

**DEVELOPMENT OF LATENT FINGERMARKS AT
EXTREMELY LOW TEMPERATURE**

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**DEVELOPMENT OF LATENT FINGERMARKS AT
EXTREMELY LOW TEMPERATURE**

by

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LIST OF SYMBOLS AND ABBREVIATIONS

CA	Cyanoacrylate
CAST	Centre for Applied Science and Technology
CV	Crystal Violet
FTIR	Fourier-Transform Infrared Spectroscopy
GC-MS	Gas Chromatography- Mass Spectrometry
HDPE	High-density Polyethylene
LDPE	Low-density Polyethylene
LFM	Latent Fingerprint
ORO	Oil Red O
PET	Polyethylene Terephthalate
PP	Polypropylene
PS	Polystyrene
RH	Relative Humidity
SPR	Small Particle Reagent
VMD	Vacuum Metal Deposition

ABSTRAK

Cap jari merupakan antara bukti forensik yang paling penting disebabkan oleh sifatnya yang kekal dan keunikan setiap individu. Walau bagaimanapun, kestabilannya boleh terjejas oleh faktor persekitaran dan ciri substrat. Dalam usaha menyembunyikan bukti jenayah, cap jari sering terdedah kepada keadaan ekstrem seperti pembekuan. Oleh itu, pemulihan cap jari pendam daripada permukaan yang terdedah kepada suhu sangat rendah masih merupakan satu cabaran utama akibat degradasi residu dan kesan pemeluwapan. Kajian ini menyiasat pembangunan cap jari pendam pada pelbagai substrat termasuk bahan makanan (epal dan oren), lima jenis plastik (HDPE, PET, polipropilena, polistirena dan LDPE), logam serta slaid kaca selepas pendedahan kepada suhu -20°C dalam peti sejuk beku selama satu minggu. Kajian ini dijalankan dalam dua fasa; iaitu eksperimen awal dan eksperimen utama. Eksperimen awal bertujuan mengenal pasti perubahan ciri permukaan substrat selepas pembekuan serta menentukan kaedah pembangunan cap jari pendam yang paling berkesan bagi cap jari bersebum segar. Lapan kaedah digunakan, iaitu serbuk bukan magnetik, serbuk magnetik, SPR, Sudan Black, Amido Black, Crystal Violet, Oil Red O dan ninhidrin. Sudan Black, Oil Red O dan serbuk magnetik menunjukkan keberkesanan yang lebih baik dan konsisten bagi kebanyakan substrat yang diuji dalam eksperimen awal. Eksperimen utama menilai keberkesanan teknik pembangunan cap jari pendam selepas pembekuan. Keputusan menunjukkan bahawa cap jari pendam masih boleh dibangunkan selepas pembekuan pada -20°C selama satu minggu. Walaubagaimanapun, kualitinya menurun dengan perincian rabung yang lebih rendah. Kualiti cap jari yang dibangunkan dipengaruhi oleh suhu ekstrem, jenis substrat dan kaedah pembangunan. Permukaan tidak berliang seperti plastik, logam dan kaca

mengekalkan perincian rabung lebih lama berbanding substrat makanan yang mengalami degradasi lebih cepat. Dapatan kajian ini memberi gambaran penting mengenai hubungan antara persekitaran sejuk melampau, jenis substrat dan teknik pembangunan cap jari, serta menyokong pembangunan protokol yang lebih baik untuk visualisasi dan pemeliharaan cap jari pendam dalam persekitaran sejuk atau beku.

ABSTRACT

Fingermarks are a crucial form of forensic evidence due to their persistence and individuality. However, their stability can be affected by environmental exposure and substrate characteristics. Criminals may attempt to conceal evidence by subjecting it to extreme conditions such as freezing, making the recovery of usable fingermarks a significant forensic challenge due to residue degradation and condensation effects. This study investigated the development of latent fingermarks on various substrates, including food (apple and orange), five types of plastics (HDPE, PET, polypropylene, polystyrene and LDPE), metal and glass after exposure to -20°C in the freezer for one week. The study was conducted in two phases; a preliminary experiment to assess surface changes and identify effective development methods for fresh sebaceous fingermarks, and a main experiment to evaluate development performance after freezing. Eight development techniques were examined: non-magnetic powder, magnetic powder, SPR, Sudan Black, Amido Black, Crystal Violet, Oil Red O and ninhydrin. Sudan Black, Oil Red O and magnetic powder consistently showed higher effectiveness in the preliminary phase for most tested substrates. Results from the main experiment indicated that latent fingermarks could still be developed after being frozen at -20°C for one week. However, a general reduction in quality and ridge detail was observed. Fingerprint quality was influenced by substrate type and development technique. Non-porous substrates such as plastic, metal and glass retained ridge detail longer than food substrates, which exhibited faster degradation due to higher moisture content. These findings provide valuable insight into the effects of extreme cold exposure on fingerprint development and support the improvement of protocols for latent fingerprint visualisation and preservation in cold or frozen environments.

CHAPTER 1: INTRODUCTION

1.1 Introduction

Fingermarks are marks retained on the substrate, produced by various secretions from body (Kapoor et al., 2019). Fingermarks are made up of impression of fingers on a material and the sweat secretions together with fatty components (Soták et al., 2025) contribute to the formation of mark. There are two types of commonly found fingermarks which are latent and patent (Frisby et al., 2016) but the latent fingermarks in nature are more common (Azman et al., 2022). Patent fingermarks are visible to human eyes and can be preserved simply from the crime scene while latent fingermarks are invisible to human eyes, hence development technique is needed to enhance it.

