**ABSTRACT**
The Journal of Forensic Radiology and Imaging was launched in 2013 with the aim to collate the literature and demonstrate high-quality case studies on image-based modalities across the forensic sciences. Largely, the focus of this journal has been on the transmissive aspect of forensic imaging, and therefore a significant number of high-quality case studies have been published focusing on computed tomography and magnetic resonance imaging. As a result, the 'and imaging' aspect is often neglected. Since 2013, technology has fundamentally evolved, and a number of new techniques have become accessible or have been demonstrated as particularly useful within many sub-disciplines of forensic science. These include active and passive surface scanning techniques, and the availability of three-dimensional printing. Therefore, this article discusses non-contact techniques, their applications, advantages, and considerations on the current state of play of imaging in forensic science.

**HIGHLIGHTS**

- We discuss the application of 3D imaging within the context of forensic science.
- We highlight the available documentation techniques assessing their advantages and disadvantages.
- This article provides several recommendations for future best practice.

## 1. Introduction

In 2013, the Journal of Forensic Radiology and Imaging (JOFRI) was launched to help collate the literature on imaging-based modalities across the forensic sciences. This was achieved by presenting high-quality case studies and specialist reviews with the underlying theme of non-invasive documentation techniques. Arguably, the use of imaging techniques within this discipline and the development of this journal was instigated by the large amount of research undertaken on virtual autopsies. However, now five years on, the use of imaging has rapidly developed across many sub-disciplines within the forensic sciences.

The focus of JOFRI has been on living and deceased individuals, and the application of non-contact transmissive imaging. Therefore, a large body of the literature published has focused on both computed tomography (CT) and magnetic resonance imaging (MRI). This is unsurprising as JOFRI has 'forensic radiology' in its title. However, it is the opinion of the authors that the 'and imaging' aspect is often neglected, despite there being substantial overlap between reflective and transmissive techniques.

Numerous forensic science sub-disciplines have utilised these imaging techniques often in an inter-disciplinary manner. These include, but are not limited to, anthropology, archaeology, odontology, crime scene investigation, footwear mark recovery and analysis, courtroom visualisation, and ballistic comparison. Given that these rapidly evolving techniques are situated within the changing face of forensic science, this article has collated the current developments within the discipline, focussing on the use of non-contact techniques. Consequently, the aim of this review is to be informative with regards to the different techniques available and how they are currently being used, but to also suggest future directions and potential issues that should be taken into consideration.

## 2. Types of Imaging Modalities

The multitude of imaging modalities can be classified by acquisition type as illustrated in Figure 1. The recording processes reviewed here are all non-contact, and further categorised as either transmissive or reflective, as discussed below.

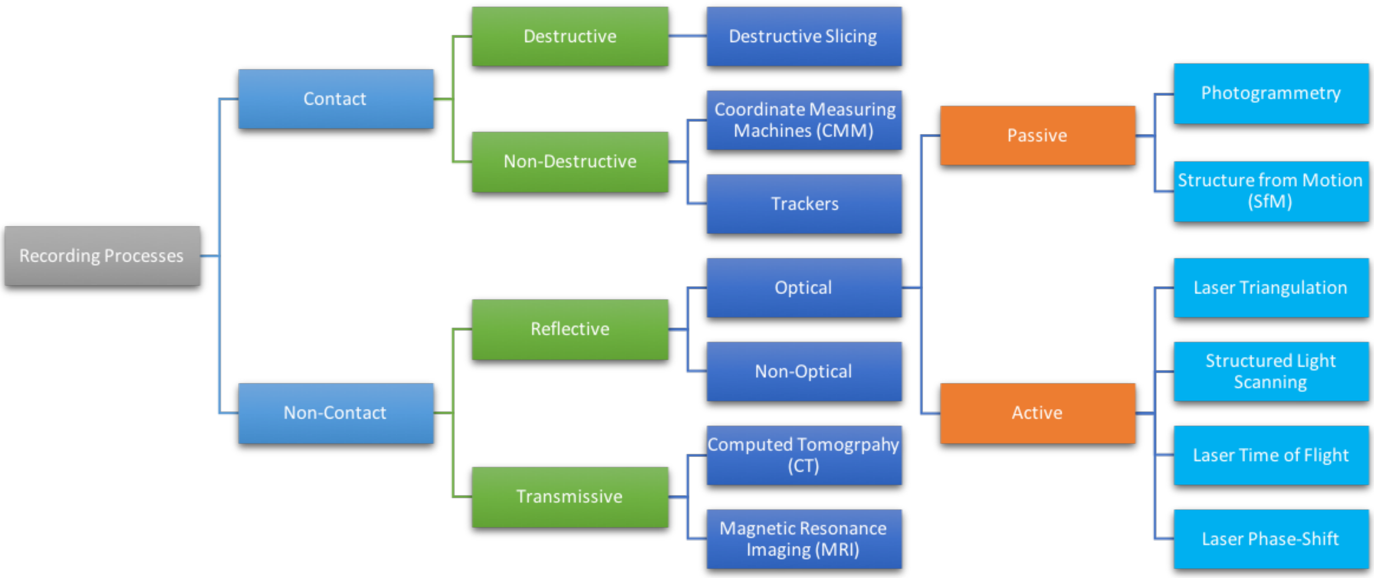


*Figure 1. Flowchart demonstrating the different imaging modalities available in forensic science documentation.*

### 2.1. Reflective

Reflective techniques work by reflecting a light source onto a subject and recording the reflected data. As such, the surface of a subject must be exposed. The quality of the data recorded is affected by surface features and conditions, such as whether the surface is smooth/rough or wet/dry as well as the shape, temperature and accessibility of the subject (Sansoni *et al.* 2009). The primary advantages of reflective techniques are the short acquisition time, lower cost of equipment and high quality of the data (Sansoni *et al.* 2009). The advantages and limitations of several recording techniques are summarised in Table 1. While many reflective acquisition techniques are easy to operate, skilled users are required to manipulate the data and create the 3D models.

