

Chapter 3

Novel Technological Applications for Latent and Blood-Stained Fingerprint Aging Studies



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Abstract At the present time, there are no standard methodologies to reliably determine the age of (latent) fingerprints recovered from crime scenes. Estimating the time of deposition of this type of evidence is a complex challenge that remains scientifically unsolved in the forensic domain. This chapter addresses the effort to investigate and evaluate the age of fingerprints, and answer the question: how much information can “imaging technologies” provide on fingerprint aging? The objective is to introduce the reader to novel applications of existing technologies—Optical Profilometry (OP) and visible wavelength Hyperspectral Imaging (HSI)—that can visualize and record variations in the topography of ridges and follow spectral changes in blood-stained fingerprints, respectively. OP has been typically used for the 3D analysis of surface roughness of materials; whereas HSI has been previously used to detect and identify blood stains in a forensic context and estimate their age in laboratory settings. These non-destructive, contactless, imaging technologies eliminate the need for manipulating friction ridge skin impressions and minimizing sample destruction. Most importantly, they allow the simultaneous collection of qualitative and quantitative data that can be analyzed using spatio-temporal statistical models to investigate the mechanisms involved in ridge degradation. OP and HSI, among other technologies, are establishing new foundational research to integrate the *age* variable in future fingerprint examination flowcharts. This inclusion could potentially reduce identification errors that are caused by time inconsistencies between the evidence discovered and the crime committed, as well as maximize the use of resources by decreasing the number of traces to be processed.

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3.1 Introduction

For decades, forensic sciences have adapted scientific principles and technologies from other disciplines for the analysis of crime scene evidence and the identification of suspects. The goal has been to obtain valid proof with maximum objectivity and reliability to associate the true perpetrators with the crime, beyond reasonable doubt during the judicial process. To date, fingerprints remain, together with DNA analysis, the core tool for human identification and are often the fastest and most accessible type of forensic evidence available for this purpose. In addition, fingerprints are more than just a biometric tool; they can also provide chemical trace information about the donor; for example, on the use of illicit or prescription drugs, donor's diet, and health conditions, among others [1–3].

Current friction ridge skin methodologies—mostly fingerprints¹—identify suspects by their morphological patterns; however, the time of fingerprint deposition cannot be reliably estimated and remains an unsolved issue in forensic science [4, 5]. The absence of (international) standards to detect inconsistencies between time of deposition and the perpetration of a crime has a negative impact on the criminal justice system. For example, no information on the age of a trace can invalidate otherwise strong items of evidence or wrongly implicate innocent individuals not directly related to the crime. As a result, many suspects are released and innocent citizens wrongly implicated when fingerprint evidence cannot be substantiated in court by the time of deposition (i.e. the age of the fingerprint).

The ideal scenario is that in which any investigator/scientist would be able to objectively qualify and quantify changes in ridge topography of unprocessed fresh and aged latent fingerprints and blood-stained fingerprints, either at the scene or in the laboratory. Variations in ridge characteristics over time would be statistically tested and include a measurement of error. Previous studies [6–19] have correlated the time of deposition with certain visual and chemical changes in ridge patterns and the effect of the surrounding environment but with limited and partial results (see Sect. 3.4 for further details). These include research on the chemical composition of sweat secretions [6–8, 12], visual examinations of topographical changes over time [10, 15–20] or chemical imaging of fingerprint components [11, 13, 14, 21, 22]. All these studies have provided relevant insights for a better understanding of fingerprint aging, but results have shown some limitations. In this chapter, the focus will be on the novel use of Optical Profilometry (OP) to visually characterize and measure latent fingerprint ridges in 3D and the potential of HyperSpectral Imaging (HSI) to detect spectral changes in blood-stained fingerprints over time.

Ideally, crime scene investigators would have available easy-to-use, inexpensive, portable and quick analytical tools to estimate the age of latent and blood-stained fingerprints. To this day, and from a scientific perspective, the development and

¹This term refers to latent or invisible impressions (undetectable to the naked eye), plastic or molded impressions (e.g. prints on clay or wax) and patent (aka visible prints) unintentionally made by friction ridge skin on a surface. They require a specific enhancement or processing for analysis. The term *fingerprint* refers to controlled setting (e.g. inked prints taken from detainees).

operational deployment of these very desirable technologies have been difficult due to several factors which include:

- *Environmental challenges*—Numerous environmental variables may affect fingerprint degradation and these pose a complex challenge to determining which one(s) is/are most significant in the aging process. Extrapolation of data in the form of a significant population study has also proven to be an experiment design limitation.
- *Limited financial resources*—Trends in innovation have traditionally focused on other branches of science, such as genetics, while forensic science has fallen behind, in part due to limited and dedicated funding.
- *Technological barriers*—Recent technological advances have enabled the development of economically affordable, easy-to-use software and hardware for many mobile applications. Despite these advancements, no commercial computer-based tools are yet available for dating latent fingerprints due to the aforementioned issues.

From the range of currently available technologies to be used for latent fingerprint aging studies, an Optical Profilometer (OP) was chosen for its potential and already proven capabilities in analyzing very small surfaces in 3D. OPs have been used for years in the visual study and data collection of surface roughness of materials, proving to have many advantages and a few limitations [23]. Optical Profilometry is a non-destructive, contactless, three-dimensional (3D) microscopic imaging technology that is presented in this chapter as a novel tool for analyzing latent fingerprint ridge topography [23]. One of the key features of an OP is that it eliminates the need for enhancing (e.g. by powdering) latent fingerprints to visualize them in a research context; minimizing specimen manipulation and avoiding the introduction of potential error in ridge measurements. It also allows the simultaneous analysis of several visual ridge features (e.g. ridge height, area, volume and width) beyond the simple visualization of ridges. Figure 3.1 shows a typical equipment setup.

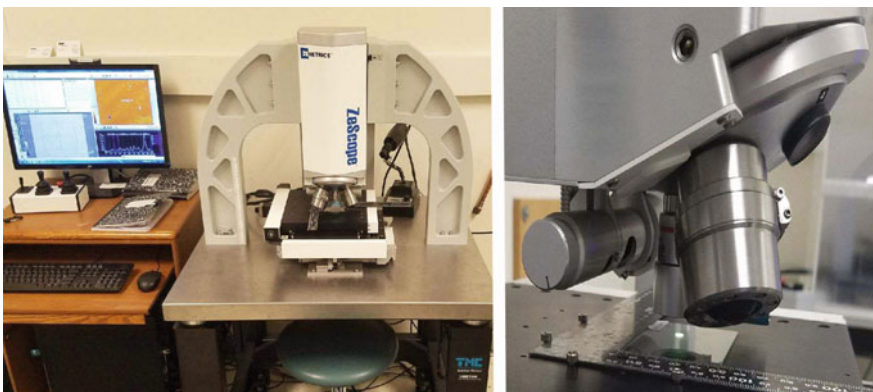


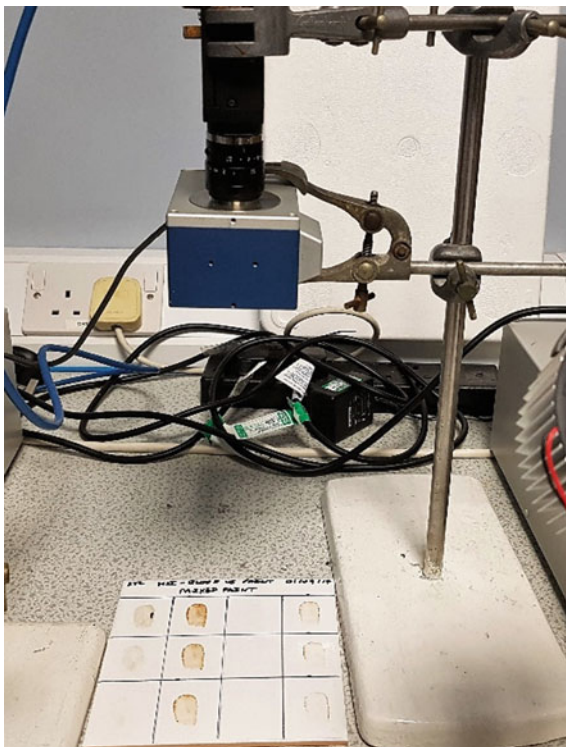
Fig. 3.1 Typical optical profilometer set up (left) and detail of microscope objective (right) with a microscope glass slide mounted on the moveable platform

The other technology covered in this chapter is hyperspectral imaging (HSI) and will concern blood-stained fingerprints. This technique can only be applied when blood is present. In a forensic context, blood is found to be the most common contaminant of fingerprints. An assumption of the technique is that the age of the fingerprint is the same as the age of the blood stain. However, the technique cannot determine whether the fingerprint was made in blood or was deposited sometime before and, then, subsequently covered with blood at the time of the crime. HSI is an established non-contact, non-destructive technique which was originally developed for satellite-based monitoring of the earth but has recently been used in forensic applications, including the detection, identification and age estimation of blood stains [24, 25]. It is based on recording images at series of wavelengths and combining the information to create a 'datacube' such that spatial information is recorded in x and y dimensions and spectral information is recorded in the z direction. Thus, in a hyperspectral image, every pixel in the image also contains spectral information across a range of wavelength bands. This information can be used to detect and identify substances in an image by statistically comparing the spectrum in the pixels against a database reference spectrum. HSI can be performed in several ways and also across different wavelength ranges from the ultraviolet (UV) to the infrared (IR). The most commonly used and most accessible wavelength range is the visible range from 400 to 700 nm while one of the simplest ways of obtaining visible wavelength hyperspectral images is to attach a liquid crystal tunable filter (LCTF) in front of a monochrome camera and scan across the wavelength range while recording images at each wavelength. Custom software can then be used to create and analyze the resulting 'datacube'. Figure 3.2 shows a typical equipment setup.

Constant technological advances, our better understanding of latent fingerprint chemistry, and of the effect of the environment on topographical changes of ridges over time, make age estimation a more feasible endeavor. In order to accomplish this objective, it is of paramount importance that scientists from diverse disciplines (e.g. biology, chemistry, forensic sciences, statistics, computer science, etc.) come together in multidisciplinary collaborations to share and build knowledge from their respective fields.

A robust estimate of a fingerprint's age could be used in the near future as admissible data in court, increasing the probative value of evidence, with a direct positive impact on public confidence in criminal justice. It would also fulfill an emerging demand for obtaining rapid analytical results as well as tackling current scientific, legal and societal demands that have weakened the reliability of forensic evidence in the judicial system. The technologies presented in this chapter demonstrate the significant advances in forensic research in the field of fingerprint aging that could be used towards increasing robustness of this type of evidence.

