain the unique characteristics (*if* vein patterns are unique) of the vein pattern.

The same holds for vein matching: the less information is used for matching the less unique this information will be. Matching of the vein pattern obtained in the former step is usually done via some kind of template matching algorithm and a subsequent correlation threshold value decides whether the two patterns are similar or not. The database template image is usually composed from 3 or more images taken during enrolment and therefore contains more information and detail on the vein pattern than the test image taken for verification. Due to this, and due to the fact that a vein pattern differs slightly from day to day, and lighting conditions may vary from image to image, simple pixel by pixel matching is not sufficient. Template matching is more sophisticated, but also during template matching some possibility for shifting has to be allowed due to the variations. The balance between accepting and rejecting these non-similarities in the verification process is very important: it should be strict enough to prevent false matches, but flexible enough to allow small variations of an authentic vein pattern to pass.

The only way to find out whether hand vein pattern recognition techniques perform well is to put them to test. Test results put forward by the biometric commercial industry usually show very low error rates. It is, however, hard to repeat these experiments because minimal information is given on the applied methods and conditions. Scientific tests so far used low subject numbers and are hard to compare. Only two devices, one utilizing veins in the finger, the other in the palm of the hand, have been tested by an independent organization, in a comparative biometric test setting with 650 subjects [115]. The result of this experiment is that the hand vein recognition technique performance is comparable to iris recognition systems (tested in the same round), and also a serious competitor to fingerprint and hand geometry systems. For stronger conclusions more hand vein recognition devices should be tested by independent institutes, for example the National Institute of Standards and Technologies (NIST, [155]).

As well as for several desired properties of a biometric system discussed in the first research question, the properties storability, performance, convenience and costs can be evaluated at the end of this second question. Storing the hand vein pattern templates is possible in an electronic database which is with modern technology not a problem. When many users are enrolled sufficiently powerful systems are needed, which might increase the costs. Also fast processors are important when there is a high demand on the speed of the verification process, especially for large scale usage. This will also increase costs. In general the hand vein pattern devices are equipped with relatively low cost parts like CCD imaging devices, NIR LED's and system software and processors, but compared to fingerprint scanners ($500) they are expensive ($2000 to $4000) [156]. The devices that are equipped with thermal sensors sensitive in the MIR region are somewhat more expensive. As for convenience it can be said that hand vein verification technology feels less crime-related to the consumer than fingerprint verification. The fact that the technology studies the subcutaneous level however, gives some people

an invasive feeling [156]. Given the safe, rather fast and painless characteristics of this method users can overcome this when they get familiar with the method. The inconvenience left is the large size of the apparatus. Some of the hand vein recognition devices might be very small, they are not small enough to be integrated with notebooks or cell phones, the way silicon fingerprint sensors are [156]. The performance of the techniques is extensively discussed in chapter 3.3.6, page 94. According to the comparative biometric test report the performance is rather high [115], according to the perception of three biometric experts in [16] the performance of the hand vein verification technique is 'medium'. Their opinion on the acceptability is also 'medium'. The property exclusivity is closely related to the uniqueness and performance of the systems; a good verification process checking unique characteristics can be used on its own without any further identity checks, but only when the systems are defended against fraudulent users.

How can the systems defend themselves against impostor attacks?

Before answering this question it should first be assessed why such defence is necessary when the performance of the system is high. A system with high performance metrics can still be a weak biometric security technique when spoofing is an easy task. Biometric security is often expressed in low false acceptance rates; the probability that a test sample is incorrectly matched to a template enrolled by another user. This statistically determined error probability only refers to zero effort attempts: an unauthorized user making an attempt with their own biometric feature to gain access to a system [22]. This number does not reflect the vulnerability of a system against impostors: '*Unlike empirical scientific procedure, a hacker is scarcely likely to muster a battery of a thousand experimental subjects in the hope that one of them might perhaps be mistakenly accepted by the system*' [120]. The biometric industry solely reports low error rates that do not include vulnerabilities to attack. The only way to find out is to 'test-it, assail-it and outfox-it yourself' [120], which shows the need for vendor-independent large scale testing of spoof vulnerability [4, 22, 118]. One such test has shown there is indeed a serious threat to hand vein verification systems by simple impostor attacks (paper hands, plastic gloves) [11]. Other threats include the attack via the USB port and via database entrees.