#### 2.1.1. Laser Triangulation

Laser-based techniques are one of the most commonly used active methods in 3D documentation as they are more affordable and easier to operate (Kuzminsky and Gardiner 2012). In triangulation systems there are two known positions, the positioning laser and the detector (Errickson *et al.* 2017). The laser is projected onto a surface, and as it returns to the detector, the angle of return allows the topography of the documented object to be accurately recorded as a cloud of points. The triangulation method is more appropriate for recording smaller objects where a sample is normally placed onto a turntable and the surface is captured from various angles. A 3D surface mesh is generated, which contains geometry and morphology data of the subject. These meshes can be cleaned and stitched together to form a complete 3D model of the entire surface. In some systems (such as the NextEngine) the surface is also photo-captured to document the texture/colour, which in turn can be applied to the final model (Kuzminsky and Gardiner 2012).

Although laser triangulation is accurate and mostly insensitive to surface light and texture (Sansoni *et al.* 2009), there are a number of limiting factors that should be considered (see Komar *et al.* 2012 for a further discussion). First, the method can create superfluous data (referred to as noise), due to ambient light, reflection off irregular surfaces, or an increase in points in the capture process (Edwards and Rogers 2017; Errickson *et al.* 2017). This problem is exemplified when reflective surfaces (such as mirrors) are recorded (Hołowko *et al.* 2016), because such data must be amended in the post-processing stage. In forensic science, this editing stage must be fully documented as it may later create problems with admissibility in a court of law.

Additionally, there is a need for a power source for data acquisition. When documenting smaller objects, it is common place for the object to be transported to the institution. However, this may be difficult to do with forensic evidence. Further, it may not be cost effective for individual police units to have their own equipment. While initial equipment costs today are much more affordable, most police units do not have the budget (of around £3000) available for this. Finally, it is suggested that those using the equipment are appropriately trained. It has been demonstrated quantitatively that better results are achieved with increased level of operator experience (Errickson *et al.* 2015).

#### 2.1.2. Laser Time of Flight

For larger areas, such open fields and rooms within a building, ground-based laser scanners are suitable (terrestrial laser scanners). These scanners use either a pulsed (time of flight) or continuous frequency modulated (phase-shift) laser that measures a distance to the surface of an object (Newnham *et al.* 2015). Once the scanner is in position, it will automatically send a laser around the investigative environment while rotating horizontally and vertically, capturing the surrounding visible surfaces as a point cloud. When applying this technique to large areas, the scanner needs to be moved around the scene to ensure the laser scan captures previously unseen surfaces. As a result, individual scans are manually stitched together to create a full representation of the whole scene.

Although these systems are much larger than hand-held scanners, they are considered portable and capable of performing rapid, true-colour 3D digitisation (Buck *et al.* 2013). On the other hand, terrestrial based scanners can cost upwards of £30,000 for the basic digitising equipment.

#### 2.1.3. Structured Light

Structured light scanning has primarily been utilised for documenting hand-held objects. The technique uses a combination of cameras and projectors, initially calibrated by projecting patterns of light onto the surface of a known patterned board. When the patterns are then projected onto an object's surface, the pattern deforms enabling the topographic surface to be accurately documented (see Errickson 2017; Errickson *et al.* 2017). Structured light scanning has the ability to capture geometric, morphometric, and colour surface data (Sansoni 2009). Like the laser-based methods, Thompson and Norris (2018) demonstrated that structured light scanning is non-destructive, has fast acquisition and processing times, is portable, accurate, and reliable. The high computational power required to process the scan data is noted as a limitation (McPherron 2009). Further, although most scanning is undertaken in a controlled environment, external light can disrupt the scanning process.

#### 2.1.4. Photogrammetry

This technique can encompass single- or multiple-camera documentation. Single camera photogrammetry (sometimes referred to as structure from motion (SfM)) works by taking multiple overlapping images from digital cameras (often in the form of a video). On the other hand, multiple-camera documentation uses two or more overlapping 2D photographs of an object (Michienzi *et al.* 2018). These data sets via photogrammetric software will produce a point cloud that can be manipulated and measured (Carlton *et al.* 2018).

Single camera photogrammetry differs from multiple-camera photogrammetry in that the software uses a set of algorithms to automatically detect and match features. The software then triangulates from these features to form a point cloud and thus a 3D model (Peterson *et al.* 2015). Single camera capture does not require targets or reference makers to be placed on the subject (Carlton *et al.* 2018), where multi-camera documentation can use reference markers placed on or around a subject, but they should only be used after the recording and/or recovery of other physical evidence (Ebert *et al.* 2016). Given the ease-of-use and high accuracy associated with photogrammetry, it is a popular technique (Carlton *et al.* 2018). For both techniques, a texture map can be applied for a photo-realistic appearance (Sansoni *et al.* 2009), and the utility of creating 3D models has been illustrated through case examples (Peterson *et al.* 2015).

Limitations of photogrammetry include that hidden or covered parts are not captured (Ebert *et al.* 2016), and that the condition of the surface affects the recording. For example, data capture can be problematic if a surface is covered in hair, is reflective or wet (Urbanova *et al.* 2015, Ebert *et al.* 2016). The documentation of smooth surfaces are also challenging as demonstrated by Peterson *et al* (2015) when imaging a pocket knife. In addition, the scale for the photogrammetric technique is manually added to the data (normally using reference target points from the initial capture), this therefore has the potential of incorporating error into the data set.

### 1.1. Transmissive

Transmissive imaging techniques work by passing through a sample to capture volumetric data, as such the major advantage is that a sample does not need to be uncovered or unpackaged, or in the case of human cadavers, macerated. Transmissive imaging facilitates viewing of internal features, such as bones or organs in humans, but also objects within other objects, such as items inside a suitcase. The surface of a subject may be documented, but with differing quality.

The two transmissive techniques discussed are computed tomography (CT) and magnetic resonance imaging (MRI). These are more complex than reflective techniques and require specialist radiographers to perform the image acquisition, however, the image processing may be carried out by skilled users.

