SENSITIVITIES OF VARIOUS IMAGING MODALITIES IN DETECTING SKELETAL TRAUMA IN SIMULATED VIOLENT CRIME AND PHYSICAL CHILD ABUSE: A PIG MODEL

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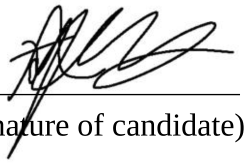
Declaration

I, Amy Joy Spies, declare that this Thesis is my own, unaided work. It is being submitted for the degree of Doctor of Philosophy at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

The results of this study include published work(s). The level of contribution by the student to the research and writing of the published work(s) and the input by the co-authors is indicated in Appendix 8.2: Declaration: Student's contribution to article(s) and agreement of co-author(s).



(Signature of candidate)

2nd day of August 2021 in Johannesburg

To my Mama, Cindy Spies, for always being my biggest cheerleader. This is as much your victory as it is mine.

This thesis is also dedicated in loving memory of my sweet Granny, Joyce Lilian Sclanders, who was the epitome of dignity and grace.

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Abstract

Radiology is frequently used to detect skeletal blunt (BFT) and sharp force trauma (SFT). Forensic anthropologists may therefore be required to interpret radiological images when evaluating skeletons for trauma. Computed tomography (CT) and conventional X-ray scans have traditionally been used but more recently, low-dose full-body X-rays, or Lodox scans, are being increasingly utilized in medico-legal institutions, particularly in South Africa. The sensitivity of this modality to detect trauma must be compared to more traditional methods. Moreover, the trauma detection abilities of the specialists performing these virtual assessments must be established.

Fracture detection rates of a novice forensic anthropologist (NFA) with some radiological training, and two experienced forensic anthropologists (EFA) with no radiological experience, were compared against a radiologist. CT, X-ray and Lodox scans of five piglet carcasses with BFT were assessed. Fracture detection rates between the NFA and radiologist were comparable and were on average 22.0% higher than the EFA. Even brief radiological training substantially improves an observer’s trauma detection ability using radiological means. It is recommended that forensic anthropologists required to perform virtual trauma assessments receive some radiological training.

The second aim was to compare the abilities of CT, X-ray and Lodox for detecting skeletal BFT and SFT. Piglet (5-15 kg) and adult-sized pig (47-82 kg) carcasses were used as proxies for human children and adults. To determine the sensitivity of each method, the defleshed skeletons were the gold standard. Ten piglets and ten adult-sized pigs were subjected to BFT, and ten separate adult-sized pigs were subjected to SFT. CT had the highest sensitivity for both types of trauma in both pig samples. It is therefore suggested that during post-mortem investigations of skeletal trauma, CT be the preferred radiological method. X-rays may be an alternative when imaging children with suspected BFT, while Lodox may be an alternative for BFT and SFT in adults.

Results showed that broadly determining the class of sharp weapon used, namely a kitchen knife and a panga, was possible radiologically by interpreting the macroscopic characteristics of the associated SFT.

This study added valuable new information on the ability of various imaging modalities to detect trauma.

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Chapter 1: Introduction

1.1. Background

Radiological imaging is frequently employed in both clinical and forensic settings and is crucial for the management of patient treatment and post-mortem death investigations (Whiley *et al.,* 2013; Franklin *et al.,* 2016; Garvin & Stock, 2016; Obertová *et al.,* 2019). One of the most critical uses of radiological imaging in these contexts is the assessment of skeletal trauma which is common in victims of violent crime, torture and physical child abuse (Bilo *et al.,* 2010; İşcan & Steyn, 2013; Franklin *et al.,* 2016; Garvin & Stock, 2016), and also occurs as a result of accidents and mass disasters (Narayanan *et al.,* 2018; Rowbotham *et al.,* 2019; Buschmann *et al.,* 2020). The accurate and rapid detection and analysis of skeletal trauma is essential for the proper clinical and forensic investigation of these cases.

According to Statistics South Africa (2019), 51 164 (11.5%) of the recorded 446 544 deaths that occurred in 2017 in South Africa were classified as non-natural, which include deaths related to causes such as violence or accidents. Accidental injuries accounted for most of these non-natural deaths (78.6%), while assault was the second most common cause (15.0%). Approximately 45.0 – 56.0% of all non-natural deaths in South Africa are the result of homicide (Otieno *et al.,* 2015; Meel, 2017).

According to the Inquest Act of South Africa (No. 58 of 1959), individuals whose deaths are classified as non-natural must undergo an autopsy as part of the post-mortem investigation. During an autopsy, the detection of skeletal trauma is critical in order to determine the cause and manner of death, and potentially distinguish between accidental and non-accidental trauma (Garvin & Stock, 2016; Love & Wiersema, 2016; Obertová *et al.,* 2019). However, this trauma is often very difficult to detect during traditional autopsies, particularly when the trauma was sustained peri-mortem (Cattaneo *et al.,* 2006; Cappella & Cattaneo, 2019), or when the remains are decomposed or charred (Dedouit *et al.,* 2007; Coty *et al.,* 2018). While remains may be macerated so that a forensic anthropological examination of skeletal trauma can be performed, this is an invasive, time-consuming, and labour-intensive process (Cattaneo *et al.,* 2006; Brough *et al.,* 2012; King & Birch, 2015). However, in surviving victims of violent crimes or accidental incidents, dissection and maceration of bodies to detect osteological trauma is not possible.

As a result, radiological imaging is frequently employed during clinical, forensic pathological and forensic anthropological examinations, and knowledge of the abilities of these methods to accurately detect skeletal trauma is of utmost importance. However, little information is available about how these modalities perform when compared against osteological assessments as the gold standard, particularly using low-dose full-body X-ray (Lodox) scans, which are commonly used in South African institutions. In addition, there is a paucity of research investigating the ability of radiological methods to specifically detect and interpret sharp force trauma to the skeleton, which is among the most common types of trauma seen in individuals in South African hospitals and medico-legal laboratories (Cocks & Saayman, 2013; Nicol *et al.,* 2014; Saimen *et al.,* 2016).

As the field of forensic anthropology is becoming more virtual in its approach and practice, these specialists are frequently required to perform radiological examinations of skeletal trauma. However, forensic anthropologists typically have little to no radiological training and experience (Franklin *et al.,* 2016), and their ability to accurately detect osteological trauma using radiographic material is not currently known.

1.2. Aims and objectives

The aim of this study is to compare the abilities of CT, X-ray and Lodox scans to detect blunt and sharp force skeletal trauma in simulated cases of physical child abuse and violent crime using a pig model, using the dry bones as the gold standard. In addition, the ability of forensic anthropologists to accurately identify this trauma will be assessed.

The objectives of this study are as follows:

1. To determine the ability of both novice and more experienced forensic anthropologists, in comparison to a clinical radiologist, to accurately detect the number and location of fractures using CT, X-ray and Lodox scans.
2. To determine the abilities of CT, X-ray and Lodox scans to detect the number, type, and location of fractures, as well as the directionality of trauma and minimum number of impacts, in piglets that have been subjected to blunt force trauma in order to simulate physical child abuse.
3. To determine the abilities of CT, X-ray and Lodox scans to detect the number and location of fractures, as well as the minimum number of impacts, in adult-sized pigs that have been subjected to blunt force trauma in order to simulate violent crime.
4. To determine the abilities of CT, X-ray and Lodox scans to detect the number, type and location of sharp force defects, as well as the minimum number of impacts, in adult-sized pigs that have been subjected to sharp force trauma in order to simulate violent crime.

5. To formulate recommendations regarding which diagnostic imaging tools should be used in order to accurately investigate suspected cases of physical child abuse and violent crime.

This thesis is presented in the "divided block" format which is recognized and accepted by the Faculty of Health Sciences at the University of the Witwatersrand according to the Faculty's "Style Guide for Theses, Dissertations and Research Reports" (https://www.wits.ac.za/media/wits-university/faculties-and-schools/health-sciences/research-entities/documents/FACULTY%20OF%20HEALTH%20SCIENCES%20STYLE%20GUIDE%20FOR%20THESES-DISSERTATIONS-AND-RESEARCH%20REPORTS-Updated%20Marh%202016.pdf). Chapter 2 of this thesis includes a review of previous research conducted and highlights some potential limitations of this research. Chapter 3 comprises an overview of the materials and methods used in this study, and Chapter 4 includes the results of this study, which are presented as a series of published and/or submitted research papers that each addresses the objectives of this thesis. Included in each paper is its own introduction, materials and methods, results, discussion, and conclusion sections. Paper 1 addresses study objective 1, papers 2 and 3 address study objective 2, paper 4 addresses study objective 3, and paper 5 addresses study objective 4. Objective 5 of the study is addressed in all papers as well as in Chapter 5 (Discussion), which includes an overall discussion of all the results, as well as potential limitations of the study and recommendations for future research. This will be followed by Chapter 6 (Conclusion), which will provide an overall conclusion of the study.

Chapter 2: Literature review

The use of virtual imaging to aid in clinical, forensic pathological and forensic anthropological examinations has become common practice (Dirnhofer *et al.,* 2006; Whiley *et al.,* 2013; Franklin *et al.,* 2016; Ali *et al.,* 2020; Ducray *et al.,* 2021). While radiological methods have a wide range of applications in both clinical and medico-legal settings, the detection of skeletal trauma is perhaps one of the most significant (Franklin *et al.,* 2016; Garvin & Stock, 2016; Obertová *et al.,* 2019). Understanding the uses and diagnostic abilities of these tools is paramount.

2.1. Radiological imaging

2.1.1. Brief history of radiological imaging

Since the discovery of X-rays in 1895 by Wilhelm Roentgen, radiological imaging has been used widely in medical and clinical contexts as a diagnostic tool (Franklin *et al.,* 2016). Not long after its initial discovery, X-rays, and later, computed tomography (CT), were applied to palaeoanthropological contexts, with the aim of non-invasively examining fossilized remains and the internal structure of hominid bones (Jungers & Minns, 1979; Franklin *et al.,* 2016). More recently, the applicability of radiological imaging to the forensic sciences has been realized (Dirnhofer *et al.,* 2006; Franklin *et al.,* 2016; Garvin & Stock, 2016; Obertová *et al.,* 2019). Virtual imaging in a medico-legal context was first used by Culbert & Law (1927), who compared ante- and post-mortem cranial radiographs in order to positively identify an individual by matching distinctive skeletal characteristics. Radiological imaging is now considered an invaluable tool during post-mortem investigations and is widely used by forensic pathology, odontology and anthropology specialists (Franklin *et al.,* 2016; Garvin & Stock, 2016; Obertová *et al.,* 2019).