A first defence of the biometric industry against such attacks is to avow the vulnerability and deal with it. Openness gives users the conscious of treating the systems with care, and in appropriate circumstances. By taking the divinity away from the systems, its strength will actually increase [19]. Other countermeasures that can be taken are to incorporate a liveness detector in the biometric devices. Several ways of liveness detection have been discussed in chapter 4. The main thing to take into account is that liveness detection is most safe when it works together with the pattern verification method, on the same time, on exactly the same object in the same way, to reduce the possibility that the lifeness detector is presented a living hand, while the spoof is presented to the pattern verification technique. The best options for the hand vein verification devices seem to be:

- Thermal imaging: The MIR radiation that naturally emanates from the hand, with higher intensity above vein regions, is captured to obtain a vein pattern. Most spoof vein patterns do not emanate this thermal radiation.
- Multi-wavelength NIR imaging: by using more than one wavelength to capture the vein pattern, specific absorption properties of (de)oxygenated blood can be used as liveness detection, which are harder to simulate with spoof materials
- Multi-wavelength NIR imaging over time: this way not only specific absorption properties of blood cells can be measured, also the pulse is present in the detected signal.

All three methods have the disadvantage that they are more expensive, and the second and third method will also decrease user convenience: long verification times and to prevent contamination with ambient light physical contact is needed (cavities) which reduces hygiene. In addition, the second and third method have to be proven to work for the back of the hand, since only veins are present in that area which do not posses a pulse and mainly contain deoxygenated blood.

Liveness detection in the biometric hand vein industry is in its infancy. Three biometric vendors state to have incorporated liveness detection [87, 94, 95], but exactly which technique is used is not found. Liveness detection should also have the necessary openness for criticism and improvement. It should get more involved in system design, because it is a stage in the verification process. Therefore, it must be treated as part of the biometric system, in that it has impact on the FRR, FAR, FTE and other statistics and properties such as universality and user acceptance. Finally, liveness detection is not spoof-proof and will therefore also have a varying degree of spoofing vulnerability [22]. The international biometric group states more bluntly that liveness detection is ‘effectively nonexistent’ [19], and that it is unlikely to be ever fully addressed in biometric systems – nor does it need to be. Most important is to limit the risks and change the closed attitude towards technology implementations, unrealistic performance claims, and lack of assessing the application specificity of the different systems.

5.2 On the main question

How suitable is the hand vein pattern as a biometric feature

The main question of this thesis is actually an oversimplified question and the answer is not straightforward. Hopefully the full body of this thesis makes this clear. Some main statements address the answer to this question:

- The vascular structure is highly variable, but not (yet) *proven* to be unique
- The veins are rather stable through live, but their visibility is significantly influenced by subcutaneous fat, environmental temperatures and bodily conditions. Solutions to these imaging problems should be assessed. In addition, a serious threat might arise from surgical procedures: since plastic surgery is getting into a crazy hype and money can buy anything, any wanted vein pattern might be possible in the future. However, on this moment only minor changes can be made and real vein pattern changes are unpredictable [90, 91], and scars will be visible on the hand.
- The vein pattern is rather simple; it is important that algorithms retain as much information as possible, while allowing variations in vein patterns due to changing circumstances.
- The first independent large scale performance test on two hand vein biometric devices resulted in a positive evaluation of the performance of these devices [115]. However, this rather new technology should be evaluated more often, including spoof vulnerabilities; a property that should be included in performance statistics [22].
- Liveness detection is essential, because hand vein pattern recognition is shown to be spoofed by artificial hands [11].
- Fingerprints and DNA are easier to obtain from somebody than the hand vein pattern.
- The secrecy of the industry makes it hard to asses the vulnerabilities. The unwillingness of the industry to have their liveness detection methods held up for third party inspection, analysis and improvement makes it the weakest part of the device [19]. '*Instead of finally laying its cards on the table, the biometrics line of business prefers to hide behind error rates it has measured itself*' [120].

All together, the hand vein pattern recognition technique is a potential biometric application, but like all biometric identification methods, in spite of what the industry claims, it is a vulnerable system. Whether due to spoof attacks or false matches and non-matches, a biometric decision based on hand vein pattern recognition cannot be taken in and of itself as unassailable, legal proof that an individual really executed a transaction or entered a facility. However, it might be an appropriate tool to protect access to private areas, as long as you know your vulnerabilities and subsequently adapt your system design.

