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Postmortem imaging of perimortem skeletal trauma

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Abstract

Various imaging modalities, including conventional radiography, computed tomography, magnetic resonance, and surface scanning have been applied in the examination of skeletal injuries in the forensic context. Although still not a substitute for a full medico-legal autopsy or the examination of skeletal remains, imaging is now increasingly used as a complementary tool in the postmortem analysis of perimortem skeletal trauma. Facilitated by the progress in general computational capacity, multimodal imaging has been proposed for comprehensive forensic documentation. A major advantage of these imaging approaches is that stored digital or physical 3D models of skeletal injuries can be reviewed at any time by various experts as well as be presented in court as evidence to clarify potentially complex medical and forensic aspects of the case. Due to constant technical progress in imaging techniques and software, continuous education, training, and sharing of expertise among engineers, computer scientists, and forensic experts, including forensic pathologists, anthropologists, and radiologists needs to be warranted to maintain high-quality expertise in the detection and interpretation of traumatic injuries on postmortem imaging. The technical developments and ever-improving user-friendliness of 3D imaging and modeling techniques present an atttactive alternative to traditional forensic approaches, but as long as the techniques have not been sufficiently tested and validated for forensic trauma analysis, and best practice manuals for forensic practice are lacking for both the technical procedures and method selection, the use of imaging techniques needs to be reevaluated on a case-by-case basis. In addition, ethical, legal, and financial aspects of the use of imaging and 3D modeling for forensic purposes need to be well understood by all parties in legal proceedings.

Keywords: fracture; computed tomography; radiography; mechanism of injury; 3D modeling

Introduction

Trauma is considered among the major causes of mortality, causing annually more than five million deaths worldwide (WHO 2014). Considering that any traumatic event that had occurred near the time of death may provide useful information about the mechanism and the cause of death, postmortem trauma analysis is essential for forensic investigations (Burke 2012). In forensic medicine and anthropology, skeletal injuries can be investigated on fresh or decomposing bodies or body parts as well as on fully skeletonized remains originating from different contexts, including single cases or mass fatalities, traffic accidents or crimes against humanity, bodies arriving from emergency departments or cases requiring complex archaeological recovery. Imaging of skeletal trauma is fast evolving as a complementary tool to conventional autopsies (Blau et al. 2018; Bolliger et al. 2008; Burke 2012; Thali et al. 2009). Constant developments in the various imaging techniques, ease of sharing digital data/images, and better availability and accessibility of the necessary infrastructure facilitate the use of imaging for skeletal trauma analysis and interpretation.

Using postmortem imaging for the assessment of bone trauma can help answer questions regarding the mechanism and cause of death, since it provides information about the structure/form of the injury (potentially in comparison to objects of interest or in comparison to antemortem imaging), the relationship of the skeletal trauma to the soft tissues (if present), the timing of injury in relation to death (perimortem, antemortem, postmortem), and in case of more than one injury about the sequence of events. Many of these topics are discussed in more detail in other papers published in this Special Issue, therefore this paper focuses particularly on the potential application of the various non-contact transmissive (i.e., conventional radiography, computed tomography (CT), magnetic resonance imaging (MRI)), and reflective (i.e., photogrammetry, laser surface scanning, structured light scanning) imaging modalities specifically in the assessment and interpretation of skeletal trauma in forensic context.

The aim of this paper is to summarize the advantages and limitations of using the various imaging techniques for the detection and interpretation of skeletal trauma in forensic cases. Since this Special Issue focuses on perimortem trauma, the discussion concentrates on the use of imaging in relation to the interpretation of the mechanism of injury and cause of death, rather than on the application for cases of personal identification, which will be mentioned only marginally.

Forensic expertise in skeletal trauma analysis

Perimortem trauma analysis is mostly undertaken by forensic pathologists or medical examiners, although forensic anthropologists are increasingly consulted in such cases because of their expertise in the assessment of skeletal remains (Blau 2017; Blau et al. 2018; Burke 2012; Passalaqua & Rainwater 2015). Consultations with clinicians may be useful for the interpretation of bone trauma in persons with bone diseases or diseases affecting bone metabolism. In addition, computer scientists, engineers, and specialized technicians may be called upon when imaging data need to be converted into three-dimensional (3D) digital or physical reconstructions of the traumatic injury within the body or visualized in relation to other forensic evidence.

The goal of medico-legal examinations in trauma victims is to answer questions regarding the number of injuries, the trauma mechanism, and the cause of death. Burke (2012) emphasized that in forensic bone trauma analysis the presence of a fracture even if extensive cannot be interpreted as a cause of death per se, and he recommended a conservative approach to the interpretation of the mechanism of injury since it is mostly evaluated in light of the information from witnesses (which may unreliable), or from sources, which are subject to interpretation as well, including scene findings, characteristics of the fracture (the same type of fracture may occur in different situations), and the assessment of associated soft tissues (when present).

In the forensic evaluation of trauma, both excellent specificity (correct identification of skeletal elements without a traumatic lesion) and sensitivity (correct identification of skeletal elements with a traumatic lesion) are fundamental. In addition to the identification of the lesion as traumatic, it is essential that the forensic expert has the ability to differentiate normal variants, developmental indicators (ossification centers), injuries not related to the forensically relevant event (antemortem fractures or cardiopulmonary resuscitation injuries), developmental anomalies, or taphonomic postmortem changes (Arthurs et al. 2015; Burke 2012; Christe et al. 2010). Moreover, imaging may show artefacts, which need to be recognized as such to avoid misdiagnosis (Barrett & Keat 2004).

Because of the diagnostic pitfalls related to imaging, including perception errors and cognitive bias, inter-disciplinary collaboration is recommended for a comprehensive appraisal of traumatic injuries to the bone (Aalders et al. 2017; Blau et al. 2018; Nakhaeizadeh et al. 2014; Pescarini & Inches 2006). Nakhaeizadeh et al. (2014) also noted that when assessing cognitive bias in trauma analysis the professional experience of the assessors needs to be considered.