#### 1.1.1. Computed Tomography (CT)

Multidetector CT (MDCT) or multislice CT (MSCT) scanning works by passing a beam of ionising radiation through a sample/subject, this radiation is then detected and converted into a digital signal, which is stored as Digital Imaging and Communications in Medicine (DICOM) data. The 2D slices/images can be converted into 3D volumetric data and viewed as a surface volume render (Franklin *et al.* 2016). CT works by separating areas of differing densities (based on x-ray attenuation), and as such pre-set algorithms can differentiate between different materials (or tissues) based on their density, e.g. metal versus bone, versus fat. The user can then segment the 3D volumetric data to further separate materials (e.g. using thresholding), in order to generate an exportable surface model such as an STL file.

Post-mortem CT (PMCT) is common place in several forensic institutes (Weiss *et al.* 2017) due to its superior visualisation capabilities, however, the technique is limited in several aspects. First, it works well for visualising bones, but less so for soft tissues (Bornik *et al.* 2018). The equipment is large and expensive (Bornik *et al.* 2018), although there is provision of a mobile CT scanner in the UK (Rutty *et al.* 2007). Additionally, CT scans are influenced by metal artefacts such as gunshot or dental amalgams (Bornik *et al.* 2018), and lastly, samples must be transportable and fit inside the CT gantry. Since the technique images in slices, the quality of the models from CT is limited and affected by the scan resolution, the parameters involved in scan acquisition (Guyomarc'h *et al.* 2012), and the user segmentation procedure (Carew *et al.* 2018).

Sub-techniques of CT may counteract some of the limitations, for example, dual-energy CT has been shown to reduce the effect of metal artefacts, as well as improve soft tissue visualisation (Norman *et al.* 2017). Dual-energy CT also holds the potential to differentiate between different drugs in body-packing cases (Alkadhi and Leschka 2013). Additionally, micro-CT can be employed for greater resolution and fine detailing (although only with small-sized specimens). Lastly, since CT uses ionising radiation it has safety and ethical limitations around living subjects.

#### 1.1.2. Magnetic Resonance Imaging (MRI)

Magnetic Resonance Imaging (MRI) creates high resolution multiplanar images and is also commonly used in forensic medicine (Aalders 2017). Unlike CT, MRI is a non-ionising imaging technique, making it a potential safer option for imaging the living. MRI uses radio waves to excite protons in the body, the spinning of these protons gives off electric signals known as nuclear magnetic resonance (NMR), which can be measured (Yoshioka *et al.* 2009). The application of a strong magnetic field and magnetic field gradients provides spatial information for the NMR signal (Yoshioka *et al.* 2009); by pulsating the radio waves, the differences in signals from hydrogen atoms in various tissue types can be visualised as images (Aniq and Campell 2011).

MRI works well for hydrogen atoms, principally those within water in the body (Errickson *et al.* 2014). As such, MRI is effective for imaging soft tissues such as muscle or fat, but it does not work as effectively for hard tissues such as bone. MRI is comparable to traditional autopsy for visualising soft tissue and brain traumas (Ampanozi *et al.* 2010). Additionally, MRI may be combined with angiography (MRA) to provide differing visualisation of tissues (Errickson *et al.* 2014).

Limitations to MRI include the high acquisition time, although new methods such as parallel imaging or using higher field strengths are overcoming this (Aniq and Campell 2011), and the sensitivity of the technique requires the subject to remain still during imaging (although not an issue for imaging the deceased). The presence of ferromagnetic metallic objects (e.g. dental restorations or orthopaedic implants) can cause safety concerns and artefacts in images (Maller *et al.* 2012). Additionally, MRI is generally not suitable for imaging skin or surface details, due to the high signal to noise ratio and limited resolution, however it is possible through using specialist MRI coils (Vogt and Ermet 2006). It is advisable to perform a CT scan prior to MRI of deceased individuals to search for the presence of ferromagnetic objects, such as jewellery, debris or shrapnel which can often be present in post-mortem situations (Ruder *et al.* 2014). Ballistic projectiles are usually not ferromagnetic, and it is noted that MRI is adept at imaging bullet tracks.

### **1.2.** Multimodal Imaging

Multimodal imaging further expands the utility of 3D digital imaging, by combining data from multiple techniques to form one conjugated model. For example, Villa *et al.* (2018a) explain that it is possible to combine multiple techniques, without the need for simultaneous acquisition or the use of reference markers. Furthermore, it is possible to combine surface and internal volumetric data, for example combining photogrammetry with CT to create unabridged 3D models that are to scale and exhibit ‘true’ colour (Villa *et al.* 2018a).

Multimodal imaging was identified by Aalders (2017) as one of the four important issues in imaging, further it has been proposed that the concurrent use of contact and non-contact techniques may overcome issues with accuracy (Sansoni *et al.* 2009). Additional possibilities for multimodal imaging, include combining macroscopic imaging with microscopic or molecular techniques (Aalders *et al.* 2017).

*Table 1* Overview of advantages and limitations of 3D recording techniques (Adapted from Sansoni *et al.* 2009)

| Technique | Advantages | Limitations |
| --- | --- | --- |
| **Laser triangulators** | Relative simplicity<br>Performance generally independent of ambient light<br>High data acquisition rate | Safety constraint associated with the use of laser source<br>Limited range and measurement volume<br>Missing data in correspondence with occlusions and shadows<br>Cost |