2.1.2. Commonly used imaging modalities

Various radiological tools are available in hospitals, morgues and forensic anthropological laboratories and they have a wide range of applications depending on the context. It is therefore important that the advantages and limitations of each radiological method are understood so that the best imaging tool for each context is used.

2.1.2.1. X-rays

X-rays are a type of electromagnetic, ionizing radiation of short wavelength and high energy which can pass through the body, allowing the internal structures of the body to be visualized. An X-ray image is produced when X-rays generated by an X-ray tube pass through the body, are absorbed by the different tissues, and then pass into a radiation sensitive detector which produces a shadow of the internal body structure. Denser tissues such as bone absorb more radiation and are therefore less exposed on the X-ray image, appearing white, while soft tissues provide little resistance for X-rays, resulting in darker, more exposed images of these regions. X-ray scanners are among the most commonly used radiological methods for imaging in clinical and forensic settings as they are widely available, easily accessible and have low maintenance costs (Obertová *et al.,* 2019; Morillas *et al.,* 2020). However, this method is not without its limitations. X-rays often scatter and change directions, even when a collimator is used to narrow the direction of X-rays, and this can result in a distinct haze on the X-ray image, decreasing the image quality (Uffmann & Schaefer-Prokop, 2009). While scatter grids can be utilized to reduce the amount of scatter, their use results in a higher radiation acquisition dose (Uffmann & Schaefer-Prokop, 2009).

The resulting image is a superimposed, two-dimensional (2D) reconstruction of the internal body structures (Franklin *et al.,* 2016; Obertová *et al.,* 2019; Morillas *et al.,* 2020). Moreover, as only small regions of the body can be scanned at any given time, imaging of the entire body can be time-consuming and labour-intensive (Obertová *et al.,* 2019; Mamabolo *et al.,* 2020). Due to the need for multiple X-rays to be taken in order to generate a full-body image or to produce images of a single region at different angles, the radiation dose that both living patients and radiographers are exposed to is high (Mantokoudis *et al.,* 2013; Morillas *et al.,* 2020), as are the costs associated with the necessary protective equipment (Morillas *et al.,* 2020). While bone is quite well visualized in X-ray images due to its high density, soft tissues are more difficult to visualize, and the use of X-rays for imaging of soft tissues such as the brain is not viable (Morillas *et al.,* 2020).

2.1.2.2. Computed tomography (CT)

CT scanning makes use of a large number of multidirectional, 2D X-ray images in order to produce cross-sectional images or “slices” of the object being scanned (Franklin *et al.,* 2016). A wide X-ray fan beam and multiple rows of radiation sensitive detectors rotate in opposing directions around the object being scanned, resulting in multiple slices generated during a single rotation (Mazonakis & Damilakis, 2016). The benefits of CT scanning are that clearer, sharper, and higher resolution images are produced (Franklin *et al.,* 2016; Obertová *et al.,* 2019; Morillas *et al.,* 2020), and include both 2D and three-dimensional (3D) volume renderings of the human body (Franklin *et al.,* 2016; Mazonakis & Damilakis, 2016;

Obertová *et al.,* 2019). As a result of the capacity for 3D volume rendering, the challenges of superimposition of body structures encountered during conventional X-ray scanning is eliminated using CT (Franklin *et al.,* 2016; Obertová *et al.,* 2019). In addition, different "windows" can be used to visualize tissues of varying densities, making subtle differences in tissue density much easier to detect and, as a result, CT imaging is beneficial for the visualization of both osseous and soft tissues (Costelloe *et al.,* 2013; Garvin & Stock, 2016).

The rotation system of the CT scanner, and the fact that scans of the entire body are generated, drastically reduces the acquisition time (Franklin *et al.,* 2016; Mazonakis & Damilakis, 2016; Morillas *et al.,* 2020). However, while scanning time may be rapid, post-processing and examination of the image slices may be very time-consuming and requires specific training (Garvin & Stock, 2016; Grabherr *et al.,* 2017; Morillas *et al.,* 2020). CT scanners, like conventional X-rays, emit high doses of radiation, although advancements in more recent systems have resulted in dosage reductions (Mori *et al.,* 2006; Franklin *et al.,* 2016; Morillas *et al.,* 2020). CT scanners also require highly trained personnel to operate and are extremely expensive to acquire and maintain (O'Donnell *et al.,* 2007; Baglivo *et al.,* 2013; Grabherr *et al.,* 2017), and as a result, CT scanners are not a feasible option in institutions with limited financial and personnel resources (Bergeron *et al.,* 2017; Willett, 2019).

2.1.2.3. Low-dose full-body X-rays (Lodox)

The low-dose, full-body X-ray scanner, commonly referred to as the Lodox scanner, was developed in South Africa with the initial purpose of performing low radiation dose, whole body scans of workers in the mining industry to prevent diamond smuggling (Lodox® Systems (Pty), 2020). Soon after its development, the use of this technology in clinical and emergency trauma settings was realized (Beningfield *et al.,* 1999). Lodox scans are generated by an X-ray tube mounted on one end of a C-arm which travels along the length of the table, producing a full-body X-ray image. The use of a collimated narrow fan-beam of X-rays reduces the amount of X-ray scatter, potentially resulting in higher quality images when compared to conventional X-rays (Amirlak *et al.,* 2009; Trauernicht *et al.,* 2017; Lodox® Systems (Pty), 2020) and also reducing the amount of radiation that both patients and operators are exposed to (Evangelopoulos *et al.,* 2011; Whiley *et al.,* 2013; Lodox® Systems (Pty), 2020). In fact, the Lodox scanner has been shown to emit an average radiation dose of between 65.0% and 94.0% less than that of conventional X-rays (Beningfield *et al.,* 2003; Mantokoudis *et al.,* 2013). These low radiation doses negate the need for safety and protective equipment for the operators when at least 1 meter away from the scanner (Bernitz & Verster, 2017) and this, together with the low associated maintenance and equipment costs (Chen *et al.,* 2010; Evangelopoulos *et al.,* 2011; du Plessis *et al.,* 2020), makes Lodox scanners far less expensive and therefore more easily accessible than other radiographic tools. In addition, the Lodox scanner does not require the expertise of highly trained personnel to either operate the scanner or process the images (Amirlak *et al.*, 2009; du Plessis *et al.,* 2020; Mamabolo *et al.,* 2020).

Acquisition time is more rapid than conventional X-rays, with a full-body scan generated in only ±13 seconds (Beningfield *et al.,* 2003; Whiley *et al.,* 2013; du Plessis *et al.,* 2020). Post-processing and analysis are also far quicker as multiple scans do not need to be "stitched" to create a full-body image as is the case with conventional X-rays (Beningfield *et al.,* 2003; Huang *et al.,* 2012; Mamabolo *et al.,* 2020). The C-arm of the scanner can be rotated axially around the individual being scanned at any angle up to 90º, which means that individuals do not need to be repositioned for scans to be taken at different angles, thus further reducing the acquisition time (Mulligan & Flye, 2006; Amirlak *et al.,* 2009). However, only 2D images are generated and Lodox scans, similar to conventional X-rays, therefore still have the challenge of superimposition of structures (Garvin & Stock, 2016; Mamabolo *et al.,* 2020). Additionally, the ability of Lodox scans to visualize soft tissues is limited (Amirlak *et al.,* 2009).

While the aim of this study is to compare the trauma detection abilities of all three previously described imaging methods, an emphasis has been placed on Lodox throughout this thesis as it is the most commonly used imaging modality in South African medico-legal institutions (Whiley *et al.,* 2013; du Plessis *et al.,* 2020) and knowledge of its ability to detect trauma is limited.

2.1.3. Radiological imaging in various settings

2.1.3.1. Clinical settings

Radiological imaging is an invaluable tool in emergency settings, where it is used for the rapid detection of major trauma to aid in correctly triaging and diagnosing patients and planning the optimal course of clinical management and treatment (Broder & Warshauer, 2006; Körner *et al.,* 2006; Pinto *et al.,* 2006; Exadactylos *et al.,* 2008; Whiley *et al.,* 2013; Linder *et al.,* 2016; Klang *et al.,* 2020). In most trauma and emergency centers, CT and X-ray are the radiological methods of choice for initial patient screening (Broder & Warshauer, 2006; Körner *et al.,* 2006; Pinto *et al.,* 2006; Linder *et al.,* 2016; Klang *et al.,* 2020).

However, Lodox is gaining in popularity and is currently utilized in multiple trauma settings both in South Africa and worldwide, such as in Switzerland, Taiwan, and the United States of America (Beningfield *et al.,* 2003; Boffard *et al.,* 2006; Mulligan & Flye, 2006; Exadactylos *et al.,* 2008; Amirlak *et al.,* 2009; Chen *et al.,* 2010; Deyle *et al.,* 2010; Evangelopoulos *et al.,* 2011; Huang *et al.,* 2012; Mantokoudis *et al.,* 2013; Whiley *et al.*, 2013). This is a result of the extremely low doses of radiation that it emits, making imaging much safer for both the patient and the radiographer (Beningfield *et al.*, 2003; Whiley *et al.*, 2013), as well as its speed, which reduces the time that each patient is triaged and appropriately treated while also increasing the number of patients that can be radiographed, triaged, and clinically managed (Beningfield *et al.,* 2003; Evangelopoulos *et al.,* 2011; Whiley *et al.,* 2013). Because the Lodox scanner has an integrated docking table, the use of this technology eliminates the need for trauma patients to be continuously transferred between stretchers and scanning tables, which aids in keeping patients stable and also saves time (Evangelopoulos *et al.*, 2011; Whiley *et al.*, 2013). Magnetic resonance imaging (MRI) is also frequently used for the imaging of living individuals, as it is non-ionizing and therefore does not emit radiation like X-ray or CT scanners (Franklin *et al.,* 2016; Obertová *et al.*, 2019). MRI also produces soft tissue images that are of better resolution and quality compared to CT scans (Grabherr *et al.,* 2017; Carew & Errickson, 2019; Morillas *et al.*, 2020), but bone is not visualized in as much detail, and X-ray and CT imaging are therefore preferred for examinations of the skeletal system (Arthurs *et al.*, 2017; Carew & Errickson, 2019; Morillas *et al.*, 2020).

Radiological methods are also frequently used to diagnose and guide the treatment of diseases, perform minimally invasive procedures, and conduct skeletal surveys in patients with injuries suspicious of abuse (Barber *et al.,* 2015; Paine & Wood, 2018; Kulkarni & Jha, 2020; Panunzio & Sartori, 2020; Too *et al.,* 2020; Aremu *et al.,* 2021; Ducray *et al.,* 2021). While it is clear that radiological imaging is extremely useful for the detection of skeletal trauma in living individuals, the rest of this thesis will focus on the application of virtual imaging for the identification of trauma in the deceased.