Fingermarks remain one of the most reliable and widely used forms of personal identification in forensic science due to their uniqueness where no individuals have same fingerprints and persistence throughout an individual's lifetime (Bleay et al., 2021; Soták et al., 2025). Fingermarks are one of the most common forms of evidence at crime scene and may found on many surfaces such as porous, non-porous and semiporous substrates and under any environmental conditions (Abedi et al., 2023; Kapoor et al., 2019; Usmani & Albanese, 2021).

They play a crucial role in linking suspects to crime scenes, verifying identities, and solving cases by providing comparison of fingerprints from crime scene to suspect's or database. In addition, fingermarks can prevent the innocent people from getting arrested as they have proof of not involving in the crime scene (Sharma et al., 2024). Fingermarks are helpful when there are no DNA, partial or smudged fingermark, or if there is no match in DNA databank because fingermark examination is rapid applicable, non-destructive and cost-

effective with zero rate of error (Brunelle et al., 2021; Usmani & Albanese, 2021).

Fingermarks can be deposited on the surfaces of substrates through different mechanisms and exposed to different environmental conditions. Thus, the chemical and physical interactions between the superficial fingermark residues and with the environments and substrates are important to determine the fingermark development technique later (Kapoor et al., 2019). Fingermark deposition is based on Locard's exchange principle, stating that there is an exchange of material between two objects when there is direct contact between them (Khare & Singla, 2022). The degradation rate and quality of the fingermarks developed are heavily depends on the substrate and environmental condition.

Criminals love to conceal their crime evidence by disposing the evidence in water, burying them in soil, and exposed the evidence to heat (Abedi et al., 2023; Guo et al., 2021; Kapoor et al., 2019; Kowalske et al., 2025; Madkour et al., 2017; Testoni et al., 2020; Trapecar, 2012; Vörös et al., 2022; Walia et al., 2024; Yong et al., 2020). The consequences of concealment of evidence in extreme environmental conditions lead to destroying of the evidence including latent fingermarks on them. Freezing evidence at extreme low temperature is one the popular methods for criminals to get away from being caught as they will keep the murder weapons, bodies and any proof of crime in the freezer or in the low temperature places.

However, the evidence or body is not found immediately after frozen at extreme low temperature but maybe recovered days, weeks, months or years after the freezing. Therefore, some of the latent fingermarks may lose the clarity and visibility of the ridge details, where these attributes contribute to the evidentiary value of the substrate, by degradation. It is

anticipated that latent fingerprints in the extreme low temperature will be preserved better or degraded faster depends on the type of substrate the latent fingerprints deposited on. Due to the complexity in extreme cold temperature as relative humidity is one of the factors that can also affect the latent fingerprints development and quality. Furthermore, since latent fingerprints are invisible to naked eyes, thus law enforcement tends to ignore or overlook the important fingerprint evidence at crime scene.

Previous studies were more focused on the fingerprint development techniques and the degradation of fingerprint on substrates such as glass, metal and food where they were submerged in water, exposed to high temperature and even in snow (Abedi et al., 2023; Colella et al., 2020; Dominick et al., 2011; Madkour et al., 2017; Soták et al., 2025; Trapecar, 2012; Zang et al., 2025). Yet, there is limited study about the fingerprint development technique useful to develop and enhance the fingerprints from different substrates at extremely low temperature condition. There is only little knowledge and understanding about the extreme low temperature effect on the fingerprint quality. The understanding of physical changes and changes of surfaces characteristics of substrates after freezing may help in understanding most effective latent fingerprint development method.

Volumes of studies had carried out and reported on the development of fingerprints from different substrate types and under various extreme environmental conditions. Such as latent fingerprints were exposed to extreme high temperature, submerged in water, contaminated by blood, burial in soil; on fired cartridges and sticky tape (Abedi et al., 2025; Bentolila et al., 2017; Bumbrah, 2016, 2017; Frick et al., 2024; Girelli et al., 2015; Harush-Brosh et al., 2021; Jasuja et al., 2015; Kim et al., 2020; Lam et al., 2022; Olszowska et al., 2020; SAID et al.,

2021; Wightman & O'Connor, 2011; Yong et al., 2020). At the same time, there are many studies conducted investigating the development of latent fingermark on various kinds of substrates such as porous, semi-porous and non-porous (Barros et al., 2020; Berkil Akar, 2021; Grover et al., 2024; Hallez et al., 2019; Loh et al., 2020; Ma et al., 2012; Shahbazi et al., 2020; Spindler et al., 2011; Xiong et al., 2016). However, there is no study about the effects of extreme environmental factor (low temperature) and type of substrate together on the development of latent fingermark.

This study was carried out to understand the effect of extreme low temperature condition and substrates to the fingermark development as well as to discover the most effective method to develop the latent fingermark. The possibility of developing latent fingermarks can be studied based on the visibility and recoverability of the latent fingermarks using development methods. This study may contribute to forensic science field particularly fingermark examination in solving cases involving concealment of evidence in freezer or forensic cases occurred in cold countries.

1.2 Problem Statement

In general, there are various methods exist for developing latent fingermarks on porous and non-porous substrates. However, their effectiveness can be significantly reduced by substrate type and environmental factors such as extreme low temperatures, which may alter the chemical and physical properties of both the substrate and the fingermark residue.