Fig. 3.2 A typical HSI setup based on a LCTF attached to a camera



3.2 The Impact of Fingerprint Identification Errors

Fingermarks have aided in the resolution of millions of criminal cases worldwide for over a century. However, in our modern technological society, errors in identifications have become a grave concern with many being caused, in part, by the examiner's subjective analysis and/or conclusions during the process of "matching" the unknown fingerprint to its donor [25–28]. We can ascertain with high degree of confidence that these errors are not caused by the intrinsic identification power of the trace itself. The degree of subjectivity on the analysis and the reported errors in biometric identifications have caused much controversy in the criminal justice system and beyond. It was, in fact, brought to the forensic science community attention by the National Research Council (NRC) report in 2009 in the US,² among other reports published around the same time, or soon after, in other countries.³ These

²Strengthening Forensic Science in the United States: A Path Forward. Committee on Identifying the Needs of the Forensic Sciences Community, National Research Council. 2009. ISBN 978-0-309-13135-3.

³Issues also noted by the Scottish Report "The Fingerprint Inquiry"; APS Group Scotland. 2011. ISBN: 978-0-85759-002-2.

reports strongly criticized the absence of reliable scientific methods in some forensic disciplines that led to mis-attributions and mis-identifications of fingerprints.

In the context of this chapter, mis-attribution and mis-identification refer to different closely related concepts (Fig. 3.3). The former denotes cases where a fingerprint is correctly associated to a suspect but is inconsistent with the time the crime was committed, while the latter matches incorrectly the trace to a donor because not enough clear identifiers are present, i.e. poor quality and/or quantity of necessary ridge detail; in this case, an error in interpretation by the expert has been made, leading to a wrongful match. Despite standardization of the fingerprint examination process (ACE-V⁴) and the development of protocols in crime laboratories, these types of errors still occur.

Regarding mis-identifications, false positive rates⁵ are estimated at 0.1–3% depending on the sources, mostly from proficiency tests [28–30]. For example, according to data published by Simon A. Cole [28] based on Federal Bureau of Investigations (FBI) research in the US, an estimated 0.8% false positive rate exists in the current methodology for analysis, i.e. the incorrect association of a person with a recovered fingerprint.

Whilst mis-identification remains an issue, the most common situation arises when a suspect has legitimate access to a scene before or after the actual crime; then, the inability to date the time of fingerprint deposition often invalidates otherwise strong pieces of evidence or wrongly implicates innocent individuals. Issues of reliability of fingerprints as a means of human identification frequently arise in court when evidence cannot be directly correlated to the moment a crime was committed [5].

But, how much do these identification errors impact our society? For example, a Eurostat report by the European Commission⁶ indicated that there were over 28 million serious crimes reported in the European Union in 2008, impacting, directly or indirectly, over 75 million individuals.⁷ Of these crimes, and based on typical figures,⁸ it could be estimated that fingerprints were recovered from approximately 30% of cases, and of these, and in the absence of official global figures, a conservative average of at least 25% would be positively correlated to a donor. In Europe each year, 2.1 million offenders are identified by fingerprinting, and although there are no official reports on error rates, it could be estimated that nearly 17,000 cases annually may result in false positives due to both mis-attributions and mis-identifications. Different areas of the criminal justice system could benefit from age evaluations of

⁴ACE-V: Analysis, Comparison, Evaluation, and Verification, referred as being a standard scientific method in the comparison and identification of friction ridge impressions.

⁵Refers to the prevalence of cases that incorrectly associates a person to a recovered fingerprint.

⁶http://ec.europa.eu/eurostat/statistics-explained/index.php?title=Archive:Crime_and_criminal_justice_statistics_data_2008-2013.

⁷As mentioned on page 141 of the REGULATION (EU) _o.../2013 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of the Horizon 2020—the Framework Programme for Research and Innovation (2014–2020).

⁸ANZPAA NIFS (Australian New Zealand Policing Advisory Agency) report “End-to-end forensic identification process project”, in 2012.



Fig. 3.3 Diagram depicting types of error and how the inclusion of the “time” factor can improve the reliability of evidence

fingermarks; for example, by decreasing the number of traces to be processed, expediting the prosecution process and minimizing exposure to primary and secondary victimization⁹ of individuals directly or indirectly related to the crime.

It is clear that fingerprint examinations have come with errors as well as bias [31] which must be addressed. However, there are some valuable aspects of using the cognitive system in the process of fingerprint analysis. As Dror mentioned in 2013 “*expert opinions can be valuable in court, not for being fact but simply as a matter of only [expert] opinion*”. Another positive aspect is that a degree of subjectivity and cognitive nature can increase the value of these decisions by introducing experience and instincts into the already standardized and successful processes. This involves taking counter measures that can help minimize the contextual influences, biases and even the possibility of error [32]. There is no harm in being a human (subjective) science, the cognitive underpinning of decisions just needs to be understood by the investigators when making an arrest, by the forensic scientist when preparing a report as well as by the jury in court. As individuals become experts, it can be helpful to determine how shortcuts are taken, past experiences are more relied on and how certain marks are examined more selectively due to their initial appearance to the examiners. Once the cognitive architecture of human experts in fingerprint forensic science is understood, there can be steps taken in developing best practices [31], as well as implementing a statistical, quantitative aspect to the science. Given the widespread use of fingerprint evidence and the public demand for higher scientific standards, it is critical that the methodology for analysis becomes as accurate and error free as possible. Fingerprint aging can provide a degree of knowledge and intelligence to help reduce error in identifications.

There has been no shortage of critiques that have cast doubt on the practice of fingerprint identification and their use in court. There have been strides made since the publication of the National Research Council Report in 2009, and with these advancements have come more areas of expertise that can yield great knowledge. Fingerprint research has developed to encompass incorporating the following:

- Various statistical models for different aspects of fingerprinting;
- Qualitative and quantitative data to support fingerprints as evidence;
- Methods to estimate the age of a fingerprint.

Convictions can hinge on the unknown factor of whether or not a particular mark was left within the timeframe of a crime. This is one of the reasons research has taken form to investigate an accurate model for determining the age of latent fingerprints [34] and place a suspect within the timeframe of a crime beyond any subjective witness or victim statements. With the information that new research is providing, the errors made and controversies that emerged in (latent) fingerprint decisions could greatly decrease in the years to come. The evolution of an age-old science has gained

⁹Secondary victimization (also known as post crime victimization or double victimization) is the re-traumatization of the (sexual assault, abuse or rape) crime victim. It is an indirect result of assault which occurs through the responses of individuals and institutions to the victim. The types of secondary victimization include victim blaming, inappropriate behavior or language by medical personnel and by other organizations with access to the victim post assault [33].

great steam as research has taken off in the last decade. There is great hope for what forensic scientists have yet to uncover with the knowledge that has already been obtained.

3.3 The Estimation of Age Will Improve the Robustness of Fingerprint Evidence

The possibility of estimating the age of fingerprints has been implicitly or explicitly discussed in at least 28 court cases from 1961 to 2011 as reported by Girod et al. [2]. The study reported, that, in some instances, experts stated that it was impossible to determine the exact age of fingerprints. However, they provided the court with personal opinions based on experience. Opinions were (and are) subjective in nature, with potential for biases. Also, the majority of the literature on fingerprint analysis has emphatically stated that it is “impossible” to precisely determine the age of (latent) fingerprints [35] and it has been recommended that “(...) *age estimation should never be based solely on the quality of a developed mark (...)*”. Despite these objections to fingerprint aging, researchers have studied and established evidence of degradation processes, including qualitative and quantitative visual methods, and chemical profiling of fingerprint deposition compounds [2–19, 36–38].

We advocate for the inclusion, in the near future, of the factor *age* in the fingerprint examination process (Fig. 3.4), because it could significantly improve the overall robustness of evidence beyond the most immediate attribute of estimating a specific time of deposition. The increased value of the probative power of evidence could be summarized as [37]:

- Temporal location of a suspect during the perpetration of a crime: the order in which objects were touched and, therefore, the sequence of certain events could be inferred.
- Screening of relevant or priority fingerprints: age estimation offers the possibility of pre-selecting high-priority processing fingerprints from irrelevant ones (low-priority) to prioritize lines of investigation with respect to relevant time periods. Indiscriminate submission (and storage) of “questioned” fingerprints to databases would become limited to a pre-selection of fingerprints with respect to time periods of interest. Age estimation would therefore diminish the potential for biased results when conducting identifications.
- Age distinction of overlapped fingerprints: If the prints can be adequately separated (as it has been demonstrated by Matrix Assisted Laser Desorption Ionisation Mass Spectrometry (MALDI MS) [10]), the proposed age estimation scheme could be applied to each print separately and the age of both could be compared.
- New applications of existing technologies: for example, OP is broadly used in material science to analyze surfaces. New developments in the instrumentation could make equipment affordable and potentially portable to the scene.

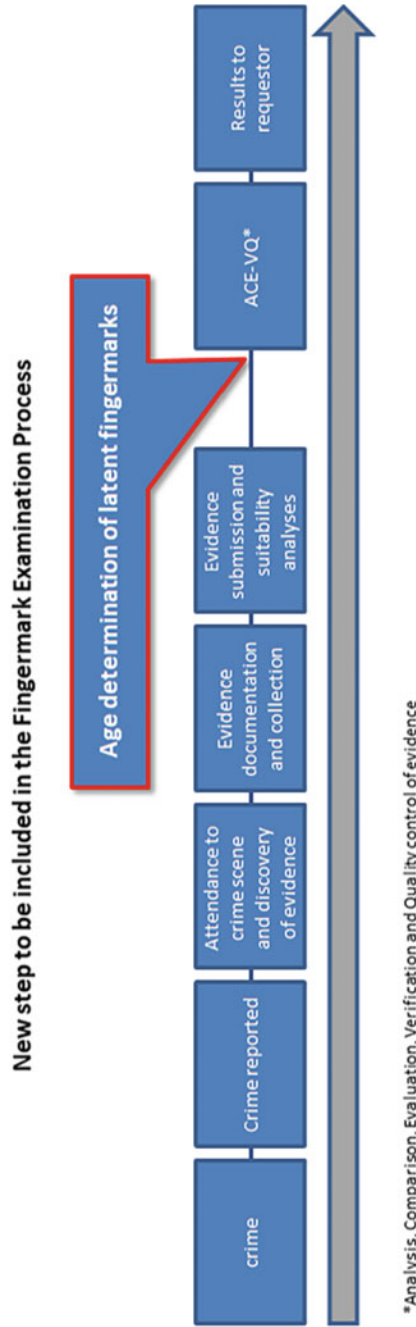


Fig. 3.4 Fingerprint examination flow chart. Highlighted is the new stage suggested to be included in the future

From a more general perspective, the criminal justice system and the general public could directly benefit from the inclusion of the *age* factor because it has the potential to:

- Improve the efficiency of public financial resources devoted to criminal investigations by giving crime laboratories a new tool for in situ crime inspections;
- Minimize errors in the identification of suspects by placing them outside the time-frame of a crime;
- Reduce the amount of evidence necessary to secure or overturn a conviction, thus reducing redundant crime evidence analyses and backlogs;
- Speed-up and reduce the cost of judicial processes which involve fingerprints as crime evidence;
- Improve the quality of criminal justice system services by decreasing the annoyance to victims and individuals indirectly involved (secondary victimization) whose testimony is no longer required;
- Reduce overall public administration expenditures.