| | | |
|---|---|---|
| **Structured Light Scanning** | High data acquisition rate<br>Intermediate measurement volume<br>Performance generally dependent of ambient light<br>Relatively small data files in comparison to other techniques | Safety constraints, if laser based<br>Computationally middle-complex<br>Missing data in correspondence with occlusions and shadows |
| **Photogrammetry** | Simple and inexpensive<br>High accuracy on well-defined targets | Computationally demanding<br>Sparse data covering<br>Limited to well defined scenes<br>Low data acquisition rate |
| **Structure from Motion (SfM)** | Simple and inexpensive<br>Can document large areas in a short time frame | Can be a complex technique<br>Sparse data covering<br>Based on resolution of images taken |
| **Time-of-Flight** | Medium to large measurement range<br>Good data acquisition rate<br>Performance generally independent of ambient light | Cost<br>Accuracy is inferior to triangulation at close ranges |
| **Computed Tomography (CT)** | High resolution<br>Volumetric data<br>Good definition of skeletal elements<br>Independent of exterior conditions (e.g. light) | Cost<br>Complex technique<br>Computationally demanding<br>Affected by metallic artefacts<br>Ionising radiation |
| **Magnetic Resonance Imaging (MRI)** | High resolution<br>Independent of exterior conditions (e.g. light)<br>Good definition of tissues | Cost<br>Complex technique<br>Computationally demanding<br>Generally poor definition of skeletal elements<br>Affected by metallic artefacts |

## 2. Application of techniques

The application of digital imaging techniques to several forensic sub-disciplines is discussed.

### 2.1. Forensic anthropology

Utilising imaging techniques to digitise and reconstruct forensic osteological samples is known as virtual forensic anthropology (Franklin *et al.* 2016), several areas of applications are discussed below.

#### 2.1.1. Biological profiling

Digital imaging can be used for the application of traditional biological profiling techniques, as well as the development of new techniques, for example using the cranial sinuses (Aalders *et al.* 2017). There is a multitude of literature on biological profiling in forensic anthropology using digital data (see Villa *et al.* 2016), primarily from CT but also several using MRI. For example, Martinez Vera *et al.* (2017) studied MRI images of the manubrium for age estimation with promising results, this is particularly useful since MRI is a non-ionising technique and offers a more ethical solution for age estimation of the living (e.g. in legal maturity cases). Sex estimation techniques have recently been reviewed by Krishan *et al* (2016), and although there are many methods that are useful, including geometric morphometrics, re-evaluation of traditional methods and validation of newer techniques should be achieved.

Further applications include the possibility of using photogrammetry for estimating the height of individuals (Michienzi *et al.* 2018), or superimposing 3D models of skulls generated using photogrammetry, onto photographs of missing people (Santoro *et al.* 2017). This latter method found that it was possible to match photos of living individuals to 3D images of skulls and could be applied in missing person cases or with unidentified remains (Santoro *et al.* (2017).

#### 2.1.2. Weapon identification

A weapon (or weapon-type) may be identified from, or ‘matched’ to, a 3D model of a bone injury. This may be achieved by morphologically identifying the shape of the object, interpreting volume renderings, or with the use of stereolithography (de Bakker *et al* 2013). For example, Woźniak *et al.* (2012) created a 3D model from ante-mortem CT scans of a victim and scanned suspected weapons, they successfully matched the injury pattern to an object using 3D modelling to the demonstrate results. The accuracy of these techniques has since been addressed, and the possibility of using techniques such as micro-CT scanning to facilitate quantitative data has been demonstrated (Norman *et al* 2018); which is advantageous as it has the potential to reduce interpretation bias. Similarly, 3D printed replicas have been shown to be reliable forms of documentation (Edwards & Rogers 2017), however further research focusing on the methodological approach is necessary.

### **2.2.** Scene capture

A variety of 3D recording techniques have been employed for the documentation, analysis and presentation of a crime scene. 3D data capture methods provide precise scene recording that does not suffer from the spatial distortion effects associated with 2D photographic recording (Raneri 2018). Raneri (2018) reports that over the past two decades investigators have had access to 3D imaging equipment but were struggling to use and apply the data. However, with the advent of equipment that is faster and easier to use, and the recent advances in software, police forces can now regularly capture and more importantly utilise 3D data for crime scene documentation (Raneri 2018).

Empirical research has investigated the accuracy of 3D scene recording, for example a comparison of measurement data from two different methods for documenting crime scenes (a tape measure and a 360 camera with photogrammetry), found the manual method to be more accurate but the software application method more precise (Sheppard *et al.* 2017). Additionally, drone-based aerial photography was found to produce high-quality images and therefore accurate large-scale 3D models of mock forensic scenes (Urbanova *et al.* 2017a). The authors recommended processing aerial and ground imagery separately, and in parallel to using scene markers if precise detail (e.g. of physical evidence or human remains) is required.

A scene or sequence of events may be reconstructed in accident investigations, for example photographs of incidents from different spatial angles can be used to reconstruct the 3D geometry of a scene and aid in scene interpretation (Verolme and Mieremet 2017). Further, 3D scan data may be combined with CCTV or eyewitness photographs, which can for example aid with identifying the spatial position of an individual or for profiling individuals (e.g. to estimate height) (Raneri 2018). A simulated bus explosion was successfully documented and 3D modelled using photogrammetry, it was noted that the 3D reconstructions allowed for a clear and understandable view of the scene and the ‘victims’ (Villa *et al.* 2018b).

Further applications include crime scene and traffic recording using photogrammetry (Michienzi *et al.* 2018); 3D modelling of shooting incidents (Ward and Sheridan 2018); 3D scanning of weapons at a crime scene, for comparison with wounds on a victim or of impressions found at the scene (Raneri 2018). Further, 3D imaging at a crime scene can also facilitate analysis of evidence in the 3D space whilst at a scene (Raneri 2018).

## **2.3.** Forensic Medicine

The use of digital imaging with autopsy investigations is well-documented and not discussed in this review. However, novel applications within forensic medicine are emerging, for example, Ebert *et al.* (2016) state that digital surface documentation of cadavers complements traditional photography and is commonplace in Switzerland. While forensic 2D photo-documentation is the gold standard for recording injuries (Michienzi *et al.* 2018), photogrammetry in particular is noted to be beneficial for external body documentation (Urbanova *et al.* 2015). While laser scanning is discouraged for use on living individuals due to safety concerns, slow speed of capture and difficulty in imaging surfaces of dark colours (Shamata and Thompson 2018b).