Forensic imaging modalities for skeletal trauma detection

In cases of skeletal trauma analysis, imaging techniques can capture bones either within whole bodies or body parts covered with soft tissue (fresh or decomposing) or as skeletonized remains (i.e., fully exposed skeletal tissue). In the case of skeletonized remains, both reflective (surface scanning) and transmissive imaging modalities can be applied, but when soft tissues are still preserved, only trasmissive imaging modalities can depict the osseous tissues (unless skeletal tissue is exposed due to injury, or maceration).

Reflective imaging approaches are based on the reflection of a light source onto the surface of the bone and subsequent recording of the reflection in the form of digital data. Transmissive imaging allows to capture internal structures of objects (including human cadavers and bones) by passing through the object and recording volumetric data. Skeletal injuries can be captured directly if it can be assumed that the damaged osseous tissue has retained its original or close to original spatial alignment, or the injury may be reconstructed by digitally aligning the scanned bone fragments into anatomical position before interpreting the traumatic event.

In principle, data derived from CT or MRI can be used to reconstruct the external surface of bodies or skeletal elements, however, they lack the resolution for examination of small surface changes and also colour information (Ebert et al. 2016). Recently, the concept of multimodal imaging has been introduced, which encompasses the joint use of transmissive and reflective imaging techniques or the combination of imaging modalities with other techniques, including macroscopic, microscopic or molecular approaches (Aalders et al. 2017; Carew & Errickson 2019). The concurrent use of transmissive and reflective imaging may help capture, and subsequently visualize by 3D modeling both the internal and the external characteristics of the body or skeletal element true to scale, texture and colour (Aalders et al. 2017; Campana et al. 2016; Ebert et al. 2016; Villa et al. 2018).

The performance and thus the applicability of imaging methods is typically assessed by comparison, to each other (for example CT versus MRI, or passive versus active surface scanning), to conventional autopsy in case of trasmissive imaging modalities, or to 2D photography in case of 3D surface scanning. Table 1 summarizes the advantages and limitations of the various imaging approaches specifically for the forensic analysis and interpretation of perimortem skeletal trauma.

Transmissive imaging modalities

A major benefit of transmissive postmortem imaging for the detection and interpretation of bone trauma is the documentation of fracture patterns in their original context. In contrast, conventional autopsy results in the separation of bone fragments, which may be difficult to reconstruct (Burke 2012; Thali et al. 2009). Although forensic anthropologists and pathologists usually prefer to inspect the actual bone specimen, the added benefit of the images showing the trauma “in situ” (in relation to soft tissues, when present) in fresh and decomposing bodies is undeniable. In addition to the methodology being minimally invasive and nondestructive (concerning the cadaver itself as well as other forensic evidence), images can be archived for extended periods of time and with the appropriate ethical permission, shared with other parties (Thali et al. 2009). Consequently, the findings can be subject to time-, place-, and observer-independent review, facilitating quality management required in forensic practice. In case of whole-body imaging, there is the possibility of assessing body areas in detail, which have not been the focus of the initial examination as new evidence emerges in the investigation (Burke 2012). Another advantage of postmortem examinations involving the use of imaging is that in certain situations, such as in fetal and pediatric deaths or if religious doctrines would be breached by conventional autopsy, imaging procedures are more likely to be accepted by relatives as investigative tools (Berkovitz et al. 2013; Franklin et al. 2016; Gorincour et al., 2015; Sieswerda-Hoogendoorn & van Rijn 2010).

Conventional radiography

The use of conventional (plain film) X-ray imaging is a well-established practice in forensic medicine. For instance, Brodgon et al. (2003) specifically illustrated by case studies how conventional radiography can be used in forensic postmortem evaluation of injuries and in personal identification.

The main limitation of conventional radiography is that subtle bone injuries may be missed, especially in complex anatomical areas, such as the skull, the spine, or the pelvis, mainly due to the superimposition of structures (Burke 2012). Notably, skeletal surveys based on conventional radiography are still the recommended method for the assessment of skeletal trauma in children, especially when non-accidental injuries are suspected (Arthurs et al. 2017; Love et al. 2011; Shelmerdine et al. 2018; van Rijn 2009; van Rijn & Sieswerda-Hoogendoorn 2012). In comparison to computed tomography the radiation dose is lower, and the chances of obtaining previous radiographs, which may provide comparative or additional information are higher.

Computed tomography (CT)

Computed tomography has gained increasing importance in forensic practice as a quick, reproducible, and minimally invasive imaging method for postmortem assessments (Burke 2012; Grabherr et al. 2017; Leth 2009). Micro-CT may be used for fracture analysis (for individual bone specimens) when fine detail or histological structures of the bone injury need to be examined (Franklin et al. 2016; Norman et al. 2018a, b; Rutty et al. 2013; Thali et al. 2003b). Baier et al. (2017) presented a case of dismemberment, where micro-CT was used for different aspects of the investigation, including for virtual alignment of severed skeletal elements, tool mark analysis, and dissection of a charred piece of bone.

The advantage of postmortem CT in comparison with conventional radiography is the improved contrast resolution and the lack of superimposition of structures on the multiplanar CT images, although the spatial resolution is higher in conventional radiographs (Burke 2012). CT offers the possibility to either examine orthogonal views (as is the norm for conventional radiography), three-dimensional reconstructions or both. When whole-body postmortem CT (PMCT) is performed the examination of the images may be targeted to certain areas or a systematic assessment may be undertaken for each skeletal element in cases with an unclear mechanism of injury. The routine application of PMCT has been facilitated by the technological developments in computer sciences, when large digital files, including multiplanar images, and 3D reconstructions can be stored, catalogued in databases, and exchanged among practitioners (Thali et al. 2009).