Moving forward, there are still many skeptics who believe age estimations of (latent) fingerprints is an impossible endeavor. There is still a lack of consensus and a need for more research before a worldwide protocol and process can be standardized for this science; however, in the authors' view, this is not impossible. We agree when Girod et al. (2016) [5] propose that research needs to focus on the chemical, physical and quantitative aspects of fingerprint analysis. Researchers need to continue to be open and transparent when it comes to the limitations as well as potential of the (latent) fingerprint aging methodologies. The research into fingerprint degradation to eventually be able to produce age estimations has come a long way since the National Research Council Report in 2009. Forensic scientists, statisticians, law enforcement officials and other researchers have put great effort into making fingerprint analysis more reliable and it has led to the study of fingerprint aging processes and the formulation of statistical parameters for reference. Once this discipline is further developed and understood, there is no doubt it could help lessen the time and effort spent on fingerprint examinations in laboratories as well as minimize wrongful convictions related to time inconsistencies. This field has grown significantly in the past decade, and it will become more robust and provide a great source of knowledge as time and research continues.

3.4 Technologies and Methodologies Applied to Latent Fingerprint Aging Studies: Qualitative and Quantitative Analyses

The natural degradation process of latent fingerprints occurs through intrinsic biological, chemical and physical processes and interactions with extrinsic factors, such as the type of substrate—surface of deposition—and other environmental factors [12,

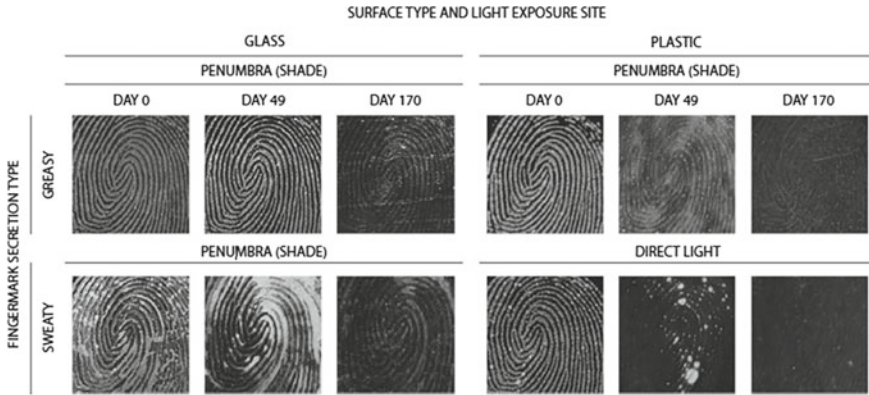


Fig. 3.5 Example of visual latent fingerprint degradation patterns dusted with titanium dioxide powder after exposure to different environmental conditions. Figure reprinted with permission from [17]. Copyright 2016, Jon Wiley and Sons

39]. The various research that investigate the aging of fingerprints typically explore chemical and physical (visual) changes. Some of the methods have involved powdering techniques [12, 13, 40], changes in fluorescence wavelengths and intensity [41], changes in chemical profiling [11], as well as electrical methods exploring decay of electrostatic charges [42]. The practical use of these techniques in casework is a concern shared by many scientists in this field. Wei et al. [21] identified the importance in not just studying the visualization and aging of fingerprints but being able to develop reliable methods/technologies that are portable to a crime scene or a mobile laboratory setting [19].

The proof-of-concept of an affordable, rapid, and easy method for estimating time of deposition is technically possible using visual examination alone, as shown in the example depicted in Fig. 3.5. For law enforcement, a visual test for a fingerprint's age in situ would prove very useful for crime scene reconstruction. Then, in addition to the *what* and *how* aspects of crime evidence, now the potential ability to include the *when* is not far reaching as a standard in investigations worldwide. Here we also describe examples of selected technologies that have been used to date for age estimations. It is not intended to be a comprehensive review but a mere illustration of the potential of these technologies in obtaining relevant data.

3.4.1 The Application of 2D Imaging to Aging Studies

Research published by De Alcaraz-Fossoul et al. [14], showed the basic concept of characterizing the degradation process of latent fingerprints, under certain environmental conditions, by visual (qualitative) means using a traditional powdering technique (Fig. 3.5) [12]. A quantitative method was developed shortly after that could

statistically model the degradation process [14–17]. Statistical data were obtained from the measurement of four visual parameters observed during the progression of degradation: (1) changes in the width of ridges; (2) decreasing color contrast between ridges and furrows; (3) increasing number of ridge discontinuities; and (4) decreasing number of observable *minutiae*.

One of the most significant findings of this aging experiment was that in some instances, and contrary to common expert belief, there was no significant visible differences between those marks aged and exposed to direct sunlight and those kept in complete darkness. For example, sebaceous-rich depositions on glass appeared astonishingly clear for identification purposes after 6 months (fresh-like appearance); however, the plastic substrate produced marks with more diverse array of results. Other conclusions from this study were in regard to the differences between sebaceous- and eccrine-rich depositions. Understandably, the “greasier” sebaceous specimens were more resilient to degradation after 6-months of aging than their counterpart eccrine-rich depositions. Despite all the relevant discoveries using this 2D methodology, it cannot provide a complete picture nor could it be used to fully understand and model visual degradation patterns. This is because a fingerprint is not a 2D object but a “live” 3D structure deposited on a substrate.

3.4.2 *The Complexity of Fingerprint Chemical Composition Studies*

Fingerprint chemical comparisons may become an effective tool to criminal investigations in the future. This showcases the importance of further understanding what a fingerprint is composed of and how this may affect the process of degradation and aging. One of the major problems in studying the chemical composition of (latent) fingerprints is the complex task of identifying a stable sweat compound (protein or lipid) that could be used as an aging reference or standard. From the large array of techniques, we will focus on a selected variety. For example, some authors have proposed the use of thin layer chromatography (TLC) and high-performance liquid chromatography (HPLC) to study the behavior of lipids over time [3, 5], but the results were not conclusive due primarily to technical limitations. Fourier transform infrared spectroscopy (FTIR) has also been used but so far with contradictory results [43].

Gas Chromatography/Mass Spectrometry (GC-MS) is destructive to the prints, but it allows for the analysis of many compounds from different substrates [6, 44]. GC-MS is an analytical method that combines the features of each technique to identify chemical substances within a test sample [45]. The GC-MS method is sensitive to amino acids that are challenging to detect or not detected by other techniques and an extensive range of fatty acids, as well as squalene. Similarly, liquid chromatography/Mass Spectrometry (LC-MS) is a technique used to separate the constituents in a liquid-phase mixture, to identify and quantify components.

Matrix-assisted laser desorption/ionization mass spectrometry (MALDI MS) is a soft ionization technique. The combination of a laser and a UV absorbing matrix allows the analysis of a variety of molecules. MALDI profiling and imaging for the detection and mapping of lipids, peptides and proteins, and amino acids in fingermarks have been shown [46–50]. This technology has demonstrated to be sensitive for the visualization of groomed, ungroomed and natural fingermarks. Good quality images of fingermark ridges were obtained based on the chemical profile of the deposition. Initial studies reported by Francese's group indicated that this technology could be used for short-term age estimation, (up to 8 days) [51] although the method was only used on "lipid pads" and not real marks. It is believed MALDI has the potential to bring new insights to the field of fingermark aging and is especially useful for chemical imaging of aging lipids [11, 46, 49, 50]. However, this equipment is, as of today, costly and requires high operator expertise.

As the focus of chemical composition is further examined, it could yield important information that could be used to estimate the age of latent fingermarks, such as specific intermediates, concentrations of various fatty acids, etc. If this type of study is conducted on a large scale and even take into account factors such as age, sex, and race, there could be a wealth of information to help further the efforts to estimate age of a latent fingermark. The design of adequate technical protocols is necessary to distinguish between short- and long-term fingermark age estimations because the techniques to be used (visual vs. chemical vs. chemical imaging) have different degrees of sensitivity to degradation changes. For example, MALDI and GC-MS/LC-MS techniques will detect changes that occur after a few minutes/hours to several days of deposition (although currently at an immature stage to scene application), whereas visual changes will assess a timeframe of several days to weeks/months [12]. These techniques provide complementary information of the aging behavior. The combination of short- and long-term aging studies is of interest because fingermarks of very different ages can be potentially found at any crime scenes. Cadd et al. [39] mentioned that distinguishing donor characteristics as well as determining the specific age of a fingermark needs to be distinct priorities to bridge the large gap in forensic science knowledge. It is also important to take into account the substrate, composition and environment when studying (latent) fingermarks because each one of these variables could cause acceleration or deceleration of the degradation process [39].

The current dilemmas in the reliability of identifications have persuaded academics to begin studying the degradation and aging patterns of (latent) fingermarks from different methodological approaches. Having a deeper knowledge in this field can help provide more statistically relevant information to CSI, detectives and prosecutors in their combined efforts to provide time-based evidence beyond a reasonable doubt in court, minimizing wrongful convictions and exonerations.

3.4.3 Approaches to Non-invasive 3D Analysis of Latent Fingermarks

One of the ways research into latent fingerprint age estimations can move forward is by shifting from a 2-dimensional train of thought into the 3-dimensional (3D) objects fingerprint truly are. The ability to visualize fingerprints in 3D gives researchers new features and metrics in terms of discovering aging patterns. Non-invasive methods to obtain high definition images have been used in several studies in fingerprint aging. Image extraction and comparison methods could clearly benefit from the study of the various ridge changes that occur over time. Liu and other researchers have noted the evolution of fingerprint techniques, showing that it is possible to use the 3D aspect of fingerprints to develop a more comprehensive aging model [52].

Merkel and his colleagues were pioneers in examining the topography of an individual latent fingerprint by using 3D technology [7]. Merkel understands that there is some aspect lacking in order to provide a definitive age for a fingerprint and believes that looking at the print with all three dimensions can help find the solution to this problem. In his research, Merkel does an excellent job at encompassing many different types of conditions in order to account for the variability that is seen throughout the various crime scenes on a daily basis. Looking towards the future, Merkel's new perspective can be used to continue and conceptualize further instrumentation, techniques and methods to help visualize and analyze latent fingerprints in 3D.

Merkel et al. [10] used Chromatic White Light sensors (CWL) and Confocal Laser Scanning Microscopy (CLSM) for image acquisitions. However, these techniques produced low quality images and were not ideal for topographic studies in 3D [12]. Ridge height functions, while derivable, were not reliably or automatically estimated or obtained. CWL and CLSM were also time-consuming imaging techniques, taking about 3–5 h to scan 20 images. Loss of image contrast was another unsolved issue that significantly reduced the quality of the prints. In another study, Dorakumbura et al. [20] used Atomic Force Microscopy (AFM) to observe adhesion and topography in 3D [18]. AFM had an advantage over CWL and CLSM because it rendered better resolution of images at the nanoscale. However, AFM had direct contact between the sample and probe, making it an invasive and potentially destructive method and required perfectly flat surfaces. Additionally, it took AFM longer to scan an image (3–4 h) and it was not used for aging purposes. Stoehr et al. [53] used energy dispersive x-ray spectroscopy, environmental scanning microscopy (ESM) and OP to determine the composition of fingerprints. Again, no aging studies were conducted. X-ray spectroscopy and ESM were also not capable of measuring the height of the sample. Lateral resolution of the ESM was too high for the analysis of ridges at a microscale, while X-ray microscopy required the analysis of large quantities of images. In Stoehr's methodology for OP, fingerprints were sputter-coated or treated before scanning, making it an invasive technique that altered the sample.