### 2.3.1. Surface injuries

Back in 2000 photogrammetry was used to match tyre treads to a facial injury with results found to be superior than the traditional 2D photographic overlay method (Thali *et al.* 2000). Recently, abundant research on 3D documentation of surface injuries has been emerging, indeed Ebert *et al.* (2016) observe that injuries with shape, such as those from “weapons, tools, shoes, dental imprints, forged coins or drugs”, have the potential to be matched with objects.

Indeed, photogrammetry has been used to match surface injuries with instruments and to reconstruct patterned injures (Michienzi *et al.* 2018). It has been demonstrated that this technique can produce high-resolution, realistic, and to-scale 3D surface models (Urbanova *et al.* 2015). A case-report by Davy-Jow *et al.* (2013) used laser scanning and photography to document evidence of abuse and starvation. Furthermore, a forensic 3D approach (using computer aided design (CAD) supported photogrammetry) was used to model a skin injury and a weapon, facilitating pattern matching of an injury with shape of the weapon (Thali *et al.* 2003). Michienzia 2018 found that they could measure injuries more accurately with photogrammetry than with standard forensic photography.

Useful guidelines for scanning bodies are included in Ebert *et al.* (2016) and Shamata and Thompson (2018b), the latter of which found structured light three-dimensional surface scanning to be appropriate for scanning different body areas, and provides notes on ideal number of scans, scanning approaches for different body areas, and for eliminating background noise. 3D surface documentation of living people is useful to document pattern skin injuries, such as footwear marks, bite marks, bruises and object imprints, particularly when 2D photographs or sketches are insufficient (Ebert *et al.* 2016). Furthermore, structured light three-dimensional surface scanning has been investigated for documenting and measuring surface injuries on living participants (Shamata and Thompson 2018a). In this case, 3D wound models were found to have extra features over 2D photographs and no statistically significant difference was seen between the 3D and traditional wound measurements. Future work proposed by Shamata and Thompson (2018a) includes scanning open injuries to ascertain depth information.

Campana *et al.* (2016) explored 3D documentation of surface injuries, using a combined method integrating CT, MRI, photogrammetry and structured-light 3D scanning to create comprehensive 3D models. Their recommendations included, placing reference markers at varying heights when on flat surfaces (to expand the area of interest), use of a vacuum mattress (also used by (Ebert *et al.* 2016)), ensuring the injury is in centre of photographs with markers placed around it (to minimize distortion), and taking one photograph perpendicular to subject. Campana *et al.* (2016) found their method to be suitable for documenting individual patterns or body parts, but less suitable for entire bodies.

Additionally, it has been proposed that further insight may be achieved by combining radiological and non-radiological techniques, for example, using spectrometry and fluoroscopy for dating bruises (useful in abuse cases), dating fractures and subdural hematomas (Aalders *et al.* 2017). Further areas of potential research where 3D imaging could be useful include, dating fractures in different post-mortem scenarios, investigating the effects of decomposition and for establishing post-mortem intervals (PMI) (Aalders *et al.* 2017).

#### 2.3.2. Taphonomy

Taphonomic changes in cadavers can be seen over time, while traditionally photographs have been used to document these changes, recently researchers have investigated using 3D recording techniques. Carlton *et al.* (2018) used SfM and GIS (Geographic Information System) to document decomposition on human cadavers and found these tools to be useful and efficient for recording the decomposition and taphonomy. Zhang *et al.* (2014) employed terrestrial laser scanning for obtaining 3D ‘volumetric’ data to investigate bloating on a human cadaver, finding good agreement between in-situ measurements and the ‘volumetric’ data.

### **2.4.** Pattern and Impression Evidence

Several potential applications for laser scanning with pattern and impression evidence are mentioned in Komar *et al.* (2012), for example documenting mass graves (tyre and bucket marks), footprints, tool marks, marks and impressions in perishable materials (such as food), as well as fire scenes containing fragile burnt human remains. Through personal communication with a number of researchers, there is some ongoing progression in the application of 3D imaging to pattern and impression evidence, however, it is difficult to find a significant amount of literature within these disciplines.

#### 2.4.1. Footwear marks

The recovery of footwear impressions is a routine process for many police forces, however the traditional method of casting is highly destructive to the impression. Therefore, 3D imaging techniques can be used to capture the details of such an impression in a non-destructive way (Gamage *et al* 2013; Andalo *et al* 2011). Komar *et al* (2012) provided examples of a shoe of a suspect and an impression in sand that had been documented using a laser scanner. In this article Komar *et al.* (2012) stated that the software allows comparison between the two datasets and that the resulting 3D model is a useful tool for courtroom demonstration. This comparison has since been demonstrated by Thompson and Norris (2018), who evidenced the reliability of using structured light scanning. However, it has been noted that further work is needed before the structured light technique can replace traditional casting techniques (Thompson and Norris 2018; Crabbe *et al.* 2015).

#### 2.4.2. Fingermarks

Mulawka and Troy (2017) demonstrated that it is possible to recover ridge detail using 3D scanners for the collection of post-mortem fingerprints. Although this study used prototyped equipment for the documentation process, it confirmed that the recovery of detail is possible. Similarly, Liu *et al* (2017) captured finger ridge detail as well as shape using structured light scanning but acknowledged that matching fingerprints through recognition needed further work.

No literature has been identified for 3D imaging of a fingermark on a surface (other than standard photography or microscopy). This is perhaps due in part to fingermarks being 2D, there is no need for a third dimension (unless recovered from a curved surface) (H.Earwaker, Personal Communication, September 12, 2018). Also, the limited resolution of surface scanners may render the techniques unsuitable, further, any fingermark would need to be visible in order for a surface scanner to capture it, thus, latent marks would not be visible without enhancement (H.Earwaker, Personal Communication, September 12, 2018).