The agreement between the findings of the conventional autopsy and PMCT regarding the presence of skeletal trauma, and the sensitivity and specificity of PMCT seem to increase with time (depending on body region), since the experience with the interpretation of the multiplanar images is increasing, the image quality as such is improving, as is the 2D/3D visualization of the findings (Jalalzadeh et al. 2015; Scholing et al. 2009). In general, PMCT precisely depicts the skeleton and accurately detects skeletal trauma (Jalalzadeh et al. 2015; Scholing et al. 2009). One exception may be the use of PMCT on severely decomposed cadavers due to the presence of putrefactive gases (Glemser et al. 2017; Levy et al. 2010). The presence of gas can simulate a fracture, especially in thin bones like the hyoid or the laryngeal bones. Since a fracture of these skeletal elements can be interpreted as being caused by strangulation, a diagnostic error would be of particular consequence.

The major benefit of CT imaging for trauma interpretation is the documentation of the fracture patterns in their original context, especially in cases of multiple or comminuted fractures of complex skeletal elements, such as the skull (Jalazadeh et al. 2015). Small bones, such as the hyoid can be visualized in detail, which facilitates the interpretation of injuries to these bones in comparison to normal variation (Kempter et al. 2009). In addition, the surface of the endocranium can be assessed without destroying the fracture pattern, which would not be possible during autopsy (Fleming-Farrell et al. 2013).

Even in the assessment of perinatal and neonatal deaths PMCT was found to give excellent detail of bony structures, which may be essential for the interpretation of developmental anomalies, as well as accidental or non-accidental injuries (Arthurs et al. 2016; Arthurs et al. 2017). There is also the additional advantage of the possibility of 3D reconstruction of the whole body or the injured bones (Schievano et al. 2010). Whole-body imaging using micro-CT seems also promising for fetal remains (Lombardi et al. 2014).

The most common application for forensic PMCT related to the evaluation of the skeletal system are cases of blunt force trauma, mostly resulting from motor vehicle accidents, falls, and violent deaths (Burke 2012; Jalazadeh et al. 2015) . Other applications include sharp force trauma, detection of foreign bodies, matching of objects with the injury, examination of charred bodies (differentiating between thermally-induced and traumatic changes to the bone), and personal identification (Bolliger et al. 2008; Brough et al. 2014; Cittadini et al. 2010; de Angelis et al. 2016; de Bakker et al. 2013; Deduit et al. 2014; Levy et al. 2009; Schnider et al. 2009; Thali et al. 2002).

A study investigating the sensitivity of PMCT compared to conventional autopsy in accidental blunt force trauma deaths showed that by assessing PMCT images more skeletal lesions were detected than during autopsy (Daly et al. 2013). This finding may partly be due to the fact that accidental blunt force trauma due to motor vehicle accidents or falls from height is often associated with multiple or comminuted fractures of the skull (including facial bones), the spine, the pelvis, and the thorax, which are difficult to assess in their complexity during autopsy (Aghayev et al. 2008; Casali et al. 2014; Daly et al. 2013; Leth et al. 2013; Makhlouf et al. 2013; Petaros et al. 2013; Rowbotham et al. 2018a, b, c; Schulze et al. 2013; Sochor et al. 2008; Thali et al. 2005; Weilemann et al. 2008). Nevertheless, Jacobsen et al. (2009) showed that PMCT missed hairline fractures to the skull, and the detected fracture lines were shorter on the CT image compared to those detected during autopsy.

Computed tomography was reported to have greater sensitivity in the detection of acute rib fractures in children compared to conventional radiography (Hong et al. 2011; Wooton-Gorges et al. 2008). The authors mentioned that acute, un-displaced rib fractures may be missed on radiography mainly because callus formation facilitates the diagnosis of rib injury on plain radiographs. The assessment of rib fractures in infants and children is important, since broken ribs (particularly in different stages of healing) are highly indicative of child abuse (Kemp et al. 2008; van Rijn & Sieswerda-Hoogendoorn 2012). In addition, CT may facilitate the assessment of fracture healing, which may be essential for differentiating accidental from non-accidental trauma in children (Hong et al. 2011; Wooton-Gorges et al. 2008).

Several studies have emphasized the importance of PMCT in gunshot trauma, which can assist in identifying bullet entrance and exit wounds, the trajectory of the bullet, and the firing distance (Andenmatten et al. 2008; Levy et al. 2006; Makhlouf et al. 2013; Usui et al. 2016). Tartaglione et al. (2012) reported that PMCT performed equally or better than autopsy in the assessment of gunshot wounds to the head, and was superior to autopsy in locating bullet or bone fragments in the bullet path.

In forensic practice, the assessment of sharp force trauma relates primarily to the evaluation of wound appearance, in order to determine the type of object or weapon involved. Nevertheless, the stab wound tracks may be difficult to follow during autopsies, as it implies a progressive dissection of multiple layers of surrounding tissue. Therefore, PMCT is seen as a useful tool to simplify the process in addition to helping visualize the original incisions (Schnider et al. 2009). Kawasumi et al. (2012) showed that PMCT adequately detected tracks of stab wounds, their shape and angle of insertion, as well as intracorporal weapon parts. Schnider et al. (2009) found a high sensitivity for deep stab injuries but a very low sensitivity (less than 10%) for superficial injuries.

PMCT is not only useful to detect and analyze injuries to the bone but it may help detect foreign objects potentially related to these injuries (de Bakker et al. 2013; Woźniak et al. 2012). In a case from the Institute of Forensic Medicine in Zürich PMCT examination revealed important clues as to the weapon used in multiple sharp force injuries to the skeleton: A man was found in his apartment with multiple stab wounds to the thorax and defensive wounds to both hands. A possible murder weapon, a knife with a missing tip, was found on the suspect. PMCT revealed a foreign object in the proximal inter-phalangeal joint of the left fourth finger, which was extracted during the autopsy, and subsequently matched with the knife.