3.5 Optical Profilometry: A Tool to Uncover Latent Fingerprint Aging Patterns in 3D

As seen earlier, fingerprint degradation patterns have been investigated using a multitude of methods that range from studying chemical changes and applying immunolabeling, to visual patterns and effects of photo and thermal degradation. From these options, the constant development of visualization methods continues to provide more knowledge that will help forensic scientists in establishing a reliable standard to estimate the age of fingerprints. Overall, the ability to visualize fingerprints in different ways (e.g. 2D vs 3D imaging) provides complementary information regarding individual characteristics of ridges as they age.

Optical profilometry (OP) is a non-destructive, contactless, 3D microscopic-imaging technology that eliminates the need for developing latent fingerprints (e.g. by powdering) at each data collection time point, thus minimizing sample manipulation and measurement error. OP allows discrete statistical data collection (i.e. as time-lapse) of topographical changes over time. From an experimental approach, OP could be developed to formulate a predictive, statistical model that estimates the age of a fingerprint as a function of its topography—height, width, and other morphological parameters—time, and deposition conditions. Spatiotemporal modeling simultaneously considers spatial, temporal, and inter- and intra-subject variability and therefore can produce robust predictive models. OP provides both qualitative (i.e. 2D + 3D images of specific aging stages) and quantitative results (i.e. measurable topographical data). In addition, the analysis of the exact same sample over time allows a time-lapse image capture of the degradation process helping understand the “live” aging process.

The OP uses white light interferometry to determine the height, volume and widths of features on the surface of the sample. A portable version is already in the market and could be potentially used at crime scenes. A CCD—charge-coupled device—camera records the image of the sample as the distance between the sample and the objective is scanned. As the microscope moves vertically, a digital image is recorded. The microscope uses interferometry objectives which split the light into two paths, one path reflected by the sample and the other by a reference mirror. When both path lengths and the same interference fringes appear, a software determines equidistant points between the image and the mirror. A cloud of (x, y, z) vectors is generated to create a 3D digital surface which can be processed using a wide range of programs. The x-y resolution is determined by a chosen magnification. The z resolution is independent of the objective and is extremely high i.e. less than 1 nm. The instrument is equipped with a 200 × 200 mm motorized stage that facilitates large number of samples to be measured sequentially and ensures that the same area is measured at each time point.

This instrument can also reliably provide functions of heights and widths along specified cross-sections in an untreated or raw (latent) fingerprint, as shown in Fig. 3.6, with the height function of a cross-section (shown as a line) displayed at the bottom of the image. The heights are measured in micrometers and are relative

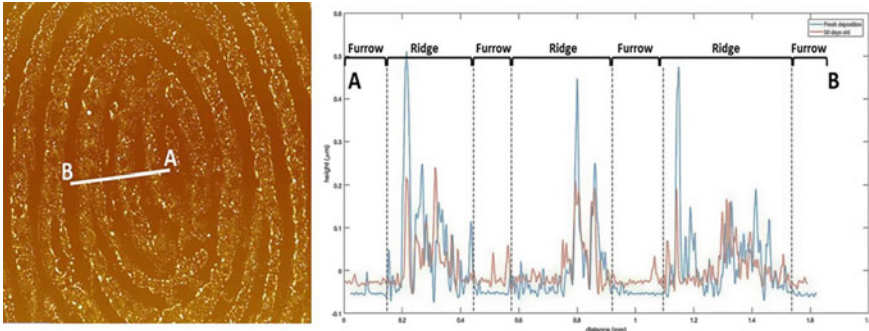


Fig. 3.6 Example 2D/3D image (left) and height functions (right) depicting the differences in ridge heights between fresh (in blue) and aged fingerprints (30 days) (in red). This sample is the middle fingerprint of the male donor deposited on glass substrate and aged in darkness. Note that ridge peaks have “eroded” within the 30-day period

to a baseline or an average. Hence, negative values in the height function are expected to be observed. This does not affect data analysis as the height functions themselves will be compared across time in an aging experiment.

OP can also obtain the average height of any given surface area, known as S_a parameter (Figs. 3.7 and 3.8). An image in 3D and topographical data is obtained in 3–4 min on the desired area, typically $\sim 30 \text{ mm}^2$. In aging studies, the same location and area size is used. It must be pointed out that the area is always maximized to cover as much viable fingerprint surface as possible within the limitations of the

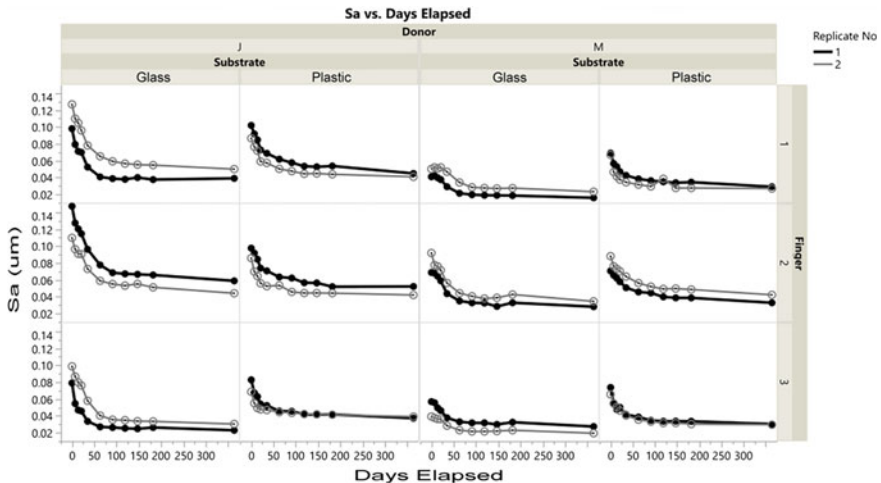


Fig. 3.7 Average height surface (S_a) values (in micrometers) of untreated latent fingerprints (shown as replicates) visualized with OP over time. Figure reprinted with permission from [22]. Copyright 2018, Jon Wiley and Sons

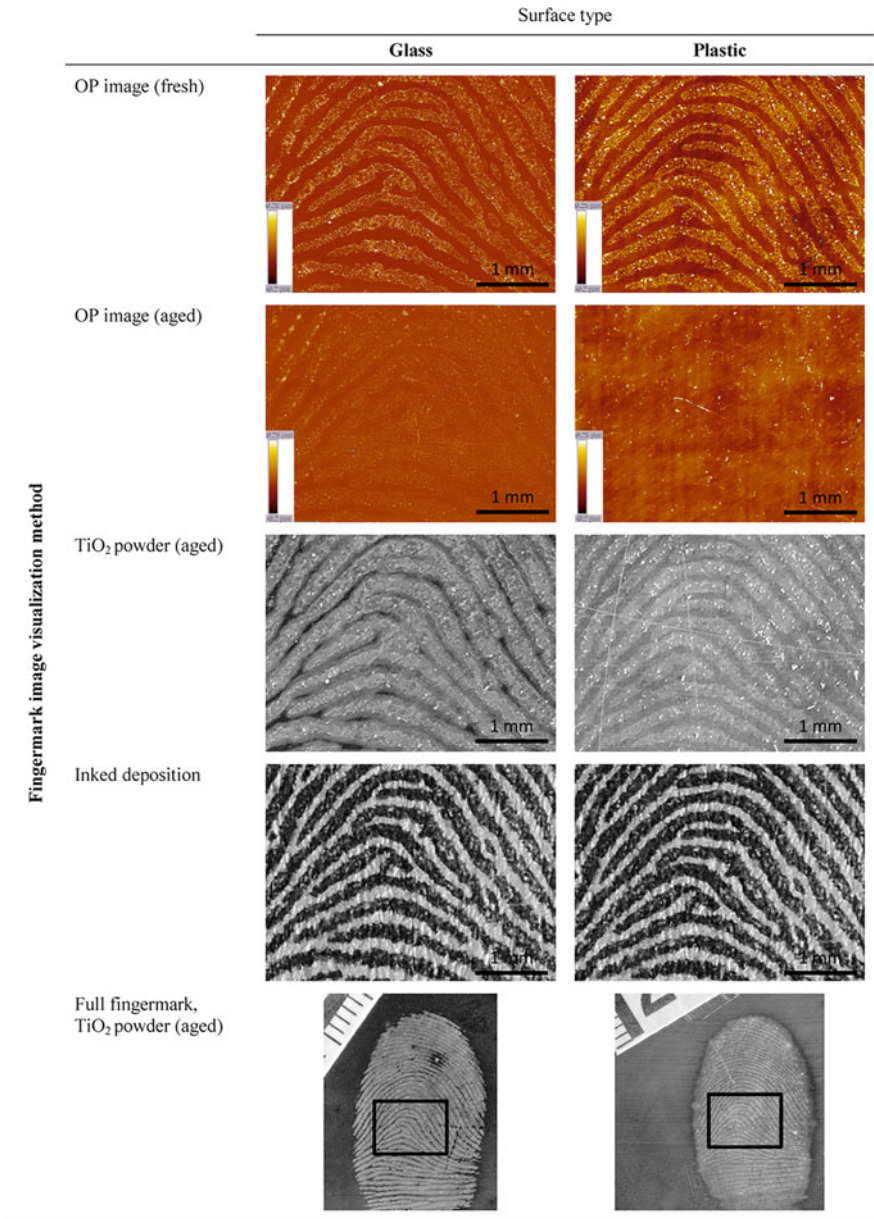


Fig. 3.8 Latent fingerprint images from a female donor captured with optical profilometer (OP); the exact same print powdered with titanium dioxide TiO₂ (ridges shown in white); and deposited with ink (ridges shown in black). The aged impressions are visualized one year after deposition. Note the “halos” around the aged latent fingerprint ridges in powdered prints. Figure reprinted with permission from [22]. Copyright 2018, Jon Wiley and Sons

microscope (i.e. larger surfaces require longer collection times). In our laboratory, non-porous surfaces, including glass, plastic and metal have shown to be amenable for analysis by OP. The object size requirements are comparable to any standard compound microscope; in our case we used thin surfaces up to 1 cm in height. There are a few disadvantages of the OP, such as the slow data acquisition times if used at high resolutions (i.e. not necessary for our aging purposes); its detection limit (i.e. insensitive to very thin layers of sweat components that can still be detected with powdering); and its high sensitivity to imperfections or “waviness” of the substrate that can mask results. These limitations could be addressed with image processing software, although non-flat surfaces—wavy at a microscopic level—would more than likely prevent (or significantly complicate) any OP analysis no-matter the level of image processing. Despite these restrictions, and compared with other techniques, OP is a sufficiently sensitive fingerprint dating technology that provides precise measurements in all dimensions coupled with high quality images.