#### 2.4.3. Bite marks

Page *et al.* (2011) highlighted that bitemark analysis may be challenged in a court, however Lasser *et al.* (2009) was one of the first examples to demonstrate the application of laser scanning in bitemark analysis. In their technical note, the use of a digitised bite was quantitatively compared to a maxillary model with the aim of working towards a less subjective analysis. Since, Sheets *et al.* (2013) addressed the variability of dentition using laser scanning, which still demonstrated that caution should be applied to bitemark analysis, and Corte-Real *et al.* (2018) found successful matching of bitemarks on bitten apples with cone-beam CT scanned dental arches in a database.

Komar *et al.* (2012) suggested that documentation of bitemarks using a laser scanner should be considered alongside traditional protocols at a postmortem. In this study, Komar *et al.* (2012) used the data to 3D print a replica model of a bitemark, stating that 3D printing could be useful for courtroom presentations and other educational purposes.

### **2.5.** Ballistics

Using the virtual autopsy approach, 3D imaging can assist forensic pathologists in providing an accurate and visual interpretation of a bullet trajectory. These techniques normally centre around CT and MRI scanning (Levy *et al.* 2006; Folio *et al.* 2011; Colard *et al.* 2013), however studies have established that although this type of imaging is useful for understanding distribution, depth and direction of projectiles (Raneri 2018), it is also important to consider the initial autopsy examination as differences in interpretation may arise (Delteil *et al.* 2018; Usui *et al.* 2016). Likewise, photogrammetry has been used in the reconstruction of external bullet trajectories (Michienzi *et al.* 2018) and in post-mortem surface documentation. While the photogrammetry imaging process is rapid, it is insufficient at imaging body characteristics such as body hair, depressions or surfaces with fluid (Urbanova *et al.* 2015).

Laser scanners have been used in crime-scene reconstruction to analyse bullet trajectories and reconstruct shootings. For example, Lisco *et al.* (2018) demonstrated that although there are several systematic errors that are present regardless of method, the laser tracker is suitable for recording trajectories in drywalls at a specific angle of incidence. Perhaps, a combination of laser scanning with forensic animation could be useful, Schofield (2011) used computer game technology as a mode of virtual simulation for reconstructing bullet trajectories.

### **2.6.** Bloodstain Pattern Analysis (BPA)

Investigators can utilise 3D imaging in bloodstain pattern analysis (BPA) to identify the trajectory and point of origin of blood droplets (Raneri 2018, Hakim *et al.* 2015). Hakim *et al.* (2015) note that laser scanning is effective for recording BPA and is non-invasive and quicker than conventional documentation. Similarly, an investigation using multiple 3D techniques with differing resolutions including laser scanning and structured light scanning, found that accurate area of origins and trajectories could be visualised and analysed using 3D scene models (Hołowko 2015).

### **2.7.** Road Traffic Collisions

The benefit of 3D technology to recording road traffic collisions was recognised very early. Buck *et al* (2013) showed that 3D data of a scene could help with the reconstruction of events and illustrated this using a case example of an individual being hit by a car. In this study, photogrammetry and 3D laser scanning was used. Subsequently, 3D accident reconstruction has been achieved and demonstrated as useful using close range photogrammetry (Osman & Tahar 2016), laser scanning (Lyu *et al* 2017), and utilising videos and still images to create 3D models (Jiao *et al* 2018).

### **2.8.** Forensic Archaeology

3D documentation has many applications in forensic archaeology, such as recording remains in-situ and recording complex sites involving commingling or mass graves. For example, SfM has been demonstrated for mass grave documentation (Baier and Rando 2016) and for recording funerary taphonomy (Knüsel and Robb 2016). Additionally, photogrammetry has been combined with GIS location-based data to document and interpret graves and remains in-situ (Wilhelmson and Dell'Unto 2015). While not strictly 'forensic' in nature, there are also examples of using structured light scanning for recording human remains in graves sites (McPherron *et al.* 2009).

Forensic archaeologists from the Committee of Missing Persons in Cyprus (CMP) have also investigated the potential of using digital imaging when conducting ground surveys and searching for potential grave sites (Sturdy Colls *et al.* 2018). Additionally, searching for objects of forensic importance that are hidden beneath floors or within walls can also be aided with 3D imaging techniques. Ruffell *et al.* (2014) describe the potential of LiDAR, laser scanning and radiography in addition to the traditional aerial photography and ground-penetrating radar (GPR) techniques.

### **2.9.** Forensic Engineering

3D documentation techniques have been employed in forensic engineering cases. For example, laser scanning was used to document the scene following the collapse of the power station in Didcot, UK in 2016 (Dr Karl Harrison at the Forensic Archaeology, Anthropology, and Ecology Symposium, London, UK, 12th June 2017). Laser scanning was also successfully used to develop 3D models in two cases of building collapses (a complex structure collapse of a shoring system and an overturned crane) a task that would be “nearly impossible” without digital imaging (Park *et al.* 2018). The authors demonstrated that they were able to reconstruct complex scenes for inspection, successfully conducting structural analysis and acquisition of dimensions (Park *et al.* 2018).

A research collective termed ‘Forensic Architecture’ (Department of Visual Cultures, Goldsmiths, University of London (https://www.forensic-architecture.org) regularly applies 3D imaging techniques in project work. For example, the team used photogrammetry to create a 3D model of a crater from a suspected chemical bomb in Khan Sheikhoun, Syria in 2017. By obtaining photographs from civilians and journalists they were able to generate a 3D model, from which they could obtain the dimensions of the crater for further analysis (Forensic Architecture, 2017, April 4). In a current project, ‘Forensic Architecture’ are using SfM to generate a source of spatial and temporal evidence of the fire at Grenfell Tower, London, UK in 2017, through combining eyewitness photographs and video footage with a 3D model of Grenfell Tower (Forensic Architecture 2017, June 14).