2.1.3.2. Forensic pathological and anthropological settings

Radiological imaging in forensic pathological and anthropological contexts is used for a very wide range of applications, many of which are beyond the scope of this research. For the purpose of this thesis, discussion surrounding the use of imaging in these settings is limited to basic identification methods, virtual autopsies, the identification of foreign bodies, and the detection of skeletal trauma, which comprises the main of this thesis.

Throughout the world, and particularly in developed countries, CT is the most frequently used imaging modality for forensic examinations. However, this technology is expensive and requires training both to operate and for post-processing and analysis (Grabherr *et al.,* 2017; Morillas *et al.,* 2020). As a result, X-ray, specifically Lodox imaging, is the preferred method in many resource-limited forensic laboratories due to its cost-effectiveness, ease of use, and speed (Whiley *et al.,* 2013; du Plessis *et al.,* 2020), which is also the case in South African mortuaries.

During post-mortem investigations, forensic pathologists, anthropologists and odontologists make use of imaging to compare ante- and post-mortem radiographs with the intent of positively identifying unknown decedents (Franklin *et al.,* 2016; Ali *et al.,* 2020). This is often performed when more traditional methods of identification, such as DNA and fingerprint analyses, are not possible, as is the case when remains are decomposed, skeletonized, or burnt (Campobasso *et al.*, 2007; Dedouit *et al.*, 2007; O'Donnell *et al.,* 2011; Silva *et al.,* 2017; Coty *et al.*, 2018). Unique, individual characteristics or features can be compared between ante- and post-mortem records of the dentition (Middleton *et al.,* 2016; Ruder *et al.*, 2016; Bernitz & Verster, 2017; Nguyen & Doyle, 2018; Wood & Gardner, 2021), the paranasal sinuses (Ruder *et al.*, 2012; Auffret *et al.*, 2016; Deloire *et al.*, 2019; Ali *et al.*, 2020), and other skeletal traits (Keuhn *et al.,* 2002; Dedouit *et al.*, 2014; De Angelis *et al.,* 2016; Cappella *et al.*, 2019; de Boer *et al.*, 2019; Ali *et al.*, 2020).

In recent years, the popularity of the conventional autopsy has declined and, as a result, the application of post-mortem imaging as an adjunct to, or even as opposed to, these procedures has increased (Thali *et al.,* 2003; Dirnhofer *et al.*, 2006; Franklin *et al.,* 2016; Herath & Herath, 2021). In some countries, the next of kin of the deceased have the right to refuse an autopsy (Berkovitz *et al.,* 2013; Arnold & Bonython, 2016; Warter & Warter, 2018), which is often the case as these procedures are extremely invasive and, as a result, are associated with many religious, cultural, and social objections, particularly when involving children (Banyini *et al.*, 2013; Berkovitz *et al.*, 2013; Kang *et al.,* 2014; Aljerian *et al.*, 2015; Lewis *et al.,* 2018; Alhawari *et al.,* 2020; Herath & Herath, 2021). In fact, up to 20% of orthodox Christians and Buddhists (Alhawari *et al.,* 2020), between 30% and 40% of individuals of Hindu belief (Alhawari *et al.*, 2020), and up to 50% of the population in Israel (Berkovitz *et al.,* 2013) do not consent to an autopsy due to religious beliefs. Virtual autopsies, or "virtopsies", have therefore become more popular and have completely replaced the traditional autopsy in some cases as they do not breach religious or cultural beliefs (Rutty *et al.,* 2008; Shiotani *et al.,* 2011; Franklin *et al.,* 2016). In these cases, radiological imaging has proven invaluable since a determination of cause and manner of death in these individuals would not be possible without the use of virtual methods (Berkovitz *et al.,* 2013; Franklin *et al.,* 2016; Lewis *et al.,* 2018). In countries like South Africa where autopsies are mandatory for all non-natural deaths, but still bear the same cultural and religious objections (Banyini *et al.,* 2013; Aljerian *et al.,* 2015), the initial use of virtual imaging may be used to justify the need for a traditional autopsy to families and communities. Virtopsy is also non-destructive and allows for the preservation of soft and osseous tissues (Filograna *et al.,* 2019), enables the examination of putrefied tissues (Tschui *et al.,* 2016) and can be used to determine the post-mortem interval (Arthurs *et al.,* 2015; Barber *et al.,* 2016; Sapienza *et al.,* 2020). Therefore, whereas traditional autopsies are time-consuming and labour-intensive, virtual imaging to complement or even replace the autopsy procedure can save time, resources, lighten the load for forensic pathologists and increase the number of forensic examinations performed (Bolliger *et al.*, 2008). The use of radiological methods in this context is therefore invaluable.

The use of radiological imaging during forensic examinations also assists in the detection of foreign bodies such as bullet fragments (Levy *et al.,* 2006; Harcke *et al.,* 2007; Andenmatten *et al.,* 2008; Kirchhoff *et al.,* 2016; Gascho *et al.*, 2021), knife blade and other sharp instrument fragments (Thali *et al.,* 2002; Kawasumi *et al.,* 2012; Ebner *et al.,* 2014; Sano *et al.,* 2018), and foreign material lodged in the airways or abdominal cavity (Oesterhelweg *et al.,* 2009; Mantokoudis *et al.,* 2013; Bolliger *et al.,* 2015; du Plessis *et al.,* 2020). During a forensic anthropological analysis of completely skeletonized remains, radiological imaging can even be used to detect evidence of lead transfer around bullet entrance and exit wounds or other areas of impact, which can aid in determining the trajectory of the bullet (Garvin & Stock, 2016; Lukefahr *et al.*, 2021).

Perhaps one of the most significant applications of radiological imaging during clinical and forensic investigations is the detection of skeletal trauma (Franklin *et al.,* 2016; Garvin & Stock, 2016; Obertová *et al.,* 2019). Victims of physical child abuse, torture and violent crime frequently have evidence of blunt and sharp force skeletal trauma (Kleinman, 1998; Le *et al.,* 2001; Bilo *et al.,* 2010; Berthold *et al.,* 2018; Narayanan *et al.,* 2018; Antúnez *et al.,* 2020). The accurate investigation of these cases, including distinguishing between accidental and non-accidental trauma and ascertaining the circumstances surrounding the traumatic incident, depends on the detection, analysis, and interpretation of this trauma.

2.2. Radiological imaging and skeletal trauma

2.2.1. Trauma in children

Crimes against children is a global epidemic and is particularly rife in South Africa (Richter & Dawes, 2008; Mathews *et al.,* 2013; Meinck *et al.,* 2017). In 2019, 42 345 crimes against children were reported to the South African Police Services, including 943 murders, 1 137 attempted murders, and 18 198 physical assaults (South African Police Services, 2020). South Africa has a tremendously high child homicide rate of 8 per 100 000, which is more than double the global average (UNICEF, 2014), and it is reported that approximately 44.5% of these child homicides are caused by physical abuse (Mathews *et al.*, 2013). Many other countries worldwide are also facing a crisis of crimes against children, with child homicide rates ranging between 4 per 100 000 in the United States of America and 27 per 100 000 in El Salvador (UNICEF, 2014). The most frequently used weapons during incidents of abuse and violence against children are personal weapons such as the fists, and other blunt instruments (Naidoo, 2000; Lee *et al.*, 2003; Bennett Jr *et al.*, 2006; Cavanagh *et al.*, 2007; Baralic *et al.*, 2010; Janssen *et al.*, 2013), which often result in evidence of blunt force trauma (BFT) to the skeleton in the form of fractures.

Fractures are one of the most common indicators of abuse and violence in children, occurring in between 25.0% and 55.0% of abused children (Loder & Bookout, 1991; Hyden & Gallagher, 1992; Loder & Feinberg, 2007; Al-Mahroos *et al.*, 2007; Leventhal *et al.*, 2008; Maguire, 2010). Fractures of the ribs have a 71.0-95.0% probability of being the result of non-accidental trauma, while probabilities of abuse given humeral and femoral fractures are 54.0-79.0% and 43.0-60.0% respectively (Thomas *et al.*, 1991; Barsness *et al.*, 2003; Kemp *et al.*, 2008). Also common in abused children and infants are skull fractures (Hobbs, 1984; Bilo *et al.*, 2010; Sharp *et al.*, 2018), which have between a 27.0% and 30.0% probability of being due to violence (Meservy *et al.*, 1987).

BFT is caused by a slow-loading impact which results in fractures or cracks in the bone (İşcan & Steyn, 2013). When subjected to various kinds of forces, including compression, tension, torsion and shearing forces, bone can be stressed to a point where the bone fails and fractures (Bilo *et al.*, 2010; İşcan & Steyn, 2013). Depending on the type of force applied, various kinds of fractures may result. In children, incomplete fractures, such as greenstick, bowing and buckle fractures are common, while in adults, transverse, oblique, spiral, butterfly and comminuted fractures are more frequent (Bilo *et al.*, 2010; İşcan & Steyn, 2013). These fractures can be observed both on the dry bone and radiologically in order to assess the type of trauma and force applied, and potentially whether this trauma was accidental or not (Bilo *et al.,* 2010; İşcan & Steyn, 2013).

While motor vehicle accidents, falls, and other accidents also result in BFT in children, (Bilo *et al.,* 2010; Statistics South Africa, 2019), the patterns and characteristics of this trauma differ between victims of non-accidental and accidental trauma (Hobbs, 1984; Worlock *et al.,* 1986; Kleinman *et al.,* 1992; Kleinman, 1998; Kemp *et al.,* 2008; Bilo *et al.,* 2010; Rowbotham *et al.,* 2021). Isolated, linear skull fractures in infants are frequently the result of falls, while multiple fractures, including complex, depressed and diastatic fractures, are more indicative of abuse or intentional blows to the head, as considerable force is required to create these patterns of trauma in children (Hobbs, 1984; Worlock *et al.,* 1986; Meservy *et al.,* 1987; Kleinman *et al.,* 1992; Kleinman, 1998; Lee *et al.,* 2003; Bilo *et al.,* 2010; İşcan & Steyn, 2013; Rowbotham *et al.,* 2021; Sidpra *et al.,* 2021).

During incidences of abuse and violence, the rib cage is often compressed antero-posteriorly when the perpetrator wraps his/her hands around the child's chest (Kleinman & Schlesinger, 1997; Bilo *et al.,* 2010). This compression results in considerable force being applied to the posterior aspects of the ribs, compressing them against the transverse processes of the vertebrae, which causes the rib heads to fracture first (Kleinman & Schlesinger, 1997; Bilo *et al.,* 2010). Posterior rib fractures are therefore extremely indicative of non-accidental trauma, while this type of fracture is uncommon as a result of accidents or cardiopulmonary resuscitation (Kleinman *et al.,* 1992; Kleinman & Schlesinger, 1997; Bilo *et al.,* 2010; Franke *et al.,* 2014).