From an end-user perspective, data acquisition and interpretation require some specific training (few hours) but no prior experience with OP or expertise in microscopy or statistics. High quality images, in 2D and 3D, and data on ridge surface roughness can be collected, transferred and edited using other commonly used software. Depending on the needs of the user, further image and data processing may be desirable which require expertise in 3D imaging and statistical software such as MATLAB[®]. As OP software evolves, it becomes more user-friendly and versatile in options. Bench top and portable optical profilers are already available in the market from different manufacturers at reasonable prices, making this technology a solid candidate for operational use at crime scenes in the future.

The work described by Merkel et al. [37] and De Alcaraz-Fossoul et al. [22] lead to great hope for age determination of fingerprints, focusing on visual parameters and the three-dimensional ridge features. In future studies, there is the need to include larger populations of donors that can help overcome limitations due to sample size and the unknown effect of variables in order to become statistically relevant. Moving forward, these visual methods must combine the evaluation of biological/chemical, environmental and substrate differences and interactions when it comes to the rate of degradation. Determining the causes of acceleration or deceleration of degradation is critical in predicting aging patterns for latent fingerprints.

3.6 Age Estimation of Blood-Stained Fingerprints

At scenes of violent crime, blood is one of the most commonly encountered types of biological evidence [54] and is the most common fingerprint contaminant [55]. The initial objective when dealing with suspected blood evidence is to conclusively establish that the substance is actually blood [56]. Dark substrates can pose considerable problems, due to the low contrast between the substrate and the fingerprint, because of the high amount of incident light absorbed by the surface [56]. Other colors or patterns particularly similar to the stain can also cause issues for identification through

visual examination alone. Presumptive tests are therefore used as part of the current forensic workflow to indicate the presence of blood [55]. Despite a high sensitivity to blood, these wet chemical tests are not specific to blood and can generate false positives [55]. Wet chemical testing can also contaminate the stain, potentially having a detrimental effect on subsequent DNA analysis [57]. Previous and current research has therefore focused on alternate methods for the non-destructive identification of blood [54, 58–66].

Convictions can depend significantly on the ability to prove beyond reasonable doubt whether a bloody fingerprint was deposited at the time a crime was committed or from a previous legitimate visit, as is often claimed by the defense team [39, 67]. There are currently no accepted analytical methods for reliably establishing a timeframe when a fingerprint was deposited and speculation around age is subject to considerable error [68]. This is primarily due to the unreliability of previously proposed methods [69]. Successful identification of blood and estimation of the age of a blood-stained fingerprint could provide the first indication to investigators as to when a crime was committed [70]. This could be especially beneficial if a blood-stained fingerprint is the only evidence available.

It has been established that the color of a blood stain changes from red to brown over time [59]. This indicates that optical methods could be used to quantify the color of blood stains. This was first explored using the reflectance spectra, whereby the effect of environmental variables on the color of the blood stain was recognized [60]. Further research quantified absorption bands independent of the amount of blood present as a possible approach for age determination [61] or the use of a small spectral window [62].

Previous research has clearly established changes to the physical and chemical properties of blood over time [59]. An optimum technique requires a high selectivity to blood; a high level of sensitivity, even with diluted blood; and high levels of precision to determine the age of a blood stain or blood-stained fingerprint in practice. One such method is the use of visible wavelength hyperspectral imaging (HSI). This was first reported for the detection and age determination of horse blood stains between 442 and 585 nm as proof of concept research [24]. The determination of age was obtained through linear discriminant analysis from data based on the progressive change of the absorption spectra over time as the composition of the blood stain altered. This approach used training and test datasets from the same blood stain in order to determine the age with high levels of accuracy. With different blood stains the accuracy was considerably lower, although this research demonstrated the potential of the method for establishing age estimation non-destructively. A similar method by a different research group has also been successfully demonstrated for the detection and age estimation of blood stains [71, 72]. The method proposed allowed for rapid, non-destructive presumptive blood stain detection as well as age estimation. Other research has explored forensic traces across a range of substrates [73]. Most recently a new blood stain identification approach was proposed based on the Soret γ band

absorption in hemoglobin [56], which indicated a higher sensitivity and specificity for the detection and identification of blood stains over previously proposed methods.

The need for a non-contact and non-destructive method for the determination of the age of a blood-stained fingermark is paramount. An ideal method should function across a practical range of ages of blood, have a high specificity to blood so as to prevent false positives and have a clear and accurate method for determining the age of a blood stain, so as to allow for reliable fingermark age estimations.

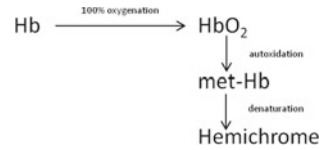
The visible wavelength HSI method described here meets all these requirements. We present the results of a novel application of visible wavelength HSI based on the absorption spectrum of hemoglobin between 400 and 680 nm for the non-contact, non-destructive detection, identification and age determination of blood-stained fingermarks on white tiles. False color scales are used to represent the age of the blood-stained specimen. A 30-day color scale is tested with nine blood-stained fingermarks of different unknown ages deposited on a single white tile to demonstrate the effectiveness of such a method for age determination. This work follows on from Cadd et al. [74–76] where hyperspectral imaging was used for the first time to detect, identify and visualize ridge detail in blood-stained marks across a wide range of substrates. The research described here demonstrates the potential of HSI, through successful non-destructive detection, identification, and age determination of this type of evidence.

3.6.1 Hyperspectral Reflectance Image Acquisition and Pre-processing

The HSI system used to obtain the results described in this chapter was similar to that detailed in Li et al. [56], consisting of a liquid crystal tunable filter (LCTF) coupled to a 2.3 megapixel Point Grey camera and a light source for scene illumination. The light source comprised of two 40 W LEDs; one violet giving an output at 410 nm and one white, giving an output between 450 and 700 nm. Control of the LCTF and image capture was performed using custom developed software written in C++ (Microsoft, USA). Images were captured between 400 and 680 nm with spectral sub sampling at 5 nm intervals, resulting in an image cube at 56 wavelengths for each scan. Spectra from the image cube were subsequently analyzed using custom routines developed in Visual Studio 2010 (Microsoft, USA) and Python 2.7 (Python Software Foundation, USA). The time required to acquire and process an image was approximately 30 s.

The hyperspectral reflectance measurements were made as follows. A reference image (R_0) was obtained using a blank substrate. This image was recorded in a 5 nm series of 56 discrete wavelengths between 400 and 680 nm. The sample image (R_s) was recorded at the same wavelengths under the same illumination conditions and integration time settings on the camera. The hyperspectral reflectance image (R) consisted of a data cube of 1280×1024 pixel values at 56 discrete wavelengths. From the reflectance images obtained, the pixels which satisfied the criterion were

Fig. 3.9 Reaction of hemoglobin in blood stains. Reprinted from ref. [24] with permission from Elsevier



marked as black, whilst all other pixels were marked as white. This allowed regions of the image where the blood-stained fingermark was present to be identified, as well as a clear distinction of the ridge detail to be obtained. Additional information regarding sample image processing can be found in [56].

3.6.2 *Criteria for the Identification of Blood-Stained Fingermarks*

The presence of hemoglobin in blood dominates the blood reflectance spectrum in the visible region [59]. The spectrum contains a strong narrow absorption at 415 nm called the Soret or γ band with two weaker and broader absorptions between 500 and 600 nm known as the β and α bands [59] (Fig. 3.9). Due to the absorption in the blue part of the visible spectrum, the Soret band is responsible for giving blood its distinctive red color. Other red substances also absorb in the blue region of the visible spectrum between 400 and 680 nm. However, the width of these absorption features is typically much broader and also not centered at 415 nm. This forms the basis of the methodology to identify and discriminate blood-stained fingermarks and blood stains from other similarly colored substances. Further information is detailed in [56, 74–76].

3.6.3 *Age Determination Methodology for Blood-Stained Fingermarks*

The age of bloody fingermarks was explored through the effect of time on the composition of the fingermark. This has already been established as a potentially viable method for age determination, due to the numerous variables which affect fingermark composition over time [39]. This research explored the compositional changes that occur within a blood-stained mark using hyperspectral imaging. After deposition, specific chemical changes occur which result in a color change from bright red to dark brown. This is attributed to the complete oxidation of hemoglobin (Hb) to oxy-hemoglobin (HbO_2), which then auto-oxidises to met-hemoglobin (met-Hb) and denatures to hemichrome (HC) [59] (Fig. 3.9).

As this process occurs, the concentration of hemoglobin decreases, which can be observed in the visible spectrum through the decrease of the Soret band at 415 nm.

After HSI analysis, the absorption spectra were analyzed and the ratio of the peak of the β band at 525 nm to the trough at 550 nm (Fig. 3.10) was determined.

As blood ages, the height of the peak decreases whilst the trough increases and so the value of the ratio also decreases. The change in this ratio was used to produce false color Red-Green-Blue aging scales, as shown with ten false colored prints in Fig. 3.11, with the value of the ratio determining the values assigned to red, green and blue in the image. This is a simpler but less accurate method of blood age determination than the previously described method of Li et al. [23, 24] which used a statistical model based on linear discriminant analysis.

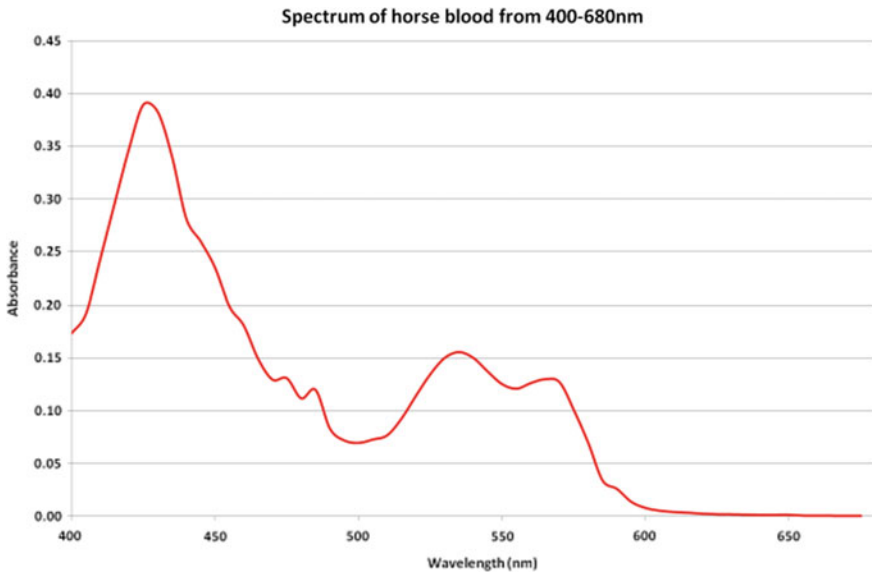


Fig. 3.10 Visible spectrum of blood from 400–680 nm. Reprinted from ref. [78] with permission from MDPI

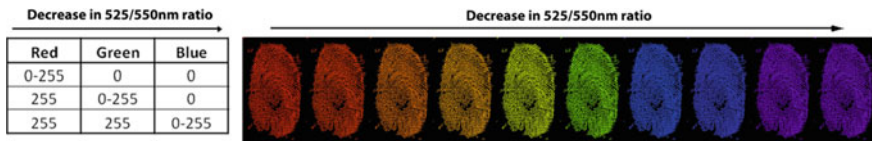


Fig. 3.11 Use of Red-Green-Blue colors to produce false color scales based on 525/550 nm ratio. Reprinted from ref. [79] with permission from MDPI

3.6.4 Age Determination of Blood Stained Fingermarks Using HSI

Detailed analyses of changes to the absorption spectrum over both twenty four hours and thirty days were carried out and separate false color scales were generated from both hyperspectral analyses. The thirty-day false color scale was then used to false color nine blood-stained fingerprints of unknown age based on their absorption spectrum obtained from hyperspectral analysis.