Currently, there is limited research addressing the reliable development of latent

fingermarks from diverse materials especially food items under such harsh cold conditions, leading to potential loss of critical forensic evidence. Previous studies were more focused on developing latent fingermarks from substrates exposed to high temperature, light, snow, submersion in water and soil, but the exposure at extreme room temperature is overlooked.

This research fills the research gap by investigating the physical changes of substrates after frozen in freezer at -20°C for 1 day and determining the most effective latent fingerprint development techniques on each of the substrate exposed to extreme low temperature after one week. It can provide insights for forensic practitioners during collection of latent fingerprint evidence.

1.3 Objectives

1.3.1 General Objective

The general objective of this study was to investigate the most effective method for the development of latent fingerprints from various substrates such as food, plastic, metal, paper and glass, under extremely low temperature.

1.3.2 Specific Objectives

1. To determine the physical changes of substrates after freezing.
2. To compare and evaluate the effectiveness of different fingerprint development techniques for developing latent fingerprints exposed at extremely low temperature.
3. To study the impact of extremely low temperature on the development of latent fingerprints.

1.4 Scope of the Study

This study explored the development of latent fingerprints deposited on five types of substrates which were food, plastic, paper, metal and glass after being exposed to extremely low temperature condition for 1 week. The substrates included 5 kinds of plastics (HDPE, LDPE, PP, PS and PET), paper, glass slide, apple, orange and metal. The research focused on both porous and non-porous materials, considering how extremely cold environments impacted the chemical and physical properties of latent fingerprints and the substrates themselves. The food substrates would be bought a day before experiment for freshness guaranteed. The experiment was conducted for 1 week duration of freezing the substrates bearing sebaceous fingerprints. This experiment aimed to develop the latent fingerprint from all substrates in extremely low temperature condition with the development techniques available. The most effective development method was determined by the degree of developed fingerprint from substrate, depending on the number of minutiae and visibility of the ridges.

The research simulated harsh environment which is extreme low temperature over a controlled time (1 week) to observe how extreme coldness influences fingerprint persistence, clarity, and detectability by using the development method. This study would not cover biometric identification, or database analysis. It also excluded chemical composition analysis using advanced instrumentation such as GC-MS or FTIR beyond the scope of basic degradation observation. Only controlled environmental exposure in laboratory freezer but not in the natural weather like outdoor environment to prevent the uncertainty. The research outcomes focused on identifying how substrate type and environmental factor affect fingerprint survival, thus affecting fingerprint development and would provide applied insights relevant to forensic

recovery and evidence handling in real-world investigations.

1.5 Significance of the Study

This study is significant as it expands the current understanding of how environmental conditions, specifically extremely low temperatures affect the visibility, quality, and recoverability of latent fingerprints on different substrates such as food, plastic, paper, metal and glass. The understanding will directly impact the forensic investigations in cold environments such as in cold country or freezer.

Fingerprints are one of the most powerful tools in forensic identification. Yet their reliability can be severely affected by environmental exposure and substrate type. In real-life investigations, evidence is often collected from diverse materials, ranging from food packaging to food or personal items, with many of which may have been subjected to harsh environmental conditions such as heat, immersion in water, and snow (Abedi et al., 2023; Colella et al., 2020; Frick et al., 2024; Madkour et al., 2017; Soták et al., 2025). In some cases, the criminals concealed the proof of their crimes by hiding in the freezer with extreme low temperature. For instance, in March 2021, a woman was killed and wrapped with towel and plastic sheets to be kept in the freezer (Camoens, 2024). Besides that, a woman named Blair killed her two children and hid them in the chest freezer with plastic bags and blankets (Silman, 2024). A woman was also killed by her son and stored in the freezer since 2021 in Taman OUG (**Figure 1**) (Farik Zolkepli, 2024) . In another case, a dead baby was put in the freezer for two weeks (Iskandar, 2024).

However, in cases involving refrigerated or frozen items and in cold environments, fingerprint preservation and development remain challenging and under-researched. The alteration of physiochemical properties and degradation of fingerprints under such conditions poses a serious challenge for forensic analysts, as it can obscure ridge detail and reduce the success rate of fingerprint recovery. Many crimes involve attempts to destroy evidence by exposing items to water, fire, or extreme temperatures. Research shows that, with the right fingerprint enhancement techniques, fingerprints can sometimes still be recovered, even after exposure to harsh conditions, guiding investigators on when and how to attempt recovery. It provides insights about the type of materials which are more likely to preserve usable and valuable fingerprint evidence after exposure. Thus, from this finding, the effectiveness to recover and develop the fingerprints from porous and non-porous surfaces at extremely cold condition can be increased with the effective methods identified. Ultimately, the findings of this research can enhance the interpretation of latent marks in real temperature-sensitive casework and enhancing the overall reliability and scientific credibility of fingerprint analysis in real-world investigations.