PMCT documentation of skeletal trauma offers the basis for 3D visualisation and reconstruction (Ebert et al. 2017; Kettner et al. 2011; Woźniak et al. 2012). The quality of the 3D reconstructions is influenced by the characteristics of the underlying CT data, such as slice thickness and resolution, as well as by the segmentation and protocols used for post-processing of the data (Carew et al. 2018; Flach et al. 2014; Ford & Decker 2016; Guyomarc'h et al. 2012). In general, there is a difference between PMCT and clinical CT as the source of information for the reconstructions (Ebert et al. 2011; Grassberger et al. 2011). Since the whole cadaver is documented during PMCT, the whole skeleton may be reconstructed if necessary. Accurate 3D models can be achieved with slice thickness of less than 1 mm (Ford & Decker 2016). In comparison, clinical CT scans are in most cases limited to the area of interest, i.e. the fracture. The slice thickness of clinical CT scans depends on the requirements for the examination of the injury, which may not be sufficient to generate accurate 3D models (Woźniak et al. 2012). Furthermore, experience shows that in some contexts in clinical practice, the most common initial documentation of fractures is still by conventional radiography, therefore CT scans of the initial fracture may not be available. When CT is performed after a surgical procedure related to the fracture, artefacts caused by medical devices may reduce the quality of the 3D model. Apart from trauma analysis, PMCT is increasingly used for personal identification of decomposing and decomposed bodies by comparing antemortem imaging and the CT scans. This method is considered to be less cost-intensive and quicker than using DNA comparisons, and therefore is highly appreciated by investigative authorities (Deduit et al. 2014; Hatch et al. 2014).

Magnetic resonance imaging (MRI)

The use of MRI for the postmortem assessment of skeletal trauma is limited. Ross et al. (2012) reported an overall sensitivity of 68% for the detection of skeletal injuries with postmortem MRI. The sensitivity ranged from 100% for fractures of lower extremities to 40% for fractures of upper extremities. When postmortem MRI was tested against the findings of conventional autopsy in fetuses and children, more than 75% agreement in the assessment of cause of death was found (Thayyil et al. 2013). Perez-Rossello et al. (2010) found that when assessing fractures whole-body MRI had high specificity but low sensitivity, particularly for the detection of metaphyseal lesions (which are considered good indicators of child abuse) compared to skeletal surveys.

In general, the disadvantages of postmortem MRI in comparison to PMCT are insufficient bone detail, slower acquisition time, the high cost of the equipment, and consequently relatively restricted access to the machines, especially for postmortem examination (Aalders et al. 2017; Arthurs et al. 2017). In addition, the presence of metallic foreign objects with ferromagnetic properties can be dangerous for the personnel, and cause artefacts in the images (Grabherr et al. 2017). Ruder et al. (2013) therefore advised to perform a CT scan prior to postmortem MRI to identify ferromagnetic objects within the body bag or body. Notably, bullets are usually not ferromagnetic, and MRI can be helpful in depicting bullet tracks.

Other applications of postmortem MRI have been identified in relation to the evaluation of bone bruises, soft tissue lesions due to blunt force trauma and strangulation, child abuse, and dating of fractures (Baron et al. 2016; Berger et al. 2013; Grabherr et al. 2017; Perez-Rossello et al. 2010). As a non-ionising imaging technique, MRI can also be applied in the forensic assessment of the living, particularly in age estimation based on ossification changes (Dedouit et al. 2012; Neymayer et al. 2018).

Reflective imaging modalities: Three-dimensional surface scanning

In addition to transmissive imaging methods, 3D surface scanning of exposed skeletal elements captures directly spatial, pathological and taphonomic data related to the injury, while surface documentation of the whole cadaver (or body parts) may provide useful information about the relation of the skeletal injury to the soft tissues, which may be relevant for a comprehensive forensic assessment (Ebert et al. 2016; Errickson & Thompson 2017; Thali et al. 2005).

Although most studies using reflective imaging modalities in the forensic context have so far focused on the assessment of skin wounds and external injuries to the body, often matching patterned injuries with objects (Buck et al. 2013; Brüschweiler et al. 2003; Ebert et al. 2016; Sansoni et al. 2009; Shamata & Thompson 2018a), the techniques with their advantages and limitations may also be applied to exposed bone tissue as shown for archaeological remains (Erickson et al. 2017). Shamata and Thompson (2018a) summarized the advantages of 3D surface scanning for soft tissue injuries in comparison to 2D photography.

Reflective imaging modalities mentioned in more detail in this paper are photogrammetry as the passive approach, and structured light scanning, and laser surface scanning as active reflective imaging methods. Passive scanning consists of taking a series of photographs, thus depends on an external light source. Active surface scanners emit a form of light that is used to capture the surface of an object. The structured light surface scanning is based on the capturing of light patterns distorted by the shape of the scanned object, while laser surface scanners generate image data using a laser beam, which is projected onto the object's surface, and then reflected to a sensor by applying the principle of triangulation (Carew & Errickson 2019; Edwards & Rogers 2018).

Photogrammetry is based on the acquisition of multiple images of an object taken from different angles, either by a single camera or multiple cameras (Carew & Errickson 2019; Villa et al. 2018). Single-camera photogrammetry includes a specific software, which automatically detects, aligns and fuses image data to create 3D models, and so does not necessarily need reference markers to be placed on the object as is the case for multiple-camera photogrammetry. The alignment and fusion of images is a crucial step in surface scanning, especially in photogrammetry, when manual alignmet may be required. The process depends on the skills of the operator, therefore may include a subjective aspect (Errickson et al. 2017; Sansoni et al. 2009). Another disadvantage of photogrammetry compared to the other surface scanning methods is that the models need to be scaled after scanning.