In the long bones, the presence of growth plates around the joints results in this being an area of weakness. Force inflicted to these regions, particularly shearing forces during violent shaking, therefore results in the tendons and ligaments fully or partially tearing off the metaphysis of the bone, commonly referred to as a classic metaphyseal lesion (Kleinman *et al.,* 1986, 2011; Kleinman, 1998; Bilo *et al.,* 2010; İşcan & Steyn, 2013; Adamsbaum *et al.,* 2019). This type of fracture has a very high specificity for non-accidental trauma and is infrequently seen in non-abusive cases (Kleinman *et al.,* 1986, 2011; Kleinman, 1998; Bilo *et al.,* 2010; Adamsbaum *et al.,* 2019).

During forensic examinations of infants and children, documenting the locations and types of fractures, as well as the minimum number of impacts sustained, can therefore be critical for establishing whether the trauma was accidental or abusive. In addition, assessing the direction of BFT based on interpreting sites of tension and compression can assist in corroborating testimonies, establishing the circumstances surrounding the traumatic event, and determining cause and manner of death (Love & Symes, 2004; Grassberger *et al.,* 2011; İşcan & Steyn, 2013; Love & Wiersema, 2016). An impact results in compression of the bone at the point of impact, while the opposite side of the bone is subjected to tensile forces (İşcan & Steyn, 2013). Ribs tend to initially fail in compression due to the very thin bone cortex, often resulting in incomplete or buckle fractures involving the bone cortex on the compression side (Love & Symes, 2004). Long bones, however, fail first in tension due to their strength in resisting compressive forces (Symes *et al.,* 2012; Reber & Simmons, 2015). This often results in a complete fracture at the point of tension, and radiating fractures at the compression side (Reber & Simmons, 2015). By locating the side of the bone subjected to compressive forces, the direction of trauma can be ascertained (Symes *et al.,* 2012; Reber & Simmons, 2015; Love & Wiersema, 2016).

2.2.2. Torture and violent crime

A large proportion of individuals in trauma units, mortuaries and forensic anthropological laboratories have evidence of BFT and SFT, which are often the result of violent crime, chronic abuse and torture (Le *et al.,* 2001; Cocks & Saayman, 2013; Nicol *et al.,* 2014; Hokkam *et al.,* 2015; Saimen *et al.,* 2016; Clark *et al.,* 2017; Narayanan *et al.,* 2018). Violent crime, which includes murders and assaults, is extremely prevalent worldwide, with 372 174 of these incidents reported in South Africa in 2019 (South African Police Services, 2020). Included in violent crime are chronic abuse and torture, which both result in repeated trauma over long periods of time (Kimmerle & Baraybar, 2008; İşcan & Steyn, 2013; Steyn *et al.,* 2021). Chronic abuse is common in cases of intimate partner violence (IPV) (Le *et al.,* 2001; Coker *et al.,* 2007; Steyn *et al.,* 2021), occurring in up to 37.0% of IPV victims (Coker *et al.,* 2007). Torture is a common political tool and is implemented in up to 141 countries worldwide (Amnesty International, 2021), with between 11.0% and 76.0% of detainees, forced migrants and refugees subjected to torture (Ghaleb *et al.,* 2014; Willard *et al.,* 2014; Sigvardsdotter *et al.,* 2016).

The weapons of choice in the majority of these incidents of violence are blunt instruments such as bats, hammers, and iron rods, as well as sharp instruments such as knives, axes and machetes (Sorenson & Wiebe, 2004; Grassberger *et al.,* 2011; Cocks & Saayman, 2013; Narayanan *et al.,* 2018; Cipolloni *et al.,* 2020; South African Police Services, 2020; Thomsen *et al.,* 2020). Trauma with both blunt and sharp weapons often results in fractures and lesions which need to be documented (Le *et al.,* 2001; Grassberger *et al.,* 2011; Narayanan *et al.,* 2018; Thomsen *et al.,* 2020).

The specific patterns of BFT and SFT in adults are significant as it can provide information regarding the circumstances surrounding the traumatic incident. Research has shown that skull fractures above the hat-brim line and fractures of the face are more likely to be the result of violence as opposed to accidental trauma (Kremer *et al.,* 2008; Kremer & Sauvageau, 2009; Guyomarc'h *et al.,* 2010). The head, chest and spine are the regions most commonly involved in cases of chronic abuse and torture (Le *et al.,* 2001; Kimmerle & Baraybar, 2008; Steyn *et al.,* 2021). Trauma to the forearm and hand often occurs as a victim attempts to defend themself and is frequently a result of violent crime or abuse (Ambade & Godbole, 2006; Gentile *et al.,* 2019; Steyn *et al.,* 2021; Thomas *et al.,* 2021). SFT to the limbs can also be indicative of attempted dismemberment for body disposal purposes (Kimmerle & Baraybar, 2008; Symes *et al.,* 2012; Ross & Cunha, 2018), while SFT to the cervical vertebra is often suggestive of a slit throat or attempted decapitation (Kimmerle & Baraybar, 2008; Symes *et al.,* 2012; İşcan & Steyn, 2013; Ross & Cunha, 2018).

The presence of ante-mortem fractures at various stages of healing indicates long-term, repeated trauma, which can provide further evidence of chronic abuse and torture (Kimmerle & Baraybar, 2008; İşcan & Steyn, 2013; Steyn *et al.,* 2021). Documenting indications of bone healing and remodeling is therefore also crucial when investigating these cases.

The examination of the specific characteristics of SFT can also add further information regarding the traumatic incident. Narrow defects such as cuts, incisions or punctures in the bone are generally a result of stabbing trauma with weapons such as knives (Ferllini, 2012; Symes *et al.,* 2012; İşcan & Steyn, 2013). On the other hand, wide defects with bone wastage and chipping, and other sharp-blunt characteristics such as fracturing and crushing of the bone, are often the result of hacking trauma with weapons such as axes, hatchets, or machetes (Humphrey & Hutchinson, 2001; Lynn *et al.,* 2009; Symes *et al.,* 2012; İşcan & Steyn, 2013). By analysing these unique characteristics, the trauma can be matched to a specific type or class of weapon, which has implications for identifying the murder/assault weapon or the instrument used in post-mortem dismemberment cases (Symes *et al.,* 2012; İşcan & Steyn, 2013; Love & Wiersema, 2016; Alsop *et al.,* 2021; Karray *et al.,* 2021; Weber *et al.,* 2021). The detection but also the interpretation of skeletal trauma is therefore crucial during investigations of torture and violent crime. The present study will aim to radiologically distinguish between defects caused by stabbing trauma with a kitchen knife, and chop marks caused by hacking trauma with a panga.

2.2.3. Limitations of traditional forensic examinations

During traditional forensic examinations, which include conventional autopsy procedures and physical examinations of the remains during forensic pathological and anthropological assessments, the detection of skeletal trauma can be challenging. In fact, approximately 9.0%-69.0% of fractures are undetected during autopsy procedures (Cattaneo *et al.,* 2006; Chevallier *et al.,* 2013).

Signs of healing are absent in cases of peri-mortem trauma which can make fractures, especially very small, incomplete or hairline fractures, as well as narrow, shallow sharp force defects, very difficult to detect during an autopsy (Cattaneo *et al.,* 2006; Jacobsen *et al.,* 2009; Flach *et al.,* 2014; Mazzarelli *et al.,* 2021).

In regions of the body that are difficult to examine or not routinely dissected during autopsy procedures, the detection of osteological trauma is even more challenging. This includes cranial and facial trauma, and trauma to the scapulae, posterior aspects of the ribs, vertebrae, pelvis, and limbs (Jacobsen *et al.*, 2009; Chevallier *et al.,* 2013, Flach *et al.,* 2014), which are many of the regions that are affected in cases of abuse, torture and violent crime (Kleinman *et al.,* 1992; Kleinman, 1998; Bilo *et al.,* 2010; Symes *et al.,* 2012; Thomsen *et al.,* 2020).

While the presence of soft tissue haemorrhages and lacerations can guide the pathologist in locating underlying osseous trauma, this soft tissue damage may be absent in cases where the trauma was sustained peri-mortem or in cases of advanced decomposition (Cattaneo *et al.,* 2006; Cappella & Cattaneo, 2019). Thermal damage may also conceal evidence of trauma as soft tissues become charred and adhere to the bone surface, which could obscure any underlying skeletal trauma (Dedouit *et al.,* 2007; Coty *et al.,* 2018).

In some cases, the autopsy procedure itself may even prevent the complete visualization of trauma. For example, sectioning of the cranial vault to expose the brain could damage pre-existing trauma to the skull, particularly involving the endocranium (Fleming-Farrell *et al.,* 2013; Kranioti, 2015), while removing the rib cage could destroy evidence of trauma to the ribs (Pokines *et al.,* 2016). In these cases, the in-situ examination of trauma is compromised (Fleming-Farrell *et al.,* 2013; Kranioti, 2015).

For more reliable detection of skeletal trauma, the complete body, or only the region of interest, may be macerated so that a forensic anthropological analysis of the dry bones can be performed. However, maceration is a time-consuming, labour-intensive process which is not always feasible, and may even damage the underlying bone and destroy evidence of pre-existing trauma (Brough *et al.,* 2012; King & Birch, 2015). In addition, dissecting out portions of the body to be macerated is invasive and has aesthetic implications which may affect funeral practices and impose even more emotional trauma on the loved ones of the deceased, particularly in cases involving children (Kettner *et al.,* 2011; Brough *et al.,* 2012).

While a traditional forensic anthropological examination of trauma is useful for decomposed and skeletonized remains, it may not always be appropriate such as when the skeleton is extremely fragile, in which case the bones may fragment and crumble if a dry bone analysis is attempted (Dedouit *et al.,* 2007).

Therefore, the challenges of detecting skeletal trauma during traditional forensic examinations can be overcome by the utilization of radiological imaging, which has the benefits of non-invasively examining the entire body without compromising the in-situ visualization of skeletal trauma (Dedouit *et al.,* 2007; Fleming-Farrell *et al.,* 2013; Franklin *et al.,* 2016). Additionally, radiological scans can be stored for future analysis and investigation, and both 2D images and 3D bone replicas can be used as evidence during trials in court (Errickson *et al.,* 2014; Baier *et al.,* 2018, 2021; Carew *et al.,* 2019).

2.2.4. Sensitivity of various imaging modalities

Since the radiological examination of skeletal trauma is common practice during post-mortem medico-legal investigations, it is imperative that the diagnostic accuracies of the various imaging modalities employed during these analyses are investigated. Several studies have assessed the ability of radiological methods in detecting, analyzing, and interpreting blunt and sharp force skeletal trauma. Since MRI scans are not ideal for visualizing osseous tissue (Arthurs *et al.,* 2017; Carew & Errickson, 2019; Morillas *et al.,* 2020), this imaging modality will not be discussed.