Figure 1.0: Police discovered the body of a woman allegedly murdered by her son and stored in a deep freezer (Farik Zolkepli, 2024)

CHAPTER 2: LITERATURE REVIEW

2.1 Fingerprint and its Type

Fingermarks are comprised of friction ridges which give differentiable and individualistic characteristics that are consistent over time (Sharma et al., 2024). The ridges are called as papillary ridges, creating distinct patterns on the fingertips (Vijay Kumbhar & Prajakta Pimpalshende, 2024). Fingerprint science is based on two key principles: uniqueness and immutability, making them a powerful tool for human identification in forensic investigations (Gomes et al., 2023; Liang & Gao, 2024). Generally, fingerprints are highly reliable, oldest and widely used forensic evidence in forensic investigations to link suspects with crime scene and victims, with the help of professional fingerprint analysts (Cao & Jain, 2017; Grover et al., 2024; Vijay Kumbhar & Prajakta Pimpalshende, 2024).

Fingermarks can be divided into three categories which are latent, patent and plastic, based on the visibility and the types of surfaces they are deposited on (Goenka, 2023; Soták et al., 2025). Mostly, latent fingerprints (LFM) are invisible marks left behind when there were direct contact between the friction ridges of human skin and a hard surface, and are commonly encountered at the crime scene. Latent fingerprints are formed by sweat and oil on, alongside with environmental contaminants on skin's surface. They are invisible to naked eyes and enhancement techniques are required to visualise them (Frisby et al., 2016; Gomes et al., 2023; Liang & Gao, 2024). Latent fingerprints are critically important in forensic identification because they provide a reliable means to link suspects to crime scenes, objects, or victims, often serving as key evidence in criminal investigations but usually goes undetected. It is developed by chemical or physical methods to visualise the fingerprint residues, allowing the

forensic experts to match crime scene marks with reference databases, significantly increasing the chances of identifying suspects or exonerating innocent individuals (Sari et al., 2018).

LFM can be classified into two categories which are groomed and natural. Groomed latent fingerprint is formed when a person rubs the fingertips on his or her oily face or neck, making the fingerprint rich with sebum. Natural latent fingerprint is formed naturally by hands without any intentional washing or cleaning before deposition (Soták et al., 2025). A natural fingerprint residue has a mixture of substances: 99 % of water and 1 % of organic and inorganic substances (Madkour et al., 2017).

Patent fingerprints are visible 2D impressions left on surface by finger. Generally, they are formed by foreign substance coating the finger, leaving a clear outline of friction ridges when depositing the marks. They are produced with the aid of ink pad traditionally during identification purpose most of the time (Chelladurai et al., 2024). Besides from that, they can be formed by blood, greases or dirt (C. Zhang, 2025).

Plastic fingerprints have three-dimensional nature and are deposited on soft, pliable substance by pressing of finger to leave a visible indentation containing unique ridge patterns. Every plastic fingerprint has own distinct characteristics such as depth and detailed ridges.

2.2 Fingerprint Ridge Patterns and Minutiae

The very first fingerprint pattern was introduced by Sir Franchis Galton and Sir William Herschel in 1800s, which were arch, loop and whorl types (Alsharman et al., 2022; Llyod, 2025). In the early 19th century, the finalized fingerprint classification system named Henry

Classification System proposed by a British fingerprint scientist, Edward Henry, and he stated that fingermarks can be classified into 5 classes which are arch, tented arch, right loop, whorl, and left loop (**Figure 2.1**) (Alsharman et al., 2022; He et al., 2023; Llyod, 2025; Militello et al., 2021).

A fingermark is comprised of 3 points which are core, delta and loop (**Figure 2.2**). Core is the center of friction ridge patterns where the ridges coincide with each other. Delta is the divergence point where two ridges will divide and form an almost parallel path. Lastly, loop is formed when several ridges cross the imaginary line between core point and delta point, resulting in a ‘U’ pattern. The loop will ultimately return to the direction it starts (He et al., 2023).

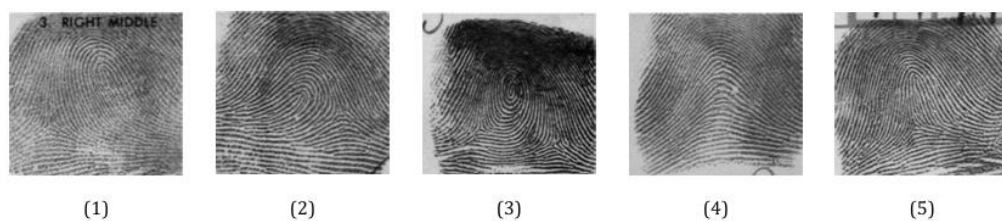


Figure 2.1: Henry fingerprint classification system; (1) Right loop; (2) Left loop; (3) Whorl; (4) Arch; and (5) Tented arch (He et al., 2023)

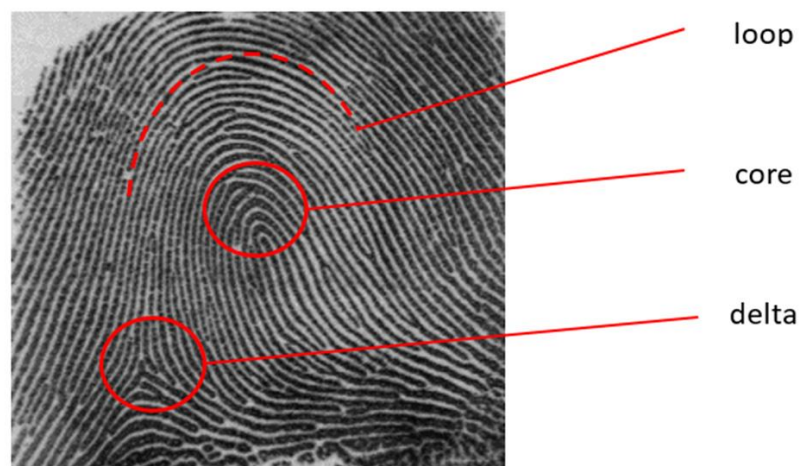


Figure 2.2: Fundamental elements for fingerprint classification (Militello et al., 2021)

2.2.1 Fingerprint Classes

Based on the elements stated above, fingerprints can be characterized into several classes. Each class of fingerprint has its own incidence frequency and subclasses.