## **3.** 3D Presentation

### **3.1.** 3D printing

3D printing, also known as additive manufacturing or rapid prototyping is a valuable extension to digital imaging in the forensic sciences. 3D polygon mesh files (primarily STL) from digital imaging techniques can be translated for a 3D printer to print. There are several different 3D printing techniques available each of which has differing advantages, limitations and considerations based on the sample morphology (Hodgdon *et al.* 2018 and Carew *et al.* 2018). The parameters employed during scanning and post-processing (such as slice thickness or surface smoothing) are crucial to the accuracy and quality of the generated 3D model and subsequent 3D print (Ford and Decker 2016, Guyomarc'h *et al.* 2012). The accuracy of a printed replica should not be affected by printer resolution, provided printer resolution is greater than scan resolution (Hodgdon *et al.* 2018 and Carew *et al.* 2018).

Physical 3D replicas can be useful for a variety of applications, from replicating bones for forensic analysis (Urbanova *et al.* 2017b, Wozniak *et al.* 2012) and replicating skulls for building facial reconstructions (Chase and LaPorte 2017), through to courtroom display of potential weapons (BBC News (Producer), 2015, April 20) or osteological evidence (Baier *et al.* 2017, Baier *et al.* 2018, Ebert *et al.* 2011).

3D printing in forensic science is an emerging area with much further research needed to validate the processes and the applications involved. As present, 3D printing in forensic science appears to be largely based around replicating skeletal elements, perhaps if future research validates physical 3D printed exhibits as having superior evidential value, other disciplines could follow suit and we could see printed replicas of fingermarks or footwear impressions in courtrooms.

### 3.2. Mixed Reality (MR)

With exception to 3D printing, many of these datasets are still presented in a 2D format on a computer screen (Ebert *et al* 2014). The concept of mixed reality (MR) incorporates virtual reality (VR) and augmented reality (AR) technologies (Eve 2018). Through VR a user is immersed in real-time in a virtual world via a computer interface, usually using VR goggles or a headset (Eve 2018; Fernandez-Palacios *et al.* 2015). Through VR 3D data can be presented complete with depth perception (Raneri 2018).

Conversely in AR, digital objects are be virtually ‘inserted’ into real-space using a smart device or goggles, this maintains a 1:1 connection to the real-world and creates a multi-sensory experience (Eve 2018; Fernndez-Palacios *et al.* 2015). Additionally, ‘virtual-tours’ can utilise 360-degree photography to allow users to ‘walk’ through a scene on a smart device (Tung *et al.* 2015). MR is a particularly important area of research as it can be applied in all stages of the forensic science process, from decision making at a crime scene through to presentation of evidence in a court of law. The process was demonstrated by Ebert *et al* (2014) where it was suggested that VR glasses could be used to immerse individuals into 3D interactive forensic scene reconstructions. Literature is also available on the use of VR and AR in archaeology (Eve 2018; Fernndez-Palacios *et al.* 2015) and forensic medicine (Kilgus *et al.* 2014) as well as the use of MR in courtroom display (see 3.4; Ebert *et al* 2014); it is anticipated that further applications and research will emerge in the near future.

### 3.3. Animation

The introduction of virtual animations is a novel area, which can depict changes over time, use zooming or animated subjects (Aalders *et al.* 2017) and/or combine photography of real-world evidence (e.g. photographs of injuries) with virtually-constructed scenes or figures (Buck *et al.* 2013). A recent example used a virtual animation to depict how a victim obtained their injuries, through animating a moving 3D skeleton with a bullet paths penetrating the body (Villa *et al.* 2017). Furthermore, combining multimodal imaging with CAD has been used to show elaborate virtual representations and interactive videos of injuries and weapons (Bornik *et al.* 2018). Incorporating CAD objects into a 3D model merges case-findings with interpretations, although useful for demonstrations the two must be clearly defined (see 3.4).

### 3.4. Courtroom Display

Thali *et al.* (2000) promoted the use of photogrammetric 3D models for demonstration of evidence, stating that 3D models are more easily understood by laypersons, a concept that is still portrayed (Villa *et al.* 2017; Blau *et al.* 2018). The utility of 3D digital data for courtroom demonstrations of osteological evidence and the potential advantages of having 3D models over 2D photographs was detailed by Errickson *et al.* (2014). However, there is currently little data to show whether 2D or 3D exhibits are more effective or comprehensible, and similarly more or less prejudicial to a jury (Aalders *et al.* 2017). A recent report highlighted that research is needed to fully explain and quantify the utility of visual aids in a court of law (Weiss *et al.* 2017).

Furthermore, using VR in criminal trials poses new issues, an article by Young (2014) noted that VR demonstrations of evidence can be particularly persuasive and even prejudicial, and the author advised courts of law to proceed with due caution (Young 2014). Contrastingly, Salmanowitz (2018) suggested that VR could aid in reducing bias in courtroom decision making. Kilgus *et al.* (2014) provided caution for using MR and Animations in courtrooms, in particular the authors state the necessity for verifying the authenticity, fairness and relevance of using of visualisations for courtroom display of evidence, noting that the data, methods and visualisation must be valid.

Virtual 3D models and physical 3D replicas have been used in courts of law as exhibits, there is high value and responsibility involved in courtroom display and several areas require clear definitions to be applied (Baier *et al.* 2017). Firstly, it is important to differentiate between findings and simulated scenarios such as scene reconstructions (Aalders *et al.* 2017). A 3D crime scene *reconstruction* is based on factual scientific evidence, in contrast to a crime scene *simulation,* which based on a predicted condition or sequences of events (Raneri 2018). The two must be distinguished when presenting 3D virtual scenes and practitioners have a responsibility to ensure that courts of law understand this distinction. Secondly, exhibits used as *demonstrative aids* or *demonstrative evidence* must be separated; each have differing rules of admissibility and moreover *demonstrative aids* are not admitted into evidence and carry no probative value (Carew *et al.* 2018; Hofer 2007).