A plethora of research assessing the abilities of various radiological methods in detecting BFT in both paediatric and adult individuals has been conducted (Tables 2.1 and 2.2). From the vast majority of these studies, it is evident that CT is the most sensitive radiological method for detecting BFT in all body regions, and is often even more sensitive than autopsy itself. CT is therefore reported to be the gold standard for detecting BFT and should be performed whenever this is a feasible or possible option. It also appears that the sensitivity of Lodox and X-rays for detecting BFT is comparable, and many studies recommend replacing X-ray protocols completely with Lodox for the initial detection of trauma in post-mortem investigations (Douglas *et al.,* 2008; Pitcher *et al.,* 2008; Chen *et al.,* 2010).

All of these studies, however, used various makes and models of scanners, sample sizes and standards of reference against which to compare the findings of the radiological methods (Tables 2.1 and 2.2). Therefore, direct comparisons of the abilities of these radiological tools, which seem to differ in sensitivity between these studies, is not recommended. Moreover, all but two (Cattaneo *et al.,* 2006; Mulroy *et al.,* 2012) of these studies used either autopsy, CT or X-ray results as the gold standard. Since research has shown that these methods frequently fail to detect osteological trauma (Cattaneo *et al.,* 2006; Jacobsen *et al.,* 2009; Thomsen *et al.,* 2009; Chevallier *et al.,* 2013; Flach *et al.,* 2014; Shelmerdine *et al.,* 2018; Mazzarelli *et al.,* 2021), the sensitivity of the radiological methods reported by these studies should be treated with caution. In order to accurately test the abilities of the various imaging modalities, the cleaned skeletal remains should be used as the gold standard to be sure that no fractures are missed by this standard (Cattaneo *et al.,* 2006; Mulroy *et al.,* 2012), which would result in more accurate measures of sensitivity.

The studies performed by Cattaneo *et al.* (2006) and Mulroy *et al.* (2012) are the only ones that utilized the dry bone as the gold standard. Both studies compared the abilities of CT and X-ray scans, finding that CT is consistently more sensitive for detecting BFT and should therefore be the radiological method of choice. However, as can be seen by the results for detecting skull fractures using CT (Table 2.1), there were a large number of false-positive fracture identifications made in the Cattaneo *et al.* (2006) study, and no effort was made to distinguish between the number of true-positive and false-positive detections. As a result, the actual sensitivity of these radiological methods is not known. It is therefore imperative to distinguish between the number of true- and false-positive fractures identified, and as a result, both the sensitivity and specificity of each radiological method.

While these two studies (Cattaneo *et al.,* 2006; Mulroy *et al.,* 2012) did use dry bone as the reference standard, only CT and X-ray were assessed, and other imaging modalities such as Lodox were not included in the study design. This is significant since Lodox scanners are commonly employed in forensic institutions in South Africa and worldwide (Boffard *et al.,* 2006; Mulligan & Flye, 2006; Exadactylos *et al.,* 2008; Amirlak *et al.,* 2009; Huang *et al.,* 2012; Mantokoudis *et al.,* 2013; Whiley *et al.,* 2013) and are frequently the only radiological tool available in these mortuaries.

Table 2.1. Main findings and conclusions of the studies assessing the radiological detection of blunt force skeletal trauma in infants and children

Author and year	Type of trauma	Sample age	Sample size	Imaging modality(s)	Gold standard	Body region(s)	Main findings	Conclusions
Klotzbach *et al.* (2003)	BFT	Infants ≤ 13 weeks	3	X-ray	Autopsy	Full body	Sensitivity of X-rays: 61.4%. Most unidentified fractures were acute rib fractures	X-rays are sensitive for detecting fractures and should be performed in conjunction with autopsy
Cattaneo *et al.* (2006)	BFT	Piglets (3 kg) as proxies for human infants	4	X-ray and CT	Dry bone	Full body	Sensitivity of X-rays: 35.0% for skull, 47.0% for rib, 73.0% for anterior limb and 100.0% for posterior limb fractures Sensitivity of CT: 126.0% for skull, 34.0% for rib, 73.0% for anterior limb and 100.0% for posterior limb fractures	A combination of autopsy, CT, X-ray and dry bone analysis should be performed for suspected cases of child abuse
Cabarrus *et al.* (2008)	BFT	Children and adults (13 – 101 years)	64	CT	CT, MRI and X-ray; imaging follow-up; clinical history	Pelvis and proximal femur	Sensitivity of CT: 69.0%	CT is moderately sensitive for detecting fractures of the pelvis and proximal femur
Douglas *et al.* (2008)	BFT	Children 5 – 7 years	3	Lodox	X-ray	Limbs	A humeral, a radial and a tibial fracture were detected by Lodox but not X-ray	Lodox has greater diagnostic accuracy than X-ray for the detection of long bone fractures in children

Table 2.1. Continued

Author and year	Type of trauma	Sample age	Sample size	Imaging modality(s)	Gold standard	Body region(s)	Main findings	Conclusions
Pitcher *et al.* (2008)	BFT	Infants and children < 16 years	23	Lodox	X-ray	Limbs	Sensitivity of Lodox: 96.0% Lodox identified 2 fractures not suspected clinically	Lodox increases the sensitivity of triage evaluation and can be used instead of X-ray to detect major trauma
Welling *et al.* (2008)	BFT	Children and adults (10 – 80 years)	60	X-ray	CT	Wrist	Sensitivity of X-ray: 69.6%	CT should still be performed to evaluate suspected wrist fractures even if an X-ray scan is negative
Wootton-Gorges *et al.* (2008)	BFT	Infants 1.2 – 5.6 months	12	X-ray	CT	Ribs	Sensitivity of X-rays: 60.3%	CT is more sensitive than X-rays in detecting rib fractures and should be performed whenever feasible
Weber *et al.* (2009)	BFT	Infants ≤ 10 months	24	X-ray	Autopsy	Ribs	Sensitivity of X-rays: 93.0% for healing rib fractures; 22.0% for fresh rib fractures	X-rays are not sensitive for detecting acute rib fractures and should not replace autopsy
Hong *et al.* (2011)	BFT	Infants and children < 8 years	56	X-ray and CT	Autopsy	Ribs	Sensitivity of X-rays: 46.0% Sensitivity of CT: 85.0%	CT is significantly more sensitive than X-rays for identifying rib fractures and is preferred over X-rays for suspected cases of child abuse
Kim *et al.* (2012)	BFT	Infants and children < 12 years	100	X-ray	CT	Skull	Sensitivity of X-rays: 77.0% for linear, 50.0% for depressed, and 21.4% for diastatic fractures	CT is more sensitive than X-rays for detecting paediatric skull fractures, especially depressed and diastatic fractures, and should be performed when evaluating these cases

Table 2.1. Continued

Author and year	Type of trauma	Sample age	Sample size	Imaging modality(s)	Gold standard	Body region(s)	Main findings	Conclusions
Mulroy *et al.* (2012)	BFT	Infants and children ≤ 16 years	6	X-ray and CT	Dry bone	Skull	Sensitivity of X-rays: 63.0% Sensitivity of CT: 71.0% Sensitivity for linear fractures (80.0% for both methods) were higher than diastatic fractures (CT: 75.0%; X-rays: 42.0%)	CT is more sensitive than X-rays for detecting paediatric skull fractures
Chawla *et al.* (2015b)	BFT	Children and adults (5 – 80 years)	60	CT	Autopsy	Skull	Sensitivity of CT: 85.4%	CT can be a useful tool for detecting skull fractures and can be used in conjunction with an autopsy
Orman *et al.* (2015)	BFT	Infants and children < 18 years	250	2D and 2D + 3D CT	2D and 2D + 3D CT read by 2 independent observers	Skull	Sensitivity of 2D CT: 74.5% Sensitivity of 2D + 3D CT: 81.3%	A combination of 2D and 3D CT images should be used to assess skull fractures in paediatric patients
Chapman *et al.* (2016)	BFT	Children and adults (4 – 101 years)	399	X-ray	CT	Ribs	Sensitivity of X-rays: 25.5%	X-rays are insensitive when compared to CT for detecting rib fractures

Table 2.1. Continued

Author and year	Type of trauma	Sample age	Sample size	Imaging modality(s)	Gold standard	Body region(s)	Main findings	Conclusions
Culotta *et al.* (2017)	BFT	Infants ≤ 1 year	177	CT	X-ray	Skull	Sensitivity of CT: 96.8% Sensitivity of X-rays (when CT was considered the gold standard): 89.6%	X-rays can be removed from the radiological protocol for detecting paediatric skull fractures when a CT is performed
Sharp *et al.* (2018)	BFT	Infants ≤ 2 years	94	X-ray	CT	Skull	Sensitivity of X-rays: 98.0%	X-rays demonstrated no additional findings over CT, and should not be used to evaluate for skull fractures when a head CT is available
Shelmerdine *et al.* (2018)	BFT	Infants and children ≤ 7 years	25	X-ray and CT	Autopsy	Ribs	Sensitivity of X-rays: 13.5% Sensitivity of CT: 44.9%	CT has greater diagnostic accuracy than X-rays, and CT should be performed rather than X-rays for assessing post-mortem rib fractures in children
Martin *et al.* (2020)	BFT	Infants ≤ 2 years	104	X-ray	CT	Skull	Sensitivity of X-rays: 90.5% However, 42.1% of these were actually false-positive identifications	CT has greater diagnostic accuracy compared to X-rays for detecting skull fractures in infants and children, and should replace X-rays in these cases

Table 2.2. Main findings and conclusions of the studies assessing the radiological detection of blunt force skeletal trauma in adults

Author and year	**Type of trauma**	**Sample age**	**Sample size**	**Imaging modality(s)**	**Gold standard**	**Body region(s)**	**Main findings**	**Conclusions**
Antevil *et al.* (2006)	BFT	Adults (mean of 37.5 years)	573	X-ray and CT	CT and X-ray	Spine	Sensitivity of X-rays: 71.0% Sensitivity of CT: 100.0%	CT is more sensitive for spinal fractures and can replace X-rays for initial evaluation of these cases
Cabarrus *et al.* (2008)	BFT	Children and adults (13 – 101 years)	64	CT	CT, MRI and X-ray; imaging follow-up; clinical history	Pelvis and proximal femur	Sensitivity of CT: 69.0%	CT is moderately sensitive for detecting fractures of the pelvis and proximal femur
Welling *et al.* (2008)	BFT	Children and adults (10 – 80 years)	60	X-ray	CT	Wrist	Sensitivity of X-ray: 69.6%	CT should still be performed to evaluate suspected wrist fractures even if an X-ray scan is negative
Chen *et al.* (2010)	BFT	Adults (mean of 35.3 years)	184	Lodox	CT	Cervical spine, thoracolumbar spine and pelvis	Sensitivity of Lodox: 57.1%, 100.0% and 96.0% respectively	CT is more sensitive than Lodox for detecting spinal and pelvic fractures, but Lodox can be used to replace traditional X-rays for examination of acute trauma
Deyle *et al.* (2010)	BFT	Adults ≥ 16 years	245	Lodox	X-ray and CT	Limbs	Sensitivity of Lodox: 73.0%	Lodox is sensitive for initial screening procedures, but should be interpreted with caution