Blood-stained fingermarks were successfully detected using HSI for the full twenty four hours explored. Clear ridge detail was identified for all scans and the absorption spectrum analyzed to produce a false color scale, as shown in Fig. 3.12. Clear changes in color can be seen on almost an hourly basis over the twenty four hour period. This scale represents the changes that occur to the absorption spectrum over the twenty-four hour aging period, as shown in Fig. 3.13. The logarithmic conversion also shown demonstrates the clear relationship between the 525/550 nm ratio and time over this period.

Blood-stained fingermarks were also successfully detected and identified using HSI for the full thirty days explored. Clear ridge detail was identified for all scans, a selection of which is shown in seven day increments from deposition to twenty eight days in Fig. 3.14.

The level of clear ridge detail observable even after thirty days demonstrates the advantage of HSI over existing chemical methods, as not only can blood be conclusively identified, as opposed to only an indication obtained with presumptive tests; but ridge detail is both preserved and photographed for potential comparison in one step, even for blood-stained fingermarks which are not freshly deposited. Analysis of the absorption spectrum between 400 and 680 nm showed a clear decrease of the Soret band and the β and α bands between 500 and 600 nm over the aging period. This change forms the basis for the age estimation methodology. False color scales were produced to represent the changes to the 525/550 nm ratio over thirty days, as shown in Fig. 3.15.

From a simple visual examination of the nine blood-stained specimens alone, as shown on the left hand side in Fig. 3.16, it is very difficult to determine any significant differences that may allow for age estimations. Hyperspectral analysis however successfully detected and conclusively identified the ridge detail as blood. This data was then used to produce false color scales which give a clear visual representation of the different ages of the prints, as shown on the right in Fig. 3.16.

The DSLR images show minimal variation between the different ages of blood-stained fingerprints. However, using the false color scales, all freshly deposited prints can be easily distinguished due to the significant differences in color, such as prints five, eight, seven and three, which correspond to zero, one, three and six days respectively. After fourteen days, the variation in the composition of the blood-stained fingermarks is less, so the difference between the assigned false colors is smaller and harder to distinguish by eye. This is apparent for prints two, four and six, which are all shades of purple, despite varying by eleven days. The use of this false color

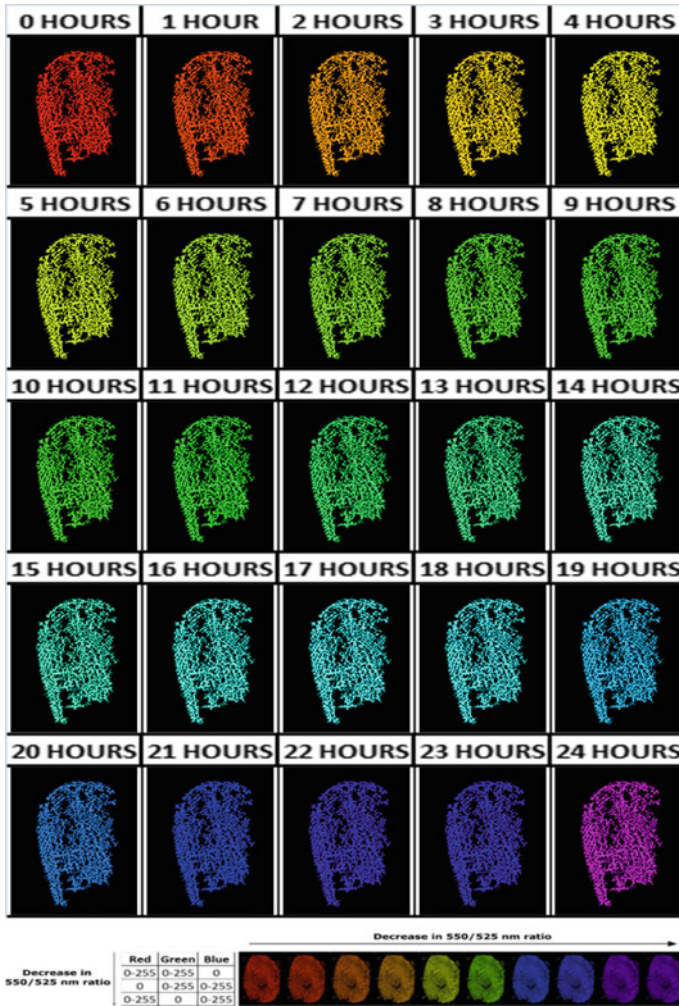


Fig. 3.12 A false color Red-Green-Blue aging scale generated from the ratio of the peak at 525 nm to the trough at 550 nm obtained through hyperspectral analysis of blood fingermarks over twenty four hours. Reprinted from ref. [79] with permission from MDPI

method for age estimations is therefore most effective for blood-stained specimens deposited within fourteen days, (and most so within the first twenty four hours), as the increased variation over the first seven days results in greater differences in the false color images produced.

The ability to determine age is greatly sought. The studies presented in this chapter have demonstrated the feasibility for such estimations, with the additional benefit of a false color aging scale to provide a clear, easy to distinguish, visual representation of the differences in ages between deposited specimens. Naturally, further research is

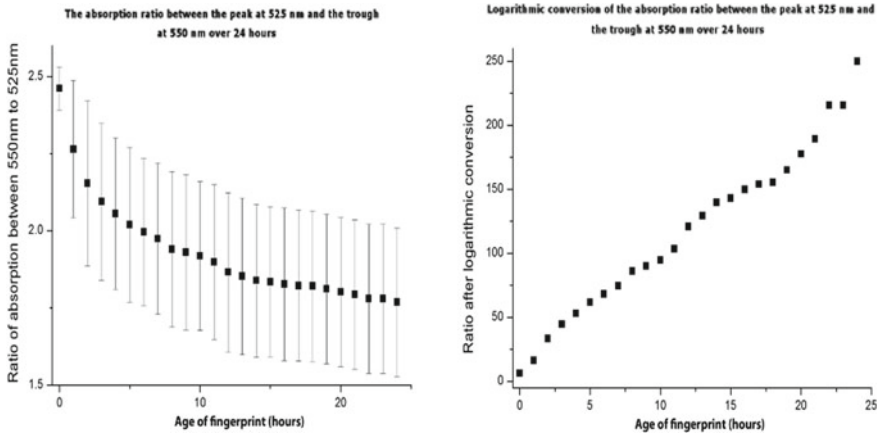


Fig. 3.13 Hyperspectral analysis was used to determine the effect of time on the absorption ratio between the peak at 525 nm and the trough at 550 nm (left) and the logarithmic conversion to show the relationship as a straight line (right) over the twenty-four hour aging period. Reprinted from reference [79] with permission from MDPI



Fig. 3.14 Visible ridge detail for blood-stained fingermarks analyzed using HSI after zero, seven, fourteen, twenty one and twenty eight days. Reprinted from ref. [79] with permission from MDPI

required before such a methodology could be implemented into the existing forensic workflow, but the research detailed in this chapter has demonstrated that such a method exists, generates reliable results on white tiles, and, perhaps most importantly, is highly specific to blood. The key additional research which needs to be performed is to investigate firstly a greatly range of substrates and then the effect of environmental variables such as temperature and humidity on the aging process. These effects can in principle be parameterized and thus allow the creation of a robust and reliable model which can be used at crime scenes. The compatibility with prior use of existing CSI techniques also needs to be investigated.

3.7 Fingerprint Age Estimations: Is There a Future?

In order to succeed in the challenging research field of fingerprint aging, it is desirable and necessary to employ a robust technique, or combination of techniques, that

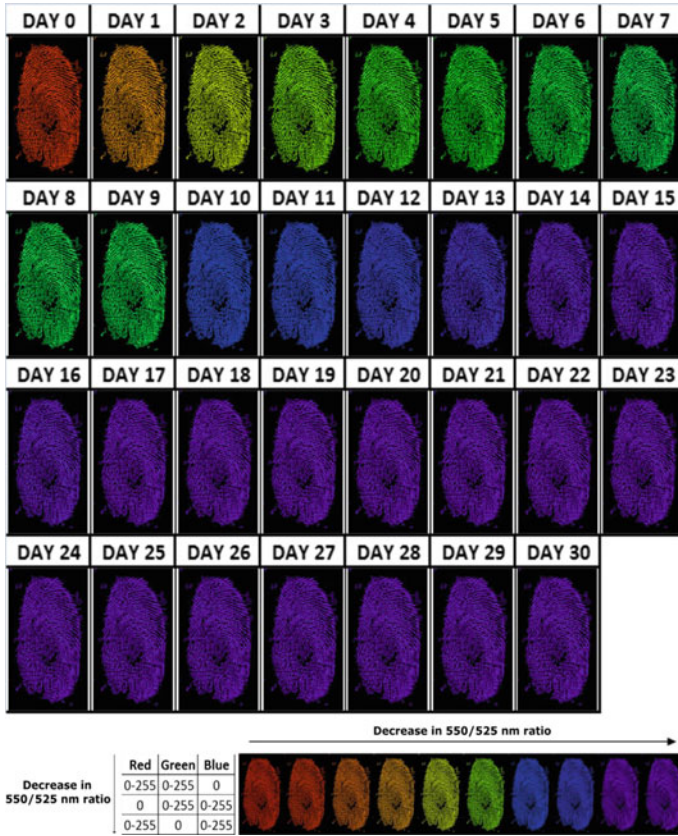


Fig. 3.15 A false color Red-Green-Blue aging scale generated from the ratio of the peak at 525 nm to the trough at 550 nm obtained through hyperspectral analysis of bloody marks over thirty days. Reprinted from ref. [79] with permission from MDPI

could overcome, and be able to explain, some or most of the variability exerted by environmental factors. Visual analyses, such as OP and HSI, can fulfill this objective because of their sensitivity to visual and chemical changes that take place during the aging process. Additionally, OP and HSI are able to collect topographical measurements that can be easily analyzed and interpreted.