In comparison to transmissive imaging, the advantages of reflective imaging are shorter acquisition time, lower cost, and higher resolution of the surface models (Carew & Errickson 2019; Ebert et al. 2016; Edwards & Rogers 2018; Erickson et al. 2014; Villa et al. 2018). On the other hand, an intrinsic limitation of the reflective imaging modalities is that only the visible parts of the object can be recorded so the object needs to be repositioned, often multiple times, to achieve a complete scan. This may be particularly necessary for skeletal elements of irregular morphology, such as the skull or the pelvic bones (Ebert et al. 2016, Errickson et al. 2014).

Additionally, although the operation of the acquisition equipment is relatively simple, data processing is complex and requires advanced training. Several authors identified high computational power required for data processing as a major restriction for the routine use of 3D surface scanning, especially when high-quality models are needed (Decker & Ford 2017; Edwards & Rogers 2018; Errickson et al. 2017; Shamata & Thompson 2018a; Urbanová et al. 2015). In addition, the alignment of images may be disturbed due to artefacts in the form of superfluous (especially in high-quality laser scanning) or missing data (often in structured light scanning or photogrammetry), which can increasingly occur when scanning thin bones, fine bony spiculae or thin sharp fracture margins, shiny (for example dental enamel or fatty bone), wet, dark, or translucent areas or concavities (Carew & Errickson 2019; Edwards & Rogers 2018; Wilson et al. 2017). Hairy areas may also cause artefacts in the models, especially when photogrammetry is used (Urbanová et al. 2015). Moreover, foramina or holes are often automatically filled during postprocessing of the data (Edwards & Rogers 2018; Wilson et al. 2017). These limitations of the reflective imaging are particularly problematic in forensic trauma analysis and interpretation.

Some methods or scanners perform better than others concerning certain characteristics, therefore the expert needs to be familiar with the various procedures to select the most suitable approach for the given case (Errickson et al. 2017; Wilson et al. 2017). For instance, Errickson et al. (2017) mentioned that the resolution of structured light scanners in standard mode is lower in comparison to laser scanners. However, laser scanners are not able to capture colour information of the objects.

Edwards & Rogers (2018) tested the accuracy of 3D models of cranial blunt force trauma (hinge, depressed, and comminuted) using different types of surface scanning, and subsequently evaluated different types of printers and print materials for creating 3D prints of the skeletal injuries. The quality of the digital models needed to be compared visually, since automatic comparison systems did not capture sufficient detail, particularly concerning texture, porosity, and fine lines (fractures). Considering that minor changes in the bone may be crucial for the interpretation of trauma, the visualization accuracy of both the digital and printed models is of utmost importance. The authors identified that several factors, including resolution, alignment, and fusion (stitching), influenced the quality of the digital models, and consequently the accuracy of the 3D prints. The effect of these factors depended on the acquisition method and the selected settings. For example, laser scanning produced more accurate models in the standard settings, while structured light scanning performed better at the customized high-quality level. For photogrammetry, customized settings allowing for higher resolution images produced more accurate models compared to standard settings.

In comparison to transmissive imaging modalities, reflective imaging modalities are still rarely used in medico-legal routine (Ebert et al. 2016; Urbanová et al. 2015). The reason for this discrepancy may be that the cost as well as the requirements for personnel, data storage and processing are comparably high, while the yield of the generated information has not yet been researched in sufficient detail.

Virtual and physical visualization of skeletal trauma

If the necessary equipment and infrastructure are present, the capturing and recording of digital imaging data using either transmissive or reflective means is mostly straightforward when compared to the next step consisting of data processing and the creation of 3D models, digital or physical. It needs to be kept in mind that for forensic purposes, each step in data processing needs to be well-documented and the forensic expert needs to be able to explain the individual steps in court (Bornik et al. 2018; Carew & Errickson 2019). There are several different approaches for (post-)processing and modeling of imaging data, which generally require appropriate training, high computational power, and time. Among others, the advances in software development specialized in radiological (CT) bone post-processing allow for partial automation of the assessment of skeletal injuries, for example through automatic labelling of ribs and vertebral bodies (Glemser et al. 2017). Additional applications enable the unfolding of complex skeletal regions, such as the skull or the ribcage (Bier et al. 2015; Glemser et al. 2017; Khung et al. 2017; Ringl et al. 2010; Ringl et al. 2015). The visualization algorithms virtually unfold and stretch naturally curved anatomical structures into single-plane reconstructions (Bier et al. 2015; Ringl et al. 2015).

A thorough assessment of rib fractures is important as they are the most common injuries caused by blunt thoracic trauma and are often indicative of severe thoracic and abdominal soft tissue injuries (Kessel et al. 2014; Khung et al. 2017; Livingston et al. 2008; Rostas et al. 2017). Although the currently used algorithms for visualization of the unfolded ribs speed up the time needed for the assessment, there are still some issues with the reconstructions, including labelling errors in rib number anomalies or single-cortex fractures (Bier et al. 2015; Khung et al. 2017; Ringl et al. 2015). Several publications reported that the reading of the unfolded images resulted in lower sensitivity and specificity compared to autopsy or the assessment of multiplanar CT images, which may partly be attributed to less experience with the new visualization technique (Bier et al. 2015; Glemser et al. 2017; Khung et al. 2017; Ringl et al. 2015). Notably, Bier et al. (2015) and Ringl et al. (2015) reported equal or increased sensitivity compared to multiplanar CT images, when the assessment was done by experienced radiologists.