Table 2.2. Continued

Author and year	**Type of trauma**	**Sample age**	**Sample size**	**Imaging modality(s)**	**Gold standard**	**Body region(s)**	**Main findings**	**Conclusions**
Deyle *et al.* (2011)	BFT	Adults ≥ 16 years	245	Lodox	CT	Skull	Sensitivity of Lodox: 32.0%	Lodox has a much lower sensitivity than CT for skull fractures, and CT therefore remains the gold standard for assessing these injuries
Grassberger *et al.* (2011)	BFT	Adults (54 and 81 years)	2 (case studies)	CT	None (victims survived)	Skull	CT was valuable in detecting the cranial fractures, determining the minimum number of blows, the sequence and direction of these blows, and identifying features that could aid in determining the weapon used	CT and its 3D reconstructions can be used in clinical and forensic examinations to provide information regarding the traumatic event
Huang *et al.* (2012)	BFT	Adults (mean of 37.1 years)	1 210	Lodox	CT	Full body	Sensitivity of Lodox: 89.7% for pelvic, 87.5% for thoracolumbar, 100.0% for long bone, and 79.3% for distal bone fractures	Lodox is sufficiently sensitive for detecting postcranial fractures, but CT remains the gold standard whenever possible
Schulze *et al.* (2013)	BFT	Children and adults (8 – 87 years)	51	CT	Autopsy	Ribs	Sensitivity of CT: 63.0%	CT has a rather low sensitivity for detecting rib fractures, and can be used to supplement autopsy
Chawla *et al.* (2015a)	BFT	Adults	42	X-ray	Autopsy and CT	Skull	Sensitivity of X-rays: 71.4% in comparison to autopsy, and 80.0% in comparison to CT	X-rays have limited sensitivity for detecting skull fractures and add no diagnostic value over CT scans

Table 2.2. Continued

Author and year	**Type of trauma**	**Sample age**	**Sample size**	**Imaging modality(s)**	**Gold standard**	**Body region(s)**	**Main findings**	**Conclusions**
Chawla *et al.* (2015b)	BFT	Children and adults (5 – 80 years)	60	CT	Autopsy	Skull	Sensitivity of CT: 85.4%	CT can be a useful tool for detecting skull fractures and can be used in conjunction with an autopsy
Chapman *et al.* (2016)	BFT	Children and adults (4 – 101 years)	399	X-ray	CT	Ribs	Sensitivity of X-rays: 25.5%	X-rays are insensitive when compared to CT for detecting rib fractures
Jöres *et al.* (2016)	BFT	Adults 16 – 93 years	106	Lodox	CT	Full body	Sensitivity of Lodox: 37.8% for rib, 16.7% for vertebral, and 44.4% for pelvic fractures	The diagnostic accuracy of Lodox for detecting fractures is limited. Lodox can therefore be used as a complementary tool to CT
Makino *et al.* (2017)	BFT	Adults 21 – 84 years	42	CT	Autopsy	Cervical spine	Sensitivity of CT: 73.9% Sensitivity of autopsy (when CT was considered the gold standard): 23.0%	CT identified significantly more fractures than autopsy, but a combination of both methods should be used for assessing cervical spine injury during forensic examinations

Table 2.2. Continued

Author and year	Type of trauma	Sample age	Sample size	Imaging modality(s)	Gold standard	Body region(s)	Main findings	Conclusions
Zhou *et al.* (2020)	BFT	Adults 20 – 97 years	974	CT evaluated by convoluted neural network (CNN)	CT evaluated by a radiologist	Ribs	Sensitivity of CT without AI assistance: 62.4% Sensitivity of CT with AI assistance: 86.3%	CT is sufficiently sensitive for detecting rib fractures, and CNN for automatic fracture detection can improve diagnostic accuracy
Häckel *et al.* (2021)	BFT	Adults ≥ 16 years	320	Lodox	CT	Spine	Sensitivity of Lodox: 9.0%	CT should be performed rather than Lodox when spinal fractures are suspected

Table 2.3. Main findings and conclusions of the studies assessing the radiological detection of sharp force skeletal trauma

Schnider *et al.* (2009)	SFT	Adults 15 – 83 years	12	CT	Autopsy	Full body	Sensitivity of CT: 100.0%	CT is sufficiently sensitive for detecting skeletal defects due to SFT and can be used prior to autopsy to detect these lesions
Thomsen *et al.* (2009)	SFT	Not specified	2 (case studies)	CT	Autopsy	Full body	CT scans were more sensitive than autopsy in detecting skeletal lesions in cases of sharp-blunt trauma	CT is a sensitive tool for detecting bone lesions as a result of SFT and could potentially be used as an adjunct to traditional autopsy
Ampanozi *et al.* (2010)	SFT	Adult	1 (case study)	CT	Autopsy	Skull	Many of the macroscopic characteristic of the bone trauma caused by this type of weapon (a hatchet) were easily identifiable radiologically, including bone crushing and fracturing. CT was superior to autopsy in determining the exact number of bone fragments, as well as the presence of bone flaking	CT is a powerful tool for documenting SFT lesions to the skull, and can be used to analyse hatchet-specific trauma characteristics to confirm the weapon used
Johnson *et al.* (2014); Wittschieber *et al.* (2016)	SFT	Adults	1 each (case studies)	CT	None (victims survived)	Skull	Fractures associated with chopping trauma with either an axe or a hatchet were identified using CT. A minimum number of blows could be determined using CT (Johnson *et al.*, 2014)	The type of sharp weapon used to inflict trauma can be confirmed based on the macroscopic characteristics of trauma visualized using CT scans.

While the studies by Cattaneo *et al.* (2006) and Mulroy *et al.* (2012) assessed radiological abilities in detecting fractures in infants or piglets as proxies for human children, studies including adults or adult proxies have yet to be conducted. The bones of children and adults differ in composition, size, strength and elasticity, and they therefore fracture very differently as a result of BFT (Love & Symes, 2004; Zimmermann *et al.,* 2005; Alcalá-Galiano *et al.,* 2008; Bilo *et al.,* 2010; İşcan & Steyn, 2013; Ross & Juarez, 2016). In the paediatric skull, the presence of open sutures provides the skull with greater elasticity and flexibility, and fractures of this region tend to be minimally displaced (Zimmermann *et al.,* 2005; Alcalá-Galiano *et al.,* 2008; İşcan & Steyn, 2013). The adult skull is much more rigid, and BFT to this region therefore results in displaced, often comminuted fractures in adults (Zimmermann *et al.,* 2005; Alcalá-Galiano *et al.,* 2008). The thicker, stronger periosteum characteristic of children's bones, together with the increased malleability as a result of a larger network of Haversian canals, makes children's bones much more resistant to fracturing (Love & Symes, 2004; Bilo *et al.,* 2010; İşcan & Steyn, 2013; Ross & Juarez, 2016). The long bones of children therefore tend to bow rather than break, resulting in incomplete, greenstick fractures at the side subjected to tensile forces, while the same force applied to adult bones frequently results in complete, displaced fractures, with failure occurring at both the tension and compression sides (Bilo *et al.,* 2010; Ross & Juarez, 2016). Moreover, the greater porosity of the paediatric skeleton prevents the propagation of fractures, which results in comminuted fractures being uncommon in children, but occurring frequently in adults (Ross & Juarez, 2016). The complete, displaced, comminuted fractures typical of adult bones may be easier to detect radiologically, which may result in increased sensitivity for detecting skeletal trauma in adult individuals compared to infants or children. According to the vast majority of results reported by studies presented in Tables 2.1 and 2.2, radiological sensitivity for detecting skull and limb fractures is generally greater in adults compared to children, while the opposite is true when considering the detection of rib fractures. However, none of these studies directly compared fracture detection rates in children and adults in the same study.

Studies evaluating the radiological detection of osteological lesions as a result of SFT are much more limited (Table 2.3). Both Schnider *et al.* (2009) and Thomsen *et al.* (2009) compared the detection of SFT using CT against autopsy findings, reporting that CT was as sensitive or even more sensitive than autopsy for detecting these skeletal lesions. CT scans can therefore be considered accurate for detecting sharp force skeletal defects, but information regarding the use of X-rays or Lodox for this purpose is not known. In addition, there is a paucity of research evaluating the radiological detection of SFT using the dry bones as the standard of comparison, and this therefore needs to be assessed.

While the detection of BFT and SFT is essential, additional information regarding this trauma can also be crucial and contribute to post-mortem medico-legal investigations (Grassberger *et al.,* 2011; İşcan & Steyn, 2013; Johnson *et al.,* 2014; Love & Wiersema, 2016). For example, the location and specific characteristics of skull fractures in infants and children may aid in distinguishing between accidental and abusive trauma. Kim *et al.* (2012) assessed the ability of X-rays to detect different types of skull fractures, including linear, depressed and diastatic fractures, but this was compared to CT findings as the gold standard (Table 2.1). While Mulroy *et al.* (2012) compared the detection of linear and diastatic fractures between X-rays and CT using the cleaned skeletons as the reference standard, additional skull fracture types such as complex and depressed fractures, as well as fracture locations, were not evaluated (Table 2.1).

The direction and number of impacts inflicted is also routinely assessed during forensic examinations (Love & Wiersema, 2016). While Grassberger *et al.* (2011) and Johnson *et al.* (2014) did indicate the potential of CT scans to determine the minimum number and direction of BFT and SFT blows, respectively, these examinations were performed in surviving victims of violent crime and a comparison against the dry bones could not be performed to confirm these findings.

The macroscopic characteristics of SFT can aid in confirming the class of weapon used during a traumatic event (Symes *et al.,* 2012; İşcan & Steyn, 2013; Love & Wiersema, 2016; Alsop *et al.,* 2021; Karray *et al.,* 2021; Weber *et al.,* 2021). Ampanozi *et al.* (2010), Johnson *et al.* (2014) and Wittschieber *et al.* (2016) all reported that CT scans can be used to accurately interpret the macroscopic features of hacking trauma to bone, and that the weapon used (either an axe or a hatchet), could be confirmed based on these characteristics. However, these studies were case studies where the exact weapon used to inflict trauma was known prior to radiological imaging, and imaging was used to confirm the use of this weapon (Table

2.3). No study could be found that has aimed to distinguish between two or more possible classes of sharp force weapons based on these characteristics.