2.2.2 First-level Classification

A fingerprint can be observed from three levels of identification features. At the first level, fingerprint pattern types such as whorl, arch, loop and other combination or complicated patterns can be observed and compared. Mostly, the specificity is not high for first level fingerprint identification (Soták et al., 2025). Arch is the most uncommon fingerprint pattern where only 5 % of them (Llyod, 2025). Arch class has ridges enter at one side, rise to form a small protuberance and exit on the opposite side, but has no delta and loops at all. It has two subtypes which are plain arch and tented arch. Plain arch class has gentle rising and falling of ridges while tented arch class has at least one ridge with high curvature than the normal arch, sometimes sharper angle in the center that resemble a pitched tent, with the presence of a loop and a delta (Llyod, 2025).

Loop class pattern is the most common fingerprint pattern with about 65 % population has it. Generally, loop is a flowing of friction ridge at one side, recurves, touches and passes between delta and core, then exits at the same side when entering (Science Regulator, 2013). It can be divided into 2 subtypes which are ulnar and radial loop. Ulnar loop opens towards the pinky finger whereas radial loop opens toward the thumb (Llyod, 2025). Both loops have a delta and a loop.

Whorl class is 30 % obtained by population (Llyod, 2025). It has at least two deltas in circular form and at least one recurving ridge, with higher number of minutiae than loops and arches (Gutiérrez et al., 2007; Militello et al., 2021). In the Whorl class, the subclasses are plain whorl, central pocket whorl, double loop whorl and accidental loop whorl (Llyod, 2025). The fingerprint pattern types are shown in **Figure 2.3**.

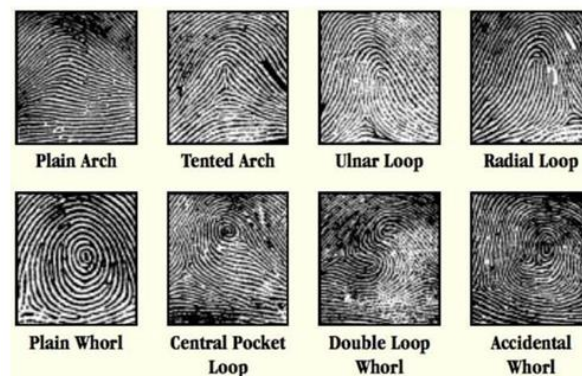


Figure 2.3: Eight general fingerprint pattern types (Fraser, 2013)

2.2.3 Second-level Classification

The second level features are irregularities found on the friction ridge skin, called minutiae. Fingerprint minutiae are points within the friction ridge patterns of finger which are specific as the ridges show discontinuities. These randomly distributed, large number of stable minutiae on the fingerprint make fingerprint unique among people, thus, it has high discriminating power for individualisation of fingerprints (Abhishek & Yogi, 2015).

The minutiae are given names based on their shapes (Soták et al., 2025). The most frequently observed minutiae types were ridge endings, convergence and bifurcations (Gao et al., 2023; Gutiérrez et al., 2007; Noor et al., 2019). The bifurcation is a point when a single ridge splits and divides into two separate sub ridges from a single ridge while ridge ending is

a point where the ridge ends abruptly (Abhishek & Yogi, 2015; Noor et al., 2019). Other less common minutiae types are dot (island); short ridge; lake or enclosure; bridges; spurs and trifurcations. The types of minutiae for fingerprints are shown in **Figure 2.4**.

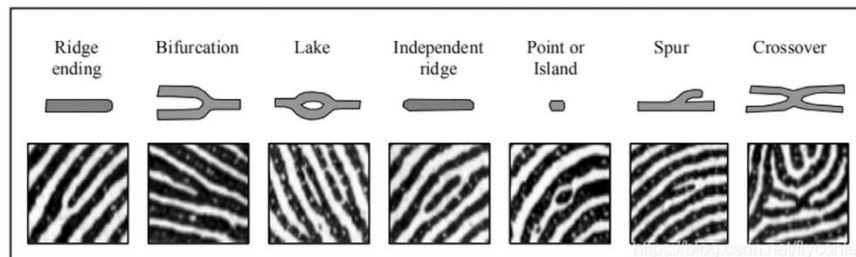


Figure 2.4: Types of the minutiae or characteristic points (Gao et al., 2023)

2.2.4 Third-level Classification

Third level identification features are highly individualistic, including scars, disease and sweat pores (Soták et al., 2025). Plus, they are microscopic and detailed features such as number, size, location, shape and edge contour of the friction ridges and pores (Shi et al., 2021). The pores can be utilized to increase the efficiency of minutiae-based latent fingerprint matching (Agarwal & Bansal, 2021). Pores can be divided into two categories: closed and open pores (Figure 2.6). Closed pores are fully enclosed by the ridge at both ends while open pores locate between two ridges and intersect with valley (Jain et al., 2006). The level 3 features of a fingerprint are shown in **Figure 2.5**.