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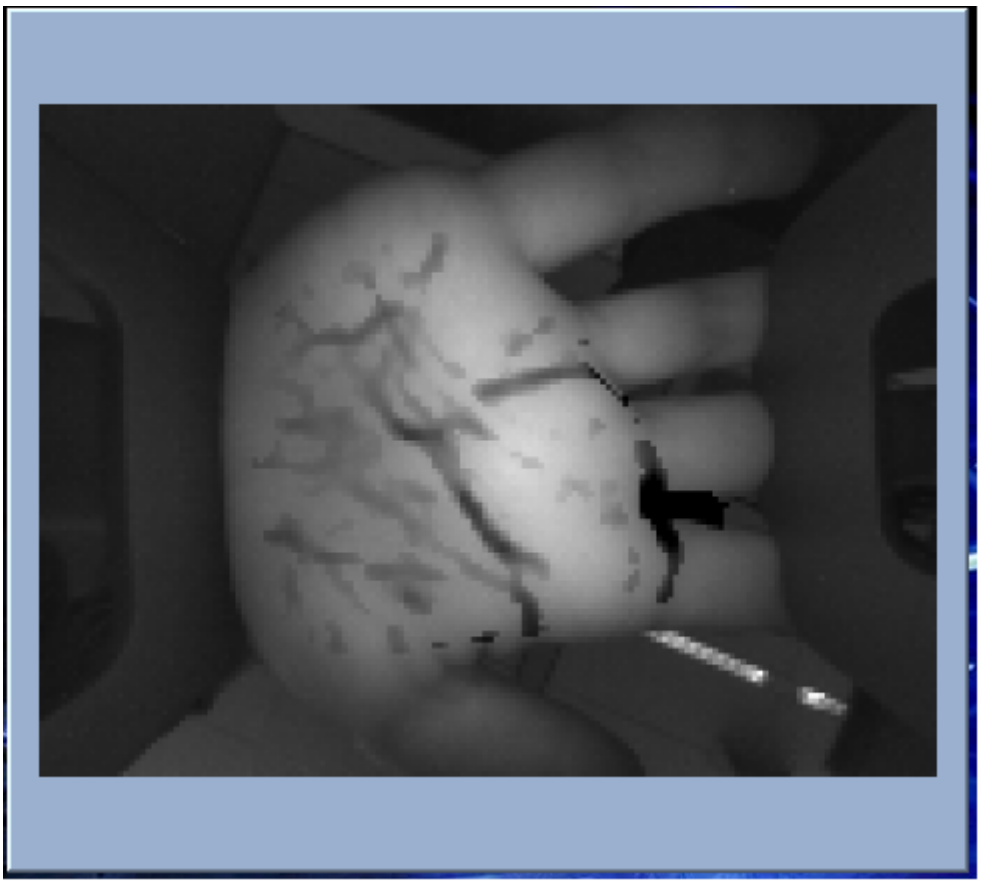

Figure 61 . PrintScreen image obtained during experiment from vein pattern of the author's left hand. Printing this image on white paper and subsequently presenting it to the device would cause verification!

8 APPENDIX A

8.1 Hand vein pattern spoofing

In an informal experiment the Fujitsu's PalmSecure was put under test by the author. The test was performed at the Netherlands Forensic Institute. Demonstration software and Fujitsu's device were available. In figure 61 the palm scanner is shown. In the set-up of the experiment it was equipped with a frame to position the hand more stable.

For enrolment of the hand, several images were taken to create a template of the right and left hand vein pattern. Verification was sometimes possible within one attempt, sometimes several attempts were needed for verification.

During the enrolment or verification process the software would image the vein pattern on screen. By simply using the 'printScreen' button and a straightforward graphic programme this vein pattern could be printed on paper. An example is shown in figure 61. Subsequently mounting this printed version on a real hand would after several attempts also cause verification. Even by mounting the paper version on a hard cover of a book and presenting it to the sensor would result in verification of the vein pattern as belonging to the authenticated person.

This experiment shows the easiness with which this biometric scanner can be fooled. However, it must be said that demonstration software was used and it is not known whether this will have caused the simple spoofing possibility of the device.

Figure 62. The Fujitsu IR palm scanner. Obtained from [102] figure 4.