An important benefit of the imaging technologies is the possibility to visualize the findings of skeletal trauma by using digital or physical (printed) 3D reconstructions (Baier et al. 2018; Bolliger et al. 2012; Carew et al. 2018; Ebert et al. 2011; Rengier et al. 2010). Although it is strongly recommended to perform the original analysis of skeletal trauma either on the actual bone specimens or using comprehensive CT-derived documentation, 3D reconstructions are helpful when presenting a case to persons in legal proceedings, who have limited knowledge of human anatomy and medicine (Baier et al. 2018; Blau et al. 2018; Edwards & Rogers 2018; Errickson et al. 2014). In particular, digital or physical 3D models of complex findings aid the explanation of the location, etiology and mechanism of the traumatic injury compared to often lengthy descriptions in relation to anatomical landmarks, and so they can serve as substitute for often visually disturbing photographs of the actual injuries (Blau et al. 2018; Ebert et al. 2011; Errickson et al. 2014; Woźniak et al. 2012). Blau et al. (2018) showed that the general public and legal community better understood verbally presented evidence concerning forensic medical evidence, including the description of injuries, when visual aids, in particular 3D prints, were used in the presentation. Using 3D prints of skeletal elements as demonstrative evidence may also prevent excessive handling of the original specimen (Carew et al. 2018; Errickson et al. 2014).

In case of PMCT data, three-dimensional visualisation is enabled through 3D volume rendering, which converts Digital Imaging and Communication in Medicine (DICOM) files (the 2D slices from CT) to 3D volumetric data (Ebert et al. 2017; Kettner et al. 2011). The volume data set delivering voxel information needs to be further processed to generate a 3D mesh in Surface Tesselation Language (Ebert et al. 2011; Ford & Decker 2016; Kettner et al. 2011). Software like Amira (FEI, Hillsboro, Oregon, USA), Materialise Mimics (Materialise GmbH, Gilching, Germany) or OsiriX (Pixmeo SARL, Geneva, Switzerland) offer the tools for the so-called segmentation (a manual or automatic procedure that removes unwanted structures from the image, so, for instance, only skeletal tissue is extracted for visualization; Bornik et al. 2018; Kettner et al. 2011). The segmentation provides a template for the computation of a polygon model. This model can be optimized by reducing the triangle count and using filters, for example to smooth the surface structure (Ebert et al. 2011). However, any changes need to be thoroughly documented, and the effect on the resulting model needs to be known. As Ebert et al. (2016) noted segmentation requires some background in anatomy and radiology, so in case of skeletal trauma, experts with knwoledge of normal as well as pathological bone tissue should be involved in this step.

Surface scan data are usually generated as point coulds, then converted to triangle meshes or polygon models by device-specific software. Some devices can combine the precision of laser scanning with photogrammetry, which captures texture data, but so far the quality of the models seems to be better when two specialized devices are used (Errickson et al. 2017). Three-dimensional polygon models provide the basis for 3D reconstructions and 3D printing.

Forensic 3D reconstructions may range from weapon-injury comparisons to elaborate shooting and accident reconstructions potentially including multiple sources of evidence (Buck et al. 2007; Buck et al. 2013; Raneri 2018; Woźniak et al. 2012). Reconstructing the location and form of fractures in 3D can give clues as to the direction of impact and the sequence of injuries (Usui et al. 2016; Wozniak et al. 2012). In motor vehicle accidents, such reconstructions can be used to illustrate the point(s) of contact between the vehicle and the injured person, and the subsequent movements of the injured person, for instance, helping to differentiate between an impact with the vehicle or to the ground (Buck et al. 2007; Burke 2012).

In ballistic trauma, scattered osseous fragments along the bullet trajectory can be visualized in CT, and thus provide indication regarding the bullet trajectory (Tartaglioni et al. 2012; Usui et al. 2016). This is especially important if entrance and exit wounds cannot be clearly identified (Jeffery et al. 2008). By reconstructing the angle and the position of the trajectory within the body and using other evidence, such as gunshot residues, conclusions about the respective position and the distance between the perpetrator and the victim, about potential defensive actions of the victim or the relationships between objects on the scene and the persons involved can be made (Buck et al. 2013; Colard et al. 2013).

Three-dimensional modelling also allows for an object to be matched with the form and size of the 3D reconstructed fracture. If a potential weapon is found, this can be documented in 3D, for example by using a surface scanner or CT. By using an appropriate software such as 3dsMax (Autodesk Inc., San Rafael, California, USA), Maya (Autodesk Inc., San Rafael, California, USA) or Blender (Stichting Blender Foundation, Amsterdam, the Netherlands), the resulting 3D model of the object can be compared with the 3D model of the skeletal injury (de Bakker et al. 2013; Norman et al. 2018a; Woźniak et al. 2012).

The physical form of visualization based on 3D polygon models is 3D printing (otherwise known as additive manufacturing or rapid prototyping). There are different 3D printing techniques utilizing different materials and printer types. Consequently, the costs as well as the time needed for producing a replica of a skeletal element vary greatly (Carew & Errickson 2019; Carew et al. 2018). However, the accuracy of 3D prints was not found to be dependent on printer resolution, when this was greater than scan resolution (Carew et al. 2018; Edwards & Rogers 2018). Carew et al. (2018) showed that 3D prints based on CT-derived digital 3D reconstructions may be produced with sufficient accuracy, although the accuracy varies between approaches depending on the scanning and modeling parameters.

Edwards & Rogers (2018) concluded that in 3D prints texture was difficult to reproduce due to the different properties of the print material, and fine details, including thin fracture lines and pores observed on the actual bone specimen were not reproduced at all. The authors emphasized that so far 3D prints may be sufficient for archival and teaching purposes but not for forensic examination.In general, the assembling of digital (or physical) imaging data into virtual collections and atlases of skeletal trauma with known biological information, mechanism and cause of death provides immense wealth of information for training purposes (Blau et al. 2018; Franklin et al. 2014; Kimmerle & Baraybar 2008; Lottering et al. 2014; Thali et al. 2009). CT-derived imaging data and 3D reconstructions of skeletal elements have been shown to provide comparable detail to real bones so reliable metric and morphological analyses can be performed on virtual specimens (Colman et al. 2017; Franklin et al. 2013; Lorkiewicz-Muszynska et al. 2015; Villa et al. 2016). The same cannot be said for 3D prints yet, although for metric assessments the difference between the real bones or skeletal injuries was found to be less than 2 mm (Edwards & Rogers 2018).