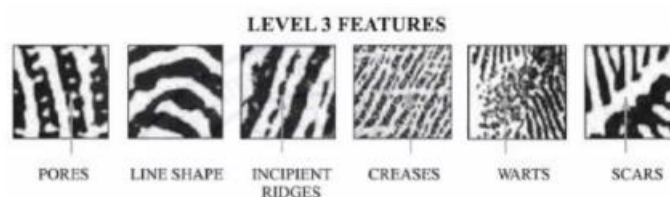


Figure 2.5: Level 3 features (Abhishek & Yogi, 2015)

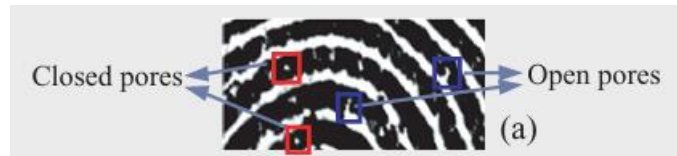


Figure 2.6: Level 3 feature - Open and closed pores (Jain et al., 2006)

2.3 Latent Fingermark Composition

Fingermarks are complex residues left by the excretory glands, consisting of endogenous organic like amino acids, inorganic compounds and exogenous substances such as cosmetics, food residue, drugs, metabolites, and other environmental contaminants such as dust and hair products (Croxtton et al., 2018; Khare & Singla, 2022). With the analysis of chemical composition of fingerprint, one can obtain information like donor's age, sex, lifestyle and occupation (Khare & Singla, 2022). The factors affecting the composition of sweat produced from skin surface are shown in **Figure 2.7**.

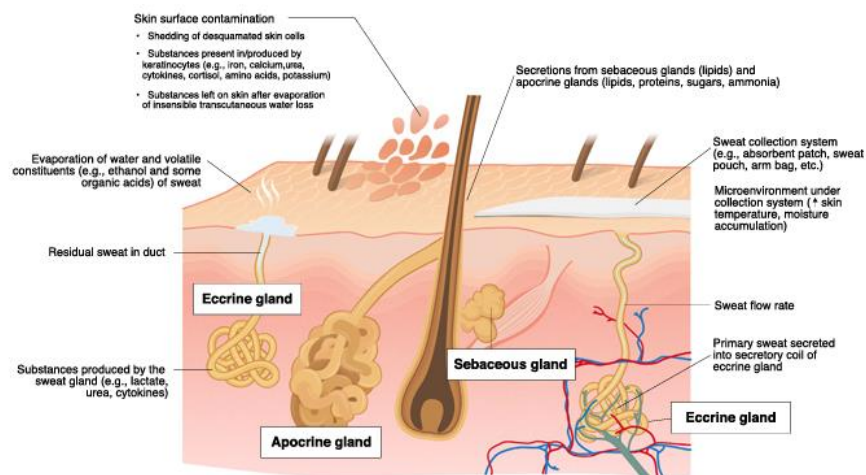


Figure 2.7: Factors impacting the composition of final sweat collected from the skin surface (Baker & Wolfe, 2020)

2.3.1 Eccrine Secretions

Eccrine secretions are very complex with mixture of solutes, where the composition is not fixed and can change significantly along passage in sweat duct and during collection onto skin surface from time to time (Croxtton et al., 2018). The primary sweat secretion has components of blood plasma. Eccrine sweat glands are the most numerous glands found on the body surface area, producing the highest volume of sweat.

Eccrine secretion is mostly comprised of salt water up to 99.5 % (Kent, 2016) with a mixture of various concentrations of organic and inorganic components, for instance, micronutrients (K^+ , Ca^{2+} , Mg^{2+} , Fe^{2+} , and vitamins), metabolites (glucose, ammonia, urea, lactate, bicarbonate, amino acids, ethanol), cortisol, cytokines, protein and peptides (Croxtton et al., 2018; Robson et al., 2022). Even though eccrine secretions are mainly water but the water is reabsorbed into body through skin or evaporated during the deposition of fingerprint so water will not coat the palmar surfaces from time to time. Eccrine gland does not only produce water-soluble components but low concentration of subcutaneous components (Kent, 2016).

Latent fingerprint produced by eccrine gland contains amino acids such as serine, glycine, alanine, histidine that are important for many fingerprint detection reagents during the development (Steiner et al., 2022).

2.3.2 Sebaceous Secretions

Sebaceous gland contains sebocytes that produce lipid droplets for rupture and release sebum which makes up large portion of oily latent fingerprint. The constituents of sebum are lipids such as glycerides, fatty acids, wax esters, cholesterol esters, cholesterol and squalene,

which is highly unlikely to be same exactly between two individuals (Croxtton et al., 2018). Since there is no sebaceous gland on the fingertips, thus the presence of sebum found in the fingermark is caused by the collection of lipid-rich substance from the face, hair and external contaminants (Kim et al., 2019; Zhang et al., 2021).

2.3.3 Apocrine Secretions

Apocrine gland is one of the three main skin glands that contribute to chemical composition of latent fingermarks and secondary source for fingermark production since it is not found in the fingertips but found in breast, genital areas, armpit and perineum (Baker, 2019; Lee & Gaensslen, 2001). Yet, apocrine secretions only developed after puberty and are rich in proteins, lipids, and pheromonal compounds for body scent that to be transferred to fingers after contact with apocrine-rich skin regions (Baker, 2019; Haskell, 2010). However, it has same minerals and metabolites as the eccrine secretions and contents mix with sebaceous secretions (Chen et al., 2020; De Alcaraz-Fossoul et al., 2013).