After the first initial studies, further ideas arose on how to examine and develop models for fingerprint aging patterns. Weyermann and Ribaux [77] describe that aging studies need to be focused on the kinetic properties of the evidence obtained and how to create a valid model that can be universally implemented. They note that although it is important to study the disappearance of features/full latent fingerprints as a function of time, it can be just as important to study the persistence of characteristics and even the alterations as a function of time. This means that although the disappearance of features can yield great knowledge, being able to determine

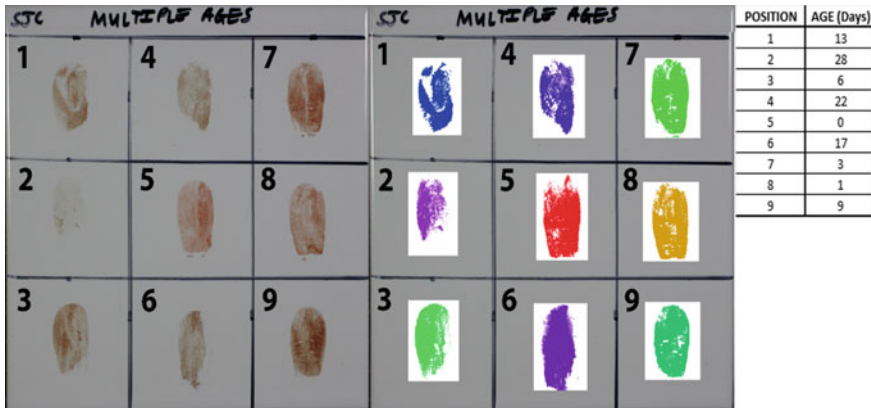


Fig. 3.16 DSLR (left) and false color images manually colored from hyperspectral analysis (right) of blood-stained fingerprints based on thirty-day false color scale. Reprinted from ref. [79] with permission from MDPI

what does not change can yield relevant information as well. The struggle noted with the models presented is the ability for them to be reproducible and consistent under controlled conditions. Researchers have found it difficult to find features and trends that can be generalized to a large population of individuals. Overall, Weyermann and Ribaux developed research to help forensic scientists think outside the realm of what is already known in fingerprint science to try to stimulate future ideas to address the challenges already facing the age determination of fingerprints [77].

From a technological perspective and based on the speed of engineering advances, OP and HSI could become operational in the field within a decade. However, these technologies will be useless to forensic scientists unless accompanied by a better understanding of degradation patterns and the effects of environmental and physical variables on age estimations. Based on past published data, from proof-of-concept studies in many cases, the time has arrived to upscale research and move beyond small, and at times unfunded, projects. This will be the only way knowledge on aging will pair with technological advancements.

As mentioned earlier, age estimations can provide, for the first time, valuable new information and intelligence about a crime beyond the possible presence of an individual. For this reason, more financial resources are needed to expand current research and ensure reliable results within a reasonable time span.

Great progress made in the field of fingerprint aging gives hope for the future endeavors and research that is to come. There has been success in certain areas regarding latent and bloody fingerprint age estimations; however, additional research efforts need to be highlighted. There are seven key points to study moving forward:

- Identification of visual parameters and chemical decomposition products of aging fingerprints. To date, studies have gathered valuable knowledge on fingerprint topography and composition; however being able to understand chemi-

cal intermediates and end-products can yield a better idea of how old the fingerprint is by how far along it is in the reaction process.

- Scientists and researchers could delve deeper into deciphering and modeling the reaction kinetics of a (latent) fingerprint. If the rates of decomposition can be determined for specific chemicals, the time intervals after deposition could be more easily estimated.
- Efforts should be made to study ratios of chemical compounds. Studies have shown how variable the quantities of different chemicals are; however, all these were conducted with a very small population of donors and/or samples. If the ratios of chemicals could be generalized using a more large-scale study, it would be easier to accurately extrapolate the age of the given print.
- One of the most important goals of future research is to carry out large-scale studies. It is very difficult for research findings to be generalized and implemented into real-world practice without enough data to produce accurate generalizations. A model, trend or any research cannot be certified as accurate, precise or reliable unless it can be completed by multiple researchers using multiple donor sets and reproduced on a large scale [39].
- The effect of donor, environmental, and substrate variables are critical areas of future focus. In a real scenario, (latent) fingerprints are not all aged under the same environmental conditions and on the same substrates. It has been shown that the location where the fingerprint is deposited can have unique effects on its visual degradation. Much like in forensic entomology, if models can be created to map the acceleration or deceleration rates dependent on donor, environmental and substrate conditions, accurate age estimations of fingerprints would ensue.
- Translation of the statistical results into software algorithms: the software developed could be used in the field or in the office. A mobile app could automatically determine the age of the questioned fingerprint based on input of a limited number of known (or estimated) environmental conditions (e.g. temperature and humidity) and certain visual degradation parameters (e.g. number of minutiae, ridge widths and heights). The software could even provide examples of reference fingerprint images that could be easily correlated to the “questioned” deposition.
- Lastly, it is critical to continue collaborations and teamwork with different fields of science and technology, including statisticians in (latent) fingerprint analysis. The only way for this forensic science to become more objective and more dependable in a court of law is to provide error rates, probabilities and other statistical models that make evidence more robust.

Overall, the ability to estimate the age of a fingerprint might appear in the distant future. It is critical to start understanding the methods that will successfully help develop techniques to further this field of research. In terms of statistical evidence, researchers such as Kellman and Neumann [28, 78] have successfully began developing equations and models that can eventually be used as mathematical proof in court. However, these researchers are aware of the limitations of their work due to the heterogeneity of prints and continue to develop computerized systems that

can minimize and overcome the subjectivity that is currently present in the field of fingerprint identifications.

In summary, many methods including visual, biological, chemical, and biochemical have shown to be valuable in providing partial knowledge to estimate the time of deposition of (latent) fingerprints. The move towards studying fingerprints in 3D seems to be the most logical and beneficial of paths moving forward. It is important to be aware that every field of research has limitations and to always draw conclusions with caution. Fingerprint aging research is not an exception and needs to move forward by studying larger number of conditions and find commonalities among them, especially because there will be multiple types of environments, substrates and other undetermined factors influencing each fingerprint's degradation process. In conclusion, this field of research will, in time, lead to answering the overarching question of how old a fingerprint is, but it will take continued and groundbreaking research to develop suitable and creative techniques to solve such a challenging subject.

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References

1. Girod A, Ramotowski R, Weyermann C (2012) Composition of fingerprint residue: a qualitative and quantitative review. *Forensic Sci Int* 223(1–3):10–24
2. Ng PHR et al (2009) Detection of illicit substances in fingerprints by infrared spectral imaging. *Anal Bioanal Chem* 394(8):2039–2048
3. Rowell F, Hudson K, Seviour J (2009) Detection of drugs and their metabolites in dusted latent fingerprints by mass spectrometry. *Analyst* 134(4):701–707
4. Wertheim K (2003) Fingerprint age determination: is there any hope? *J Forensic Ident* 53(1):42–49
5. Girod A, Ramotowski R, Lambrechts S, Misriela P, Aalders M, Weyermann C (2016) Fingerprint age determinations: Legal considerations, review of the literature and practical propositions. *Forensic Sci Int* 262:212–226
6. Archer NE, Charles Y, Elliott J, Jickells S (2005) Changes in the lipid composition of latent fingerprint residue with time after deposition on a surface. *Forensic Sci Int* 154(2–3):224–239
7. Humphreys JD, Porter G, Bell M (2008) The quantification of fingerprint quality using a relative contrast index. *Forensic Sci Int* 178(1):46–53
8. Croxton RS, Baron MG, Butler D, Kent T, Sears VG (2010) Variation in amino acid and lipid composition of latent fingerprints. *Forensic Sci Int* 199(1–3):93–102
9. Weyermann C, Roux C, Champod C (2011) Initial results on the composition of fingerprints and its evolution as a function of time by GC/MS analysis. *J Forensic Sci* 56(1):102–108
10. Merkel R, Gruhn S, Dittmann J, Vielhauer C, Brautigam A (2012) On non-invasive 2D and 3D chromatic white light image sensors for age determination of latent fingerprints. *Forensic Sci Int* 222:52–70

11. Bailey MJ, Bright RS, Croxton S, Francese LS, Ferguson S, Hinder S, Jickells BJ, Jones BN, Jones SG, Kazarian JJ, Ojeda RP, Webb R, Wolstenholme R, Bleay S (2012) Chemical characterization of latent fingerprints by matrix-assisted laser desorption ionization, time-of-flight secondary ion mass spectrometry, mega electron volt secondary mass spectrometry, gas chromatography/mass spectrometry X-ray photoelectron spectroscopy. *Anal Chem* 84(20):8514–8523
12. Bradshaw R, Rao W, Wolstenholme R, Clench MR, Bleay S, Francese S (2012) Separation of overlapping fingermarks by matrix assisted laser desorption ionisation mass spectrometry imaging. *Forensic Sci Int* 222(1–3):318–326
13. Francese S, Bradshaw R, Ferguson LS, Wolstenholme R, Clench MR, Bleay S (2013) Beyond the ridge pattern: multi-informative analysis of latent fingermarks by MALDI mass spectrometry. *Analyst* 138(15):4215–4228
14. De Alcaraz-Fossoul J, Mestres Patris C, Balaciart Muntaner A, Barrot Feixat C, Gené Badia M (2013) Determination of latent fingerprint degradation patterns—a real fieldwork study. *Int J Legal Medicine* 127(4):857–870
15. Barros RM, Faria BF, Kuckelhaus SA (2013) Morphometry of latent palmprints as a function of time. *Sci Justice* 53(4):402–408
16. De Alcaraz-Fossoul J, Roberts KA, Barrot-Feixat C, Hogrebe G, Gené Badia M (2016) Fingerprint ridge drift. *Forensic Sci Int* 258:26–31
17. De Alcaraz-Fossoul J, Mestres Patris C, Barrot Feixat C, Brandelli D, McGarr L, Stow K, Gené Badia M (2016) Latent fingerprint aging patterns (Part I): minutiae count as one indicator of degradation. *J Forensic Sci* 61(2):322–333
18. De Alcaraz-Fossoul J, Barrot Feixat C, Tasker J, McGarr L, Stow K, Carreras-Marin C, Gené Badia M (2016) Latent fingerprint aging patterns (Part II): colour contrast between ridges and furrows as one indicator of degradation. *J Forensic Sci* 61(4):947–958
19. De Alcaraz-Fossoul J, Barrot Feixat C, Tasker J, Carreras-Marin C, Zapico SC, Gené Badia M (2017) Latent fingerprint aging patterns (Part III): discontinuity index as one indicator of degradation. *J Forensic Sci* 62(5):1180–1187
20. Dorakumbura BN, Becker T, Lewis SW (2016) Nanomechanical mapping of latent fingermarks: a preliminary investigation into the changes in surface interactions and topography over time. *Forensic Sci Int* 267:16–24
21. Wei Q, Zhang M, Ogorevc B, Zhang X (2016) Recent advances in the chemical imaging of human fingermarks (a review). *Analyst* 141(22):6172–6189
22. De Alcaraz-Fossoul J, Mancenido M, Soignard E, Silverman N (2018) Application of 3D imaging technology to latent fingerprint aging studies. *J Forensic Sci* (<https://doi.org/10.1111/1556-4029.13891>; ahead of print)
23. Li B, Beveridge P, O'Hare WT, Islam M (2011) The estimation of the age of a blood stain using reflectance spectroscopy with a microspectrophotometer, spectral pre-processing and linear discriminant analysis. *Forensic Sci Int* 212(11):198–204
24. Li B, Beveridge P, O'Hare WT, Islam M (2013) The age estimation of blood stains up to 30 days old using visible wavelength hyperspectral image analysis and linear discriminant analysis. *Sci Justice* 53(3):270–277
25. Dror IE, Charlton D, Péron AE (2006) Contextual information renders experts vulnerable to making erroneous identifications. *Forensic Sci Int* 156(1):74–78
26. Charlton D, Fraser-Mackenzie PA, Dror IE (2010) Emotional experiences and motivating factors associated with fingerprint analysis. *J Forensic Sci* 55(2):385–393
27. Fraser-Mackenzie PA, Dror IE, Wertheim K (2013) Cognitive and contextual influences in determination of latent fingerprint suitability for identification judgments. *Sci Justice* 53(2):144–153
28. Kellman PJ, Mnookin JL, Erlikhman G, Garrigan P, Ghose T, Mettler E, Charlton D, Dror IE (2014) Forensic comparison and matching of fingerprints: using quantitative image measures for estimating error rates through understanding and predicting difficulty. *PLoS ONE* 9(5):e94617