Despite the advances in 3D imaging, most of the 3D data (except for 3D prints) concerning trauma analysis are still presented on two-dimensional screens. This type of visualization limits the actual advantages of providing information in 3D, therefore visualizations using virtual reality would be more appropriate (Carew & Errickson 2019; Koller et al. 2019). Virtual animations capture, for instance, the effects of a particular force in the skeletal element, which allows for better understanding of the temporal component of injury. For example, showing a moving 3D skeleton while bullets are penetrating the body (Villa et al. 2017). In these depictions, it is also possible to combine 2D photographs of injuries and objects with virtually created 3D human figures potentially based on the information from postmortem multimodal imaging (Aalders et al. 2017; Bornik et al. 2018; Buck et al. 2013). However, Koller et al. (2019) found that so far the resolution of the texture of 3D models of injuries was lower when shown in virtual reality that using the imaging software of the scanners.

Future perspective

Currently, the use of the various imaging modalities for skeletal trauma analysis in forensic cases largely depends on the local practice, access to the appropriate equipment, and availability of experienced professionals with the necessary expertise (Arthurs et al. 2016; Burke 2012; Thali et al. 2003a). The fast-paced development in imaging technologies requires a steep learning curve, and the cost of some approaches may still constitute a barrier for including some imaging modalities to be included in routine medico-legal examinations (Arthurs et al. 2016; Burke 2012). In general, the cost-effectiveness and availability of a certain type of acquisition equipment may play a role in method selection, despite the fact that for forensic purposes the suitability, validity, and accuracy of a method should be the key factors in decision-making.

Although the use of transmissive and reflective imaging methods has become routine in some forensic institutes (Burke 2012; Ebert et al. 2016; Villa et al. 2018), for many the access to imaging for postmortem examinations and forensic analysis largely depends on the cooperation with clinical (for transmissive imaging) or archaeological institutions (for surface scanning). Moreover, in forensic cases maintaining the integrity of the chain of evidence, and adhering to inter-departmental agreements and terms of use may pose limitations to imaging data acquisition and storage. Depending on the country, centres of excellence in strategic locations may provide a solution for forensic imaging services. Among others, such centres would facilitate the close cooperation among various experts, such as engineers, computer scientists, forensic pathologists, anthropologists, and radiologists in research and casework.

A major challenge for the future is to find optimal solutions incorporating the current limitations in computational capacity versus the requirements for the accuracy of 3D data and models in forensic trauma analysis. In addition, the error rates of the models developed using different imaging techniques and software solutions need to be studied in more detail. For data presentation, Bornik et al. (2018) suggested that developing software tools specifically for forensic analysis of imaging data would allow for joint visualization of data derived from transmissive and reflective scanning, and for the assessment of spatial relationships between injuries.

The documentation and storage solutions for all stages of the data acquisition and processing, including case information, metadata, raw data, potentially certain type of processed data (e.g., meshes), and the final outputs, including 3D models or prints need to be guaranteed for the forensic cases. For instance, the different parties involved in the forensic investigation and legal proceeedings need to have the capacity to view and to store the often large data produced in the modeling process. In addition, the security of the data needs to be warranted throughout the user chain (Niven & Richards 2017). Considerations and recommendations regarding the storage and management of large 3D image data can be found for example in Decker & Ford (2017) or Niven & Richards (2017).

There are currently numerous options to capture, process and present imaging data, of which not all are equally well tested and validated. It may be challenging to determine, which equipment and methodology best suits the given case (Errickson et al. 2017). A few studies have started to emerge, which tested some of the approaches for forensic trauma analysis (Buck et al. 2013; Ebert et al. 2016; Urbanová et al. 2015; Villa et al. 2018). In this context, purely experimental studies may provide different results to studies testing the methodology on routine forensic cases. Only a handful of studies have so far discussed the practical workflow of scanning injuries in forensic settings with varying recommendations (Ebert et al. 2016; Shamata & Thompson 2018b; Villa et al. 2018). For instance, more research is needed regarding the accuracy of 3D models when bone fragments are aligned into anatomical position using solely digital solutions or whether multimodal imaging allows for sufficient accuracy when attempting to link skeletal and soft tissue injuries, considering possible artefacts due to tissue movements (Bornik et al. 2018; Errickson et al. 2017; Villa et al. 2018).

In general, the application of the different imaging modalities in medico-legal examinations requires the establishment of standards, guidelines, and protocols concerning, among others, method selection, technical procedures, data storage and amanagement, diagnostic procedures, and presentation of findings (Carew & Errickson 2019; Ebert et al. 2016; Errickson et al. 2014). Although some best practice manuals for imaging modalities and their outputs do exist for other disciplines, such as archaeology or medicine, these need to be adapted for forensic practice (Decker & Ford 2017; Errickson et al. 2017; Niven & Richards 2017). Among others, it needs to be clarified what technical information needs to be included in scientific publications, and in case reports for the court. While 3D models are presented as a helpful tool for presenting complex anatomical and medical information, the complexity underlying their existence is often not well understood (Errickson et al. 2014).

Overall, the selection of the optimal approach for image data aquisition and modeling is largely case-driven (Carew & Errickson 2019; Edwards & Rogers 2018; Wilson et al. 2017). For example, Edwards and Rogers (2018) showed that using high-quality settings for scanning may not be necessarily better than standard-quality, depending on the surface scanning method used. Therefore, forensic experts in skeletal trauma assessment need to acquire good understanding of the technical elements of data acquisition for the various imaging modalities and of the subsequent 3D modeling so they can make informed choices regarding the use of the various approaches, and subsequently expertly report on the individual steps to the legal community (Bornik et al. 2018; Errickson et al. 2017).