2.4 Factors Affecting Fingermark Quality

Fingermark quality is affected by many factors like incompleteness of fingermark deposition, environmental condition, chemical and physical interaction between donor and substrate, types of substrates it deposits on and the donor's characteristics (De Alcaraz-Fossoul et al., 2013). The fingermark quality is considered over time from deposition, persistence and transfer of latent fingermark, deciding whether the fingermark will appear, survive and be recoverable.

2.4.1 Donor of Fingerprint

Donor's conditions can affect the deposition and persistence of fingerprints, thus affecting the degradation rate and quality of the fingerprint. For instance, sweat, secretions' composition and amount, race, age, sex, health status, lifestyles and mental stress of donor can influence the fingerprint deposition (Cadd et al., 2015; De Alcaraz-Fossoul et al., 2013; van Helmond et al., 2019). Individuals with different age have different composition of free fatty acids, affecting the quality of deposited fingerprints (Cadd et al., 2015; Khare & Singla, 2022). According to Galbally et al. (2016), elderly groups aged 65 and above have lowest quality of fingerprints among children and adults, where adults with age from around 25 have the highest quality of fingerprints. However, the fingerprint quality starts to decline steadily from 45 years old because the skin slowly loses elasticity and firmness, resulting in dry skin and decrease in the quality of deposited fingerprints (Galbally et al., 2016, 2024).

During development of fingerprint, sex plays important role too as male has wider but lower density of ridges than female, thus affecting the species and concentration of fingerprint residues (Li et al., 2023). The fingerprints deposited by men are higher in quality than women because the current technology favors to recognize men's latent fingerprints but not intrinsic properties of fingerprints themselves (Galbally et al., 2024).

Both inter-donor and intra-donor variability can lead to significant differences in the detectability and clarity of fingerprints. Donor can be classified into three large groups which are strong, medium and weak. There are many reasons leading to the weak donor during deposition stage such as transfer force being too strong or weak, ability to secrete, duration of deposition, frequency of washing hand, handedness and transfer angle (Cadd et al., 2015). For

inter-donor variability, different individuals have different lifestyles and habits. Some have the habits of using cosmetics while some have habit of smoking. The presence of cosmetics contaminants and nicotine in the fingermark deposited can affect the chemical composition of deposited fingermarks, providing intelligent information for forensic investigation.

For intra-donor variability, different fingers on the same hand of same individual produce different quality of fingermarks where little finger produced the least quality mark with the smallest surface area in contact with the substrate whereas thumbs and indexes were performing the best (Galbally et al., 2024). Besides that, same person will also have different skin conditions, recent activities and secretion levels on same finger type on different hands at different times (Chadwick et al., 2018). Furthermore, handedness has impact on the fingermark quality when dominant hand deposits the fingermarks, the impressions are higher in quality than non-dominant hand (Galbally et al., 2024). Additionally, contaminants such as oils, lotions, hand sanitizers, and other substances on the skin can create an extra layer that alters or obscures fingermark patterns, reducing clarity and intensity (Kumari et al., 2021; Nagar et al., 2022).

2.4.2 Substrate

Substrate for fingermark deposition plays vital role in deciding the developed fingermark quality and development methods. Surface properties such as porosity, smoothness, size, shape, moisture level, type of material, degree of cleanliness and adhesive property will affect the quality of developed latent fingermarks.

Fingermarks are deposited on surfaces, and majorly divided into 2 types: porous and non-porous (Gülekcı, 2022). The substrate's porosity affects the adhesion forces between the fingerprint deposited and substrate, thus affecting the decisions made for techniques used to develop and enhance the prints (Jang, 2025; Nagar et al., 2022). For example, porous substrates caused the absorption of deposited latent fingermarks into the porous media, staying at the absorption site and protected from degradation, resulting in developing higher quality of fingerprint (Banerjee, 2023; Bouzin et al., 2020; Chadwick et al., 2018).

Non-porous substrate cause fingermarks more susceptible to degradation with the increasing exposure to physical friction and environmental factors like mechanical stress or weathering, increasing risk of development of latent fingermarks (Banerjee, 2023; Bouzin et al., 2020; Cadd et al., 2015; Chadwick et al., 2018; Swati et al., 2018). For example, non-porous substrates like glass, metal and painted wood do not absorb the secretions at all until the compounds degrade on the surfaces (Cadd et al., 2015). Non-porous surfaces fail to hold oils and dirt tightly compared to porous surfaces (Lachance et al., 2016). On the other hand, Goenka (2023) stated that non-porous substrates do not have pores so they would not absorb anything, making them one of the easiest surfaces for development of fingermarks as the fingerprint residue would simply remain on the surfaces for lifting and preservation as well.

Semi-porous substrate can absorb water and dissolve in water entirely, resulting in the characteristic of substrate in between porous and non-porous. For instance, semi-porous substrates such as glossy papers cause eccrine and sebaceous compounds absorbed slower than in porous substrate (Cadd et al., 2015). The mechanisms of how substrates degrade on porous (**Figure 2.8**) and non-porous surfaces (**Figure 2.9**) immediately, minutes or hours and weeks

or months after deposition are shown below.