Differences in sample size, makes and models of scanning technologies, and standards of comparison used in each of these previous studies have resulted in contradictory reported sensitivity, and do not allow for direct comparisons to be made. As a result, more research using dry bone as the gold standard, and comparing all three imaging methods in a single study, is needed.

2.2.5. Forensic anthropology and the radiological analysis of skeletal trauma

Forensic pathology and forensic anthropology are both becoming more virtual in nature and including radiological imaging as part of the post-mortem examination process is becoming common practice (Franklin *et al.*, 2016; Garvin & Stock, 2016; Obertová *et al.*, 2019). As a result, these specialists are frequently required to interpret radiological images, particularly with regard to human identification and skeletal trauma examination. Research has shown that forensic pathologists, regardless of their level of radiological experience, are able to use radiographic material with the aim of identifying the deceased. Ali *et al.* (2020) assessed the abilities of a forensic pathologist with radiological experience and a non-medically trained intern to compare skeletal features on ante- and post-mortem radiological records. They found that both observers were able to positively match the records from all 20 cases, resulting in a 100.0% identification rate for both observers. These results indicate that identifying unknown remains using radiological means is possible regardless of the level of radiological experience and making a positive identification does not require the expertise of a highly trained forensic radiologist (Ali *et al.*, 2020).

The detection of skeletal trauma, however, may be more challenging and during these examinations, radiological training may be required. Several studies (Loughran, 1994; McLauchlan *et al.*, 1997; Hong *et al.*, 2011; Schulze *et al.*, 2013) have indicated that fracture detection rates increase substantially when more radiologically experienced specialists perform the virtual skeletal analyses as opposed to less experienced observers. This confirms the importance of radiological training when conducting virtual trauma examinations.

While the level of radiological experience as a predictor for fracture detection sensitivity has been evaluated using clinical radiologists and forensic pathologists, forensic anthropologists have not been assessed. This is significant since virtual imaging is becoming an increasingly essential component of modern forensic anthropology practices and these specialists, despite typically having very limited, if any, radiological training (Franklin *et al.,* 2016), are frequently required to conduct analyses of skeletal trauma using radiographic material. It is therefore important that the ability of forensic anthropologists to correctly detect fractures using virtual means is assessed.

2.3 Animals as proxies for humans in forensic research

Due to ethical reasons, animal models are frequently used in forensic research in order to study bone biomechanics and fracture patterns, tool mark analysis, and decomposition (Baumer *et al.,* 2010; Matuszewski *et al.,* 2020; Waltenberger *et al.,* 2021). Some of the animal models used to evaluate skeletal trauma include rabbits (Kleinman & Schlesinger, 1997; Yu *et al.,* 2020), deer (Wheatley, 2008; Freas, 2010) and even reptiles (Pham, 2020). The most commonly used animal model in forensic research, however, is the pig (Humphrey & Hutchinson, 2001; Cattaneo *et al.,* 2006; Lynn & Fairgrieve, 2009; Baumer *et al.,* 2010; Ferllini, 2012; Green & Schultz, 2017; Waltenberger & Schutkowski, 2017; Wei *et al.,* 2017; Waltenberger *et al.,* 2021). Pigs are of a similar size and body composition to humans, with comparable soft tissue thicknesses surrounding regions of the body such as the ribs (Matuszewski *et al.,* 2020; Waltenberger *et al.,* 2021). In addition, research has shown that SFT produces skeletal cut mark proportions that are comparable between pigs and humans, suggesting that pigs are the preferred species for conducting experimental analyses of SFT (Waltenberger *et al.,* 2021). As a result of these anatomical similarities between pigs and humans, pigs are considered suitable proxies for humans to perform forensic and skeletal related research (Matuszewski et al., 2020; Waltenberger et al., 2021). It must be noted, however, that there are some significant morphological differences between humans and pigs which could affect the radiological detection of trauma when pigs are used as proxies for humans. For example, the pig skull has a more elongated snout and face, with bones oriented more laterally and dorsally, compared to the more orthognathic face of humans where bones are oriented more anteriorly. These differences may make the radiological detection of facial fractures challenging in pigs. Growth rates between pigs and humans also differ, with epiphyseal closure occurring much earlier in pigs (Reichert *et al.,* 2009). However, growth patterns are similar, and distinguishing between fractures and epiphyseal fusion lines or sutures in pigs is similar to that in humans (Scheuer & Black, 2004; Zeder *et al.*, 2015).

Chapter 3: Materials and Methods

3.1. Study sample

To determine the diagnostic accuracies of the various radiological methods in detecting osteological trauma, deceased individuals or animal proxies should be subjected to trauma so that the dry bones can be used as the gold standard against which to compare these methods. Therefore, pig carcasses (*Sus scrofa domesticus)* were used in this study and were donated by GHB Farms in Bronkhorstspruit, South Africa (25°97’02.37”S 28°68’08.39”E).

The cause of death in these pigs was natural, most commonly as a result of haemorrhagic bowel syndrome, an intestinal disease caused by *Clostridium perfringens* or *Lawsonia intracellularis.* This disease is fatal and is a common occurrence in pigs in large pig farms (Straw *et al.*, 2002). Due to this disease being the cause of death in the pigs used, no pigs had to be euthanised or terminated specifically for the purposes of this study. This disease also does not affect the skeletal system of the pigs, which did not compromise the infliction or examination of osteological trauma.

Pig carcasses with any obvious pre-existing trauma were excluded from the study. Either on the day of or the day after death, pigs were transported from GHB Farms in double body bags to the School of Anatomical Sciences at the University of the Witwatersrand. They were stored in refrigerators at 2-4° Celsius until they were macerated, which was no longer than five days.

3.1.1. Piglets

This sample comprised of twelve piglet carcasses - each weighing between 5 and 15 kilograms, with an age range of approximately 3-6 weeks. Piglets of this weight range were selected as it is comparable to the weights of human infants and children, and therefore instances of trauma in children could be simulated more accurately.

One piglet was used as a test subject in a pilot study, which was conducted in order to establish how hard each blow should be to actually cause a lesion, to determine the best protocols for taking CT, X-ray and Lodox scans, and to determine the best way to macerate the remains without altering or exacerbating the trauma.

One piglet was not inflicted with trauma and was used as a negative control. This ensured that any skeletal anomalies or bone cortex discontinuities visible radiologically were indeed fractures caused by the inflicted trauma, and not the result of artifacts caused by the imaging modalities themselves.

The remaining ten piglets were used as study piglets in order to determine the fracture detection sensitivity of the imaging methods. Five of these study piglets were also used to address objective 1 of this study, which was to determine the ability of forensic anthropologists to detect osteological trauma.

3.1.2. Adult-sized pigs

Twenty-three adult-sized pig carcasses were used to assess the radiological detection of blunt (BFT) and sharp force (SFT) skeletal trauma in adult proxies. These pigs weighed between 47 and 82 kilograms, with an age range of approximately 14-20 weeks. While these pigs were still technically considered sub-adult as complete epiphyseal closure had yet to occur, they were much larger and older than the piglets used, and their weight range is comparable to that of the average adult human.

As with the piglet sample, one pig was used as a negative control, one pig was used as a pilot pig for the assessment of BFT, and one pig was used as a pilot pig for the assessment of SFT. The remaining twenty pigs were used as study pigs, which included ten BFT pigs and ten SFT pigs.

3.2. Infliction of trauma

Trauma was inflicted post-mortem upon piglets and adult-sized pigs in four major regions of the body: the skull, trunk (consisting of the ribs and vertebrae), forelimbs and hindlimbs. All trauma infliction was performed in a secluded, post-mortem laboratory in the Central Animal Services (CAS) at the Faculty of Health Sciences, University of the Witwatersrand, away from other staff and researchers so as not to impact on their sensitivity.

3.2.1. Blunt force trauma

Piglets and adult-sized pigs were subjected to BFT. Piglets were struck with a 55 x 55 mm, 500 g rubber mallet (Fig 3.1). This tool was chosen in order to simulate the most commonly used weapon in instances of violence against children, namely a fist (Bennett Jr *et al.*, 2006), as trauma using a fist and a hammer/mallet results in the same type of BFT fractures (Fenton *et al.,* 2003; Dedouit *et al.,* 2016). Anterior-posterior compression of the ribcage, which is the most common cause of abuse-related rib fractures (Kleinman & Schlesinger, 1997; Bilo *et al.*, 2010), was attempted in the first two study piglets. However, this type of trauma did not result in any rib fractures and was not further explored. All body regions of the remaining eight study piglets, as well as an additional two, were therefore struck with the mallet.

A 1.1 kg, 50 x 50 mm steel mallet (Fig 3.2) was used on the adult-sized pigs since this type of instrument is one of the most commonly used in cases of BFT (Sorenson & Wiebe, 2006; South African Police Services, 2020), and causes trauma similar to what is the case with other BFT instruments.

An individual in the School of Anatomical Sciences, not associated with this study, inflicted the BFT upon the pigs. This kept the primary investigator blind to the exact number of strikes that each body region was inflicted with, thus reducing bias. To prevent this independent individual from being emotionally impacted by the infliction of BFT, piglets and adult-sized pigs were placed in black bags prior to being struck. The individual isolated each body region, striking the skulls between one and five times, and each of the other three body regions between one and ten times. Strikes were inflicted upon the left and right lateral surfaces of each body region, as well as the dorsal surfaces of the skull and trunk.

3.2.2. Sharp force trauma

In South Africa, kitchen knives and pangas, weapons similar to machetes, are among the most commonly used sharp instruments causing SFT to the skeleton (South African Police Services, 2020). These two weapons result in different types of osteological SFT. Knives are generally used during incidences of stabbing, resulting in puncture or incision defects on bone (Ferllini, 2012; İşcan & Steyn, 2013), while pangas are used to inflict hacking trauma, which causes sharp-blunt, chop defects on bone (Humphrey & Hutchinson, 2001; Lynn & Fairgrieve, 2009; İşcan & Steyn, 2013).

In order to accurately simulate these types of injuries, a non-serrated kitchen knife and a panga were used to inflict SFT on ten of the adult-sized pigs, with one side of the body being subjected to stabbing trauma using the kitchen knife, and the other side hacking trauma using the panga. The kitchen knife was single-edged and non-serrated, with a stainless-steel blade measuring 163 mm in length and 28 mm in width (Fig 3.3). The panga had a curved carbon steel blade, measuring 652 mm in length and 112 mm in width (Fig 3.4).