29. Ulery BT, Hicklin RA, Buscaglia J, Roberts MA (2011) Accuracy and reliability of forensic latent fingerprint decisions. *PNAS* 108(19):7733–7738
30. Mnookin J, Kellman PJ, Dror I, Erlikhman G, Garrigan P, Ghose T, Metler E, Charlton D (2016) Error rates for latent fingerprinting as a function of visual complexity and cognitive difficulty. Report. NIJ Award 2009-DN-BX-K225
31. Dror I (2013) The ambition to be scientific: human expert performance and objectivity. *Sci Justice* 53(2):81–82
32. Kassin SM, Kukucka J, Lawson VZ, DeCarlo J (2014) Does video recording alter the behavior of police during interrogation? A mock crime-and-investigation study. *Law Hum Behav* 38(1):73–83
33. Campbell R, Sefl T, Barnes HE, Ahrens CE, Wasco SM, Zaragoza-Diesfeld Y (1999) Community services for rape survivors: enhancing psychological well-being or increasing trauma? *J Consult Clin Psychol* 67(6):847–858
34. Wertheim K (2003) Fingerprint age determination: is there any hope? *J Forensic Ident* 53(1):42–49
35. Champod C, Lennard C, Margot P, Stoilovic M (2004) *Fingerprints and other ridge skin impressions*, 1st ed., CRC Press
36. Hicklin RA, Buscaglia J, Roberts MA, Meagher SB, Burge MJ, Vera D, Pantzer LR, Calvin C (2011) Latent fingerprint quality: a survey of examiners. *J Forensic Ident* 61(4):385–418
37. Merkel R (2014) New solutions for an old challenge: chances and limitations of optical, non-invasive acquisition and digital processing techniques for the age estimation of latent fingerprints. Doctoral Thesis Universität Magdeburg
38. de Groot P (2015) Principles of interference microscopy for the measurement of surface topography. *Adv Opt Photon* 7:1–65
39. Cadd S, Islam M, Manson P, Bley S (2015) Fingerprint composition and aging: a literature review. *Sci Justice* 55(4):219–238
40. Matuszewski S, Szafałowicz M (2013) A simple computer-assisted quantification of contrast in a fingerprint. *J Forensic Sci* 58(5):1310–1313
41. van Dam A, Aalders MC, Todorovski T, van Leeuwen TG, Lambrechts SA (2016) On the autofluorescence of aged fingermarks. *Forensic Sci Int* 258:19–25
42. Rosa R, Giovanardi R, Bozza A, Veronesi P, Leonelli C (2017) Electrochemical impedance spectroscopy: a deeper and quantitative insight into the fingermarks physical modifications over time. *Forensic Sci Int* 273:144–152
43. Williams DK, Brown CJ, Bruker J (2011) Characterization of children’s latent fingerprint residues by infrared microspectroscopy: forensic implications. *Forensic Sci Int* 206(1–3):161–165
44. Girod A, Weyermann C (2014) Lipid composition of fingerprint residue and donor classification using GC/MS. *Forensic Sci Int* 238:68–82
45. Croxton RS, Baron MG, Butler D, Kent T, Sears VG (2006) Development of a GC-MS method for the simultaneous analysis of latent fingerprint components. *J Forensic Sci* 51(6):1329–1333
46. Wolstenholme R, Francese S, Bradshaw R (2010) Study of lipid distribution and degradation in latent fingerprints by spectroscopic imaging techniques. *Sci Justice* 50(1):37–38
47. Ferguson L, Bradshaw R, Wolstenholme R, Clench M, Francese S (2011) Two-step matrix application for the enhancement and imaging of latent fingermarks. *Anal Chem* 83(14):5585–5591
48. Ferguson LS, Wulfert F, Wolstenholme R, Fonville JM, Clench MR, Carolan VA, Francese S (2012) Direct detection of peptides and small proteins in fingermarks and determination of sex by MALDI mass spectrometry profiling. *Analyst* 137(20):4686–4692
49. Bradshaw R, Bley S, Wolstenholme R, Clench MR, Francese S (2013) Towards the integration of matrix assisted laser desorption ionisation mass spectrometry imaging into the current fingerprint examination workflow. *Forensic Sci Int* 232(1–3):111–124
50. Ferguson LS, Creasey S, Wolstenholme R, Clench MR, Francese S (2013) Efficiency of the dry-wet method for the MALDI-MSI analysis of latent fingermarks. *J Mass Spectrom* 48(6):677–684

51. Reed H, Stanton A, Wheat J, Kelley J, Davis L, Rao W, Smith A, Owen D, Francese S (2016) The Reed-Stanton press rig for the generation of reproducible fingerprints: towards a standardised methodology for fingerprint research. *Sci Justice* 56(1):9–17
52. Liu F, Liang J, Shen L, Yang M, Zhang D, Lai Z (2017) Case study of 3D fingerprints applications. *PLoS ONE* 12(4):e0175261
53. Stoehr B, McClure S, Höflich A, Al Kobaisi M, Hall C, Murphy PJ, Evans D (2016) Unusual nature of fingerprints and the implications for easy-to-clean coatings. *Langmuir* 32(2):619–625
54. Finnis J, Lewis J, Davidson A (2013) Comparison of methods for visualizing blood on dark surfaces. *Sci Justice* 53(2):178–186
55. Home Office CAST (2013) *Fingerprint Sourcebook*, Chapter 3, 3.1 Acid Dyes, 1st ed., Home Office
56. Li B, Beveridge P, O'Hare WT, Islam M (2014) The application of visible wavelength reflectance hyperspectral imaging for the detection and identification of blood stains. *Sci Justice* 54(6):432–438
57. Passi N, Kumar Garg R, Yadav M, Sarup Singh R, Kharoshah MA (2012) Effect of luminol and bleaching agent on the serological and DNA analysis from bloodstain. *Egypt J Forensic Sci* 2(2):54–61
58. Anderson S, Howard B, Hobbs GR, Bishop CP (2005) A method for determining the age of a bloodstain. *Forensic Sci Int* 148(1):37–45
59. Bremmer RH, Nadort A, van Leeuwen TG, van Gemert MJC, Aalders MCG (2011) Age estimation of blood stains by hemoglobin derivative determination using reflectance spectroscopy. *Forensic Sci Int* 206(1–3):166–171
60. De Wael K, Lepot L, Gason F, Gilbert B (2008) In search of blood—detection of minute particles using spectroscopic methods. *Forensic Sci Int* 180(1):37–42
61. Chun-Yen Lin A, Hsieh H, Tsai L, Linacre A, Lee JC (2007) Forensic applications of infrared imaging for the detection and recording of latent evidence. *J Forensic Sci* 52(5):1148–1150
62. McLaughlin G, Sikirzhyski V, Lednev IK (2013) Circumventing substrate interference in the Raman spectroscopic identification of blood stains. *Forensic Sci Int* 231(1–3):157–166
63. Stoilovic M (1991) Detection of semen and blood stains using polilight as a light source. *Forensic Sci Int* 51(2):289–296
64. Strasser S, Zink A, Kada G, Hinterdorfer P, Peschel O, Heckl WM, Nerlich AG, Thalhammer S (2007) Age determination of blood spots in forensic medicine by force spectroscopy. *Forensic Sci Int* 170(1):8–14
65. Turrina S, Filippini G, Atzei R, Zaglia E, De Leo D (2008) Validation studies of rapid stain identification-blood (RSID-blood) kit in forensic caseworks. *Forensic Sci Int Genet Suppl Ser* 1(1):74–75
66. Wawryk J, Odell M (2005) Fluorescent identification of biological and other stains on skin by the use of alternative light sources. *J Clin Forensic Med* 12(6):296–301
67. Gardner T, Anderson T (2009) *Criminal evidence: principles and cases*, 7th edn. Cengage Learning, Belmont, CA
68. Adebisi S (2009) Fingerprint studies—the recent challenges and advancements: a literary view. *Internet J Biol Anthropol* 2(2):3
69. Midkiff C (1993) Lifetime of a latent print how long can you tell? *J Forensic Ident* 43(4):386–396
70. Bremmer RH, de Bruin KG, van Leeuwen TG, van Gemert MJC, Aalders MCG (2012) Forensic quest for age determination of bloodstains. *Forensic Sci Int* 216(1–3):1–11
71. Janchaysang S, Sumriddetchkajorn S, Buranasiri P (2012) Tunable filter-based multispectral imaging for detection of blood stains on construction material substrates part 1: developing blood stain discrimination criteria. *Appl Opt* 51(29):6984–6996
72. Janchaysang S, Sumriddetchkajorn S, Buranasiri P (2013) Tunable filter-based multispectral imaging for detection of blood stains on construction material substrates part 2: realization of rapid blood stain detection. *Appl Opt* 52(20):4898–4910
73. Edelman GJ, Gaston E, van Leeuwen TG, Cullen PJ, Aalders MCG (2012) Hyperspectral imaging for non-contact analysis of forensic traces. *Forensic Sci Int* 223(1–3):28–39

74. Cadd S, Li B, Beveridge P, O'Hare WT, Campbell A, Islam M (2016) Non-contact detection and identification of blood stained fingerprints using visible wavelength reflectance hyperspectral imaging: part 1. *Sci Justice* 56(3):181–190
75. Cadd S, Li B, Beveridge P, O'Hare WT, Islam M (2016) The non-contact detection and identification of blood stained fingerprints using visible wavelength hyperspectral imaging: part II effectiveness on a range of substrates. *Sci Justice* 56(3):191–200
76. Cadd S, Li B, Beveridge P, O'Hare WT, Campbell A, Islam M (2016) A comparison of visible wavelength reflectance hyperspectral imaging and Acid Black 1 for the detection and identification of blood stained fingerprints. *Sci Justice* 56(4):247–255
77. Weyermann C, Ribaux O (2012) Situating forensic traces in time. *Sci Justice* 52(2):68–75
78. Neumann C, Stern H (2016) Forensic examination of fingerprints: past, present, and future. *Chance* 29(1):9–16
79. Cadd S, Li B, Beveridge P, O'Hare WT, Islam M (2018) Age determination of blood-stained fingerprints using visible wavelength reflectance hyperspectral imaging. *J Imag* 4(12):141