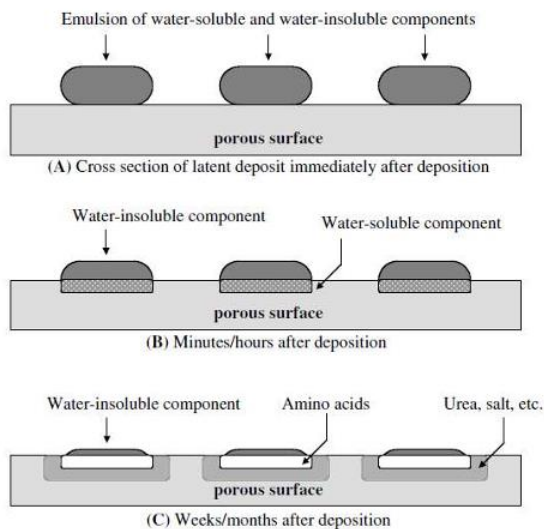


Figure 2.8: Degradation of fingerprint on porous surface (Bacon, 2012)

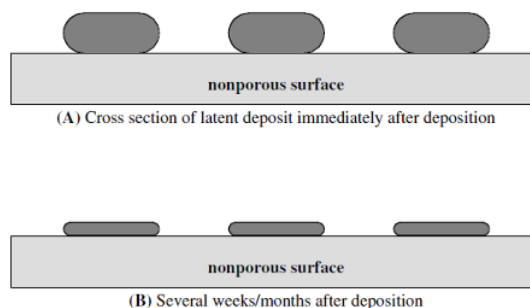


Figure 2.9: Degradation of fingerprint on non-porous surface (Bacon, 2012)

2.4.3 Environmental Factor

Several environmental factors significantly impact fingermark development and quality. Moisture and water exposure such as snow, rain, or submersion in fresh or sea water can rapidly degrade fingermark quality, reduce the number of identifiable minutiae and produce prints less usable for identification, with longer exposure and higher salinity as in sea water causing greater damage (Abedi et al., 2023; Devlin, 2009; Gülekçi, 2022; Madkour et al., 2017; Said et al., 2021; Soták et al., 2025). Soták et al. (2025) studied that natural snowfall and immersion

in show caused degradation of fingermark, the latter had more destructive effect on the fingermark quality when the number of minutiae significantly reduced.

This is because the sweat-fat substance of fingermark mixed with melted snow and water-soluble residues were prone to destruction and degradation by water, heat, low humidity, thus decreasing the quality of latent fingermarks (Abedi et al., 2023; Soták et al., 2025). Gülekçi (2022) discussed that fingermarks immersed in seawater for 30 days were lower in quality and less numbers for identification while higher quality for fingermarks immersed in fresh water for 90 days. Azman et al. (2022) reported that quality of latent fingermarks on all samples reduced significantly as the duration of immersion in the natural outdoor pond prolonged, with thick muds covering the surface of fingermarks.

It is known that not only temperature but humidity also affects the effectiveness of latent fingermarks development, quality of latent fingermarks and degradation rate (De Alcaraz-Fossoul & Javer, 2022; Hong et al., 2019). Higher humidity can lead to rehydration of latent fingermarks (De Alcaraz-Fossoul & Javer, 2022). Study from Farrugia et al. (2015) demonstrated that for cyanoacrylate (superglue) fuming, an optimal relative humidity of around 80% produces the highest quality fingermark development, as humidity affects the polymerisation process and the resulting microstructure of the developed marks. Paine et al. (2011) reported that relative humidity of 90% developed the highest quality of eccrine fingermarks by CA fuming and 70% and 90% for sebaceous fingermarks but suddenly dropped at 100%. Lower humidity around 60% leads to less effective development by using CA fuming, while too high humidity can cause background staining and less distinct ridge detail (Paine et al., 2011).

In refrigerated or cold storage conditions, the quality of fingerprints can also depend on the humidity during the development process, with cyanoacrylate fuming at high humidity (80%) outperforming other methods such as SPR and fingerprint powder on cold surfaces (Hong et al., 2019). Humidity also impacts the performance of fingerprint powder because prolonged exposure to high humidity can reduce powder effectiveness (Harrington & Gee, 2024). Vera Stimpson et al. (2025) found out that presence of humidity promoted the absorption of moisture by the substrate and affected the stability of fingerprint residues by softening the ridge structures and merging of ridge details. Thus, humidity also plays a significant role in stability and development of good quality latent fingerprints.

Temperature also plays a role; both skin and environmental temperatures can affect the clarity and success of fingerprint imaging, as can the presence of moisture on the fingertip or substrate (Cadd et al., 2015; Colella et al., 2020; De Alcaraz-Fossoul et al., 2013; Gülekçi, 2022). Latent fingerprints exposed to high temperature can cause more water loss and increased amino acids and urea degradation; and high level of moisture is more towards affecting the development of fingerprints from porous substances (Cadd et al., 2015; Kaur et al., 2024). De Alcaraz-Fossoul & Javer (2022) explained that the number of deposited fingerprints suitable for identification decreased at high temperature as the high temperature can accelerate the degradation of ridge details.

Besides that, Sodhi & Kaur (2001) stated that high temperature causes evaporation of moisture and oily components, leaving the deposition of latent fingerprints are more viscous, resulting in harder to develop latent fingerprints by powder techniques. On the other hand, extreme low temperature like -20°C caused larger loss of ridge details and quality as the latent