The use of novel techniques in the forensic assessment and presentation of skeletal trauma as evidence in the court of law has brought along ethical considerations regarding the depiction of human skeletal remains as two-dimensional images or 3D reconstructions, especially 3D-printed specimens. The emerging literature on ethics in forensic anthropology may assist in these questions (Márquez-Grant & Errickson 2017; Passalaqua & Pilloud 2018). Questions regarding the secure and ethically appropriate storage and management of digital image data related to human remains handled in forensic cases, as well as regarding the access to, sharing, publication, or use of such data for training and education purposes need to be answered within national and international legal systems.

It is still unclear in which cases 3D reconstructions of skeletal injuries, digital or physical are admissible in court as demonstrative aids or evidence, although for instance 3D printed models of skeletal injuries have already been used as demonstrative evidence in court (Errickson et al. 2014; Kettner et al. 2011). In addition, there is limited literature on how 3D models, 3D prints, and particularly virtual reality demonstrations are perceived and understood by the various participants in legal proceedings, how the presentation of 3D reconstructions affects the decision-making, and to what extent can these be prejudicial (Aalders et al. 2017; Baier et al. 2018; Blau et al. 2018; Errickson et al. 2014; Young 2014).

Conclusion

Various imaging modalities, including conventional radiography, computed tomography, magnetic resonance, and surface scanning have been applied in the examination of skeletal injuries in the forensic context. Although still not a substitute for a full medico-legal autopsy or the examination of skeletal remains, imaging is now increasingly used as a complementary tool in the postmortem analysis of perimortem skeletal trauma. Facilitated by the progress in general computational capacity, combined use of transmissive and reflective imaging modalities has been proposed for comprehensive forensic documentation and visualization of skeletal injuries in their complexity. A major advantage of these approaches is that stored digital imaging data and 3D models or physical 3D prints of skeletal injuries can be reviewed at any time by various experts as well as be presented in court as evidence to clarify potentially complex medical and forensic aspects of the case. In addition, the establishment of virtual collections and atlases of normal and abnormal skeletal findings on postmortem (as opposed to antemortem) imaging facilitates forensic interpretation of trauma, considering the broad spectrum of confounding variables (such as, biological profile of the injured person, or the circumstances of the injury).

Due to constant technical progress in imaging techniques and software, continuous education, training, and sharing of expertise among engineers, computer scientists, and forensic experts, including forensic pathologists, anthropologists, and radiologists needs to be warranted to maintain high-quality expertise in the detection and interpretation of traumatic injuries on postmortem imaging. The technical developments and ever-improving user-friendliness of 3D imaging and modeling techniques present an atttactive alternative to traditional forensic approaches, but as long as the techniques have not been sufficiently tested and validated for forensic trauma analysis, and best practice manuals for forensic practice are lacking for both the technical procedures and method selection, the use of imaging techniques needs to be reevaluated on a case-by-case basis. In addition, ethical, legal, and financial aspects of the use of imaging and 3D modeling for forensic purposes need to be well understood by all parties in legal proceedings.'

CreditAuthorStatement

Zuzana Obertová: study conception and design; drafting and revising the article; approval of the final version; agreement to be accountable for all aspects of the work related to the accuracy or integrity of any part of the work

Anja Leipner: acquisition of data; drafting and revising the article; approval of the final version; agreement to be accountable for all aspects of the work related to the accuracy or integrity of any part of the work

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Table 1. The advantages and limitations of the various imaging approaches specifically for the forensic analysis and interpretation of perimortem skeletal trauma.

	Imaging modality	Advantages	Limitations	Examples of (overview) literature
Skeletal tissue covered by soft tissue (fresh, decomposing), and exposed skeletal tissue/ skeletonized remains	Transmissive			
	X-ray	– easily accessible – extensive experience with interpretation – good source of comparative material – better spatial resolution than CT	– 2D, overlap of structures – lower contrast resolution than CT – no whole body view (except for babygram) – may miss subtle changes	Brogdon et al. 2003; Love et al. 2011
	CT	– 3D (complex osseous structures can be viewed) – whole body view (systematic assessment possible) – excellent sensitivity and specificity in detection of skeletal trauma (even subtle fractures in children) – observation of trauma patterns in original context – micro-CT captures fine detail of small-size specimens	– putrefactive gases simulate fractures – fracture lines are shorter than in autopsy – clinical CT may not provide sufficient data for 3D recontructions – surface details of low resolution and no colour information – high maintenance (including big data management) and personnel costs/requirements – metallic objects cause artefacts	Burke 2012; Thali et al. 2009
	MRI	– 3D – depicts approximate association of soft tissue and bone injuries (e.g., bullet paths)	– insufficient bone detail – slow acquisition time – more expensive than CT – safety concerns (ferromagnetic objects)	Ross et al. 2012
Exposed skeletal tissue/ skeletonized remains	Reflective			
	Photogrammetry	– inexpensive – easy to operate (but postprocessing more demanding than in other surface scanning methods) – high resolution but not in standard mode – objects of various sizes – captures colour information	– depends on ambient light – automatic setting insufficient, manual alignment of scans subjective – affected by surface features = prone to artefacts due to missing data – models need to be scaled – more than standard computational power needed	Carew & Errickson 2019; Edwards & Rogers 2018
	Structured light scanning	– high-quality models more visually representative than models based on photogrammetry or laser scanning (but standard models not good quality) – captures colour information	– not suitable for large objects – affected by surface features = prone to artefacts due to missing data – expensive – more than standard computational power needed – rarely available in medical (medico-legal) facilities	Carew & Errickson 2019; Edwards & Rogers 2018; Errickson & Thompson 2017
	Laser surface scanning	– performs well using standard settings (less computational power needed) – not as prone to artefacts due to surface features – does not depend on ambient light – high resolution	– not suitable for large objects – does not capture colour information – prone to artefacts due to superfluous data – expensive – rarely available in medical (medico-legal) facilities	Carew & Errickson 2019; Edwards & Rogers 2018