## 4. Further thoughts around forensic imaging

### 4.1. Ethical Considerations

As discussed, there are significant benefits to the use of 3D imaging techniques and consequently this data is different from any other form of data. Hirst and Smith (2019), suggest that 3D imaging demands separate ethical and legal consideration, however this deliberation is somewhat complex due to the different strands of imaging in forensic science. These ethical considerations stem from the discipline within these individual strands (i.e. biology; anthropology; archaeology; crime scene investigation), but still address similar acceptable boundaries such as what information is obtained, who's data is gathered, what is the intended use of the data, and what other individuals are affected (Hughes 2015). Some disciplines (such as medicine) have strict protocols for research, and although further disciplines have guides and recommendations, the uptake of newer imaging modalities has yet to be fully addressed.

There appears to be a much greater awareness in the fields related to the human body demonstrated by a number of recent publications (See Passalaqua and Piloud 2018; Squires *et al.* 2019). Perhaps this is a development from medical related disciplines (primarily from living individuals) where practical considerations may apply, such as determining if identifiable data collection needs to be collected and on the anonymisation of data and subsequent images or models. On the other hand, disciplines such as forensic anthropology are largely related to deceased individuals. These considerations are compounded when dealing with human subjects from forensic scenarios, for example, when dealing with imaging data from living or deceased individuals the wishes and beliefs of the individual and/or the next of kin may need to be considered when deciding whether to share the digital data. Furthermore, these areas have a strong association to international disasters, such as the mass killings in warfare, in contrast to the three-dimensional recovery of a footwear mark.

Nevertheless, these ethical discussions should be implemented into degree programmes, especially within foundation learning. This in turn would hone the skills of future graduates (Hughes 2015), however care must be taken to avoid presenting a one-sided view. For example, an action that may be perceived by many as unethical may have been undertaken in an innocent and misguided way. Therefore, presenting both sides of an ethical discussion is important (Errickson and Thompson, 2019).

### **4.2.** Bias

One of the main issues in forensic casework is the complex nature of analysing and interpreting data (Morgan and Bull 2007). As a result of the complexity of data analysis and interpretation of evidence in the forensic sciences, the issue of admissibility of evidence and expert witness testimonial accounts has been raised (Christensen *et al.* 2014). Both 2D and 3D image interpretation is affected by human perception and it has been demonstrated that expertise, experience, and cognitive bias will all impact on the decision-making process (Aalders *et al.* 2017; Morgan 2017). For example, Nakhaeizadeh *et al.* (2014) undertook an experimental study examining cognitive bias in forensic anthropology. Whereby, it was demonstrated that the decisions of forensic anthropologists based on visual assessments are vulnerable to extraneous contextual information. Therefore, bias has large implications for accuracy and error in forensic science. For example, it can corrupt the conclusions and testimony of forensic examiners, influence other evidence, and therefore change sources of information that is presented to the courtroom (Kassin *et al.* 2013).

It is encouraging to see these concerns being addressed in forensic science, and newer imaging techniques are starting to work towards reducing bias. For example, Nicolene Lottering has demonstrated how quantitative analysis using MSCT scans can assist in the removal of bias when compared with traditional methods (Sandholzer *et al.* 2013). Likewise, in drone aided survey, pre-establishing a flight path for the location of a body as opposed to manually operating the drone can ensure all areas of a particular region are documented, which in-turn reduces user bias (Urbanova *et al* 2017a).

### **4.3.** Training and Standards

Currently, forensic science is undergoing a period of standardisation and validation (Passalaqua and Piloud 2018). Training and standardisation vary between laboratories, countries, and between disciplines. The creation of standard operating procedures has been suggested to help ensure reproducibility between laboratories however these can be met with resistance and can be difficult to progress into widespread use and acceptance (Thompson 2015). Raneri (2018) note that police staff require specialist training in virtual crime scene reconstruction, and that organisations such as the International Association of Forensic and Security Metrology (IAFSM) are assisting with this through holding workshops and through the development of practice guidelines (Raneri 2018).

Hirst and Smith (2019) highlight that technological advancements in 3D imaging have had remarkable benefits to various disciplines, in particular those focusing on human remains. Although there are currently no standard protocols for creating scanned models, Sansoni *et al* (2009) state that traceability of 3D measurements is important to recognise standards. As a result, a number of publications have been developed which work towards good practice (Errickson *et al* 2017; Shamata and Thompson 2018a,b).

For instance, there are a number of factors to take into consideration in order to produce accurate models, such as the software, algorithms, and experience of the user (Kuzminsky and Gardiner 2012). This is because the settings depend on the object that is being documented. Nevertheless, it is recommended that the operator has knowledge of both the object and the scanner (Errickson *et al.* 2015) and accurate metadata should also be stored along with the digital data. The authors suggest that further studies are developed, concentrating on this accreditation process.

## 5. Conclusion and future recommendations

The development and use of digital imaging in the forensic sciences has leapt forward in the last five years. Digital imaging and immersive 3D technologies offer advanced capabilities for recording and analysing crime scenes and evidence. This review has provided a synopsis of imaging across the forensic science disciplines to include literature focused on human subjects, as well as further subject types such as trace evidence. Moreover, we have shown how 3D imaging is being utilised holistically from crime scene to court.

Through both experimental studies and casework analysis, the scientific community has advanced their understanding of the applications and limitations of digital imaging techniques. As these technologies continue to evolve, further empirical research will be required to fill in the knowledge gaps and to improve existing knowledge-bases. Future recommendations for consideration in digital imaging include:

- A true understanding of the advantages and limitations of the techniques that may be used in forensic science.
- The inclusion of full metadata and acquisition information in publications/reports.
- Early awareness training in ethics and bias in undergraduate degree programs.
- The use of noncontact digital imaging techniques over maceration or destructive techniques, wherever feasible.
- Greater consideration on the ethics surrounding the ownership and sharing of digital data, with better collaboration to enhance further understanding.
- Acknowledgment of cognitive bias and integration of control procedures in casework and analysis.
- Exploration of the impact of 3D and immersive technology in courtroom presentation of evidence.

Finally, forensic digital imaging could benefit from greater inclusion of cross-disciplinary forensic science research. We have demonstrated the wide scope and applications of digital imaging and hope that the Journal of Forensic Radiology and Imaging continues to be a host for such a broad discipline.

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