Due to the infliction of SFT being more emotionally traumatic than the infliction of BFT, the primary investigator inflicted the SFT injuries. Pigs were sealed in a single layer of plastic and placed on top of sheets of plastic prior to being struck in order to prevent any blood from leaking in the CAS facility. A radiographer confirmed that any plastic that may have become embedded in the stab/chop wounds would not affect the radiological imaging of this trauma in any way.

Each weapon was used to inflict between one and ten strikes to each of the four body regions, in locations similar to those as with BFT. Skulls were struck between one and ten times, rather than between one and five times as with BFT, since the skeletal area affected as a result of SFT is less than is the case with BFT, and therefore results in less fragmentation. The side of the body on which each sharp force instrument was used to inflict the trauma, as well as the exact number of strikes inflicted, were not kept consistent in order to reduce bias, but were recorded for each pig. These records, however, were not consulted when the pigs were radiologically assessed for trauma which further reduced bias.

Figure 3.1. Rubber mallet used to inflict BFT to piglets. The weight of the mallet is 500 g, with the head measuring 55 x 55 mm.

Figure 3.2. Steel mallet used to inflict BFT to adult-sized pigs. The weight of the mallet is 1.1 kg, with the head measuring 50 x 50 mm.

Figure 3.3. Stainless stell, single-edged, non-serrated kitchen knife used to inflict stabbing SFT to adult-sized pigs. The blade measures 163 mm in length and 28 mm in width.

Figure 3.4. Curved carbon steel panga used to inflict hacking SFT to adult-sized pigs. The blade measures 652 mm in length and 112 mm in width.

3.3. Radiological imaging

Following the infliction of trauma and prior to radiological scanning, piglets and adult-sized pigs were sealed in a double layer of plastic in order to prevent any fluids from leaking in the refrigerators where they were stored, or on the scanning tables. Pigs were also transported in double body bags to each institution where scanning took place.

CT scans were taken at the radiology practice of Dr TJ Nel Inc. at the Wits Donald Gordon Medical Centre in Johannesburg, X-rays were taken at CAS at the University of the Witwatersrand, and Lodox scans were taken at the Johannesburg Forensic Pathology Services. The parameters of each scanning method for both piglets and adult-sized pigs are presented in Table 3.1. A large number of X-ray scans were taken of each pig as a result of the small size of the X-ray cassettes available. This allowed only one body region to be scanned at a time for the piglets, while several scans needed to be taken of each body region for the adult-sized pigs because of their large size.

Table 3.1. Scanning parameters of CT, X-ray and Lodox scans of piglets and adult-sized pigs.

	Piglets			Adult-sized pigs		
	CT	**X-ray**	**Lodox**	**CT**	**X-ray**	**Lodox**
Milliampere seconds (mAs)	150	2.2-2.5	160	150-300	2-45	200
Kilovoltage (kV)	120	58	80	120	45-91	120
Slice thickness (mm)	3.0	-	-	3.0	-	-
Slice increment (mm)	1.5	-	-	1.5	-	-
Pitch	0.391	-	-	0.391	-	-
Reconstruction kernel	C: 500 W: 1500 on a D filter (bone kernel)	-	-	C: 500 W: 1500 on a D filter (bone kernel)	-	-
Scans taken	Full-body helical scan (64 Slice CT Brilliance)	Ventro-dorsal and left and right lateral views of each body region. Left 45° dorsal-right ventral oblique and right 45° dorsal-left ventral oblique views of the ribs.	Full-body ventro-dorsal and left and right lateral views of each body region, and 7° and 15° oblique views of the ribs.	Full-body helical scan (64 Slice CT Brilliance)	Ventro-dorsal and left and right lateral views of each body region.	Full-body ventro-dorsal and left and right lateral views of each body region.
Number of scans and approximate time taken per specimen	1 scan (±10 minutes total)	10-15 scans (±1 hour total)	5 scans (±2 minutes total)	1 scan (±10 minutes total)	24-28 scans (±1.5-2 hours total)	3 scans (±1.5 minutes total)

3.4. Maceration and reconstruction

The cleaned, dry bones were considered the gold standard in this study, and therefore, after all scanning had taken place, pigs were macerated in the School of Anatomical Sciences following the School's standard maceration procedures. Piglets were gently simmered for approximately one day, while adult sized-pigs were gently boiled for between one and two days. All pigs were boiled in cloth bags so that no skeletal elements went missing or became comingled with each other, as several pigs were boiled simultaneously in the same boiling pot. The soft tissue was then removed from the bones using blunt dissection with the fingers, and any remaining cartilage was delicately removed using a scalpel. The bones were then cleaned using warm water and a toothbrush, after which they were left to dry for between five and ten days.

The dry skeletons were then anatomically reconstructed by carefully gluing the skulls and other fractured bones back together using a glue gun. Extreme care was taken both during the maceration and reconstruction phases in order to ensure that no additional trauma was introduced to the bones.

The soft tissues of the pig carcasses were discarded as medical waste by the School of Anatomical Sciences, and the pig skeletons are being retained in the School for teaching and research purposes.

3.5. Data collection and analysis

3.5.1. Definitions

The number of true-positive, false-positive, true-negative and false-negative skeletal lesions identified during the radiological and dry bone assessments were recorded. The sensitivity, specificity, positive predictive value and negative predictive value were then calculated according to the following definitions.

3.5.1.1. True-positive identification

A true-positive identification is a fracture/defect that is identified radiologically and is also present on the dry bones (Parikh *et al.,* 2008).

3.5.1.2. False-positive identification

A false-positive identification is a fracture/defect that is detected radiologically, but is not actually present osteologically (Parikh *et al.*, 2008).

3.5.1.3. True-negative identification

A true-negative identification is a fracture/defect that is not identified radiologically, and which is also not present on the dry bones (Parikh *et al.*, 2008).

3.5.1.4. False-negative identification

A false-negative identification is a fracture/defect that is not detected radiologically, but which is actually present osteologically (Parikh *et al.*, 2008).

3.5.1.5. Sensitivity

Sensitivity is a radiological method's ability to identify true-positive fractures/defects (Parikh *et al.*, 2008), and is calculated as follows:

$$\frac{number\ of\ true-positives}{number\ of\ true-positives\ +\ number\ of\ false-negatives}\ x\ 100$$

3.5.1.6. Specificity

Specificity is a radiological method's ability to detect true-negative and not false-positive fractures/defects (Parikh *et al.*, 2008), and is calculated as follows:

$$\frac{number\ of\ true-negatives}{number\ of\ true-negatives+number\ of\ false-positives}\ x\ 100$$

3.5.1.7. Positive predictive value

The positive predictive value (PPV) of an imaging modality is the probability that a fracture/defect detected is indeed a true-positive identification (Parikh *et al.*, 2008), and is calculated as follows:

$$\frac{number\ of\ true-positives}{number\ of\ true-positives+number\ of\ false-positives}\ x\ 100$$

3.5.1.8. Negative predictive value

The negative predictive value (NPV) of an imaging modality is the probability that a fracture/defect not detected is indeed a true-negative identification (Parikh *et al.*, 2008), and is calculated as follows:

$$\frac{number\ of\ true - negatives}{number\ of\ true - negatives + number\ of\ false - negatives}\ x\ 100$$

3.5.2. Radiological and osteological trauma examinations

For all piglets and adult-sized pigs, the number of skeletal blunt force fractures/sharp force defects visible both radiologically and osteologically in each body region was noted. For the skull, it was noted whether the defect was present on the cranium or mandible, while for the ribs, location was recorded either as vertebral end, shaft, or sternal end. For the limbs, the exact bones on which defects were present were recorded, and for long bones, it was noted whether defects were proximal, distal, or on the shaft. Fractures or sharp force defects were identified radiologically as non-anatomical bone radiotransparencies and discontinuities of the bone cortex.

Due to the inherent nature of both conventional X-rays and Lodox scans to superimpose structures, this will always pose a challenge when assessing skeletal trauma using these methods during real life forensic examinations. As a result, no attempt was made to distinguish between whether fractures were not recognized or whether they simply could not be seen due to the limitations of imaging. In addition, no attempt was made to distinguish between no fracture identified, and a fracture mistaken for an epiphyseal fusion line or suture.

For piglets, the sensitivity of each radiological method for detecting postcranial BFT fractures was calculated, and sensitivity and specificity for detecting skull fractures were calculated. For adult-sized pigs, sensitivity, specificity, PPVs and NPVs for both BFT and SFT lesions were calculated.

For piglets and adult-sized pigs, an estimate of the minimum number of strikes inflicted was also recorded based on radiological and dry bone examinations. This was achieved by ascertaining which fractures/defects were likely the result of a single impact. A minimum number was determined as some strikes may not have resulted in any osteological lesions, and some lesions may result from more than one impact (Love & Symes, 2004; İşcan

& Steyn, 2013). The sensitivity of each imaging method for determining the minimum number of BFT and SFT impacts was calculated.

Two-way ANOVA tests were conducted in order to determine if the mean number of fractures/defects and minimum number of impacts detected radiologically were significantly different to those identified osteologically.

The primary investigator, who received brief radiological training prior to the start of this study, performed all radiological and dry bone assessments. This radiological training amounted to approximately 10 hours and included two workshops hosted by Lodox® Systems (Pty) Ltd, which covered the basics of detecting skeletal lesions. In addition, radiological image post-processing training, which included the interpretation of CT images using multi-planar reconstruction (MPR), maximum intensity projection (MIP) and 3D volume rendering, was provided by a radiologist.

CT, X-ray and Lodox scans were all viewed digitally, and RadiAnt DICOM Viewer (version 2020.2) was used to conduct all radiological assessments. For X-ray and Lodox scans, which were captured on CDs, better visualization of the bones and potential fractures was achieved by zooming in and enhancing the contrast of the images. For CT scans, 2D images, 3D reconstructions, MPR and MIP were assessed in order to ensure that each bone was viewed in its entirety in each plane. Radiological examinations were only conducted three months after the infliction of trauma, scanning and maceration, in order to reduce memory bias regarding the exact number of strikes inflicted to each pig. Dry bone examinations were only conducted after the radiological assessments had been completed.

The levels of both inter- and intra-observer agreement for detecting fractures/defects and the minimum number of impacts were calculated using Cohen's kappa. A radiologist read the CT, X-ray and Lodox scans of five BFT piglets, five BFT adult-sized pigs and five SFT adult-sized pigs to perform assessments of inter-observer repeatability. The primary investigator performed intra-observer repeatability assessments by reading and re-reading the scans of these same piglets and adult-sized pigs approximately one to two months apart. All two-way ANOVA and Cohen's cappa calculations were performed using SPSS (version 26).

Additional data collection and analyses not described above were performed on the BFT piglets and SFT adult-sized pigs in order to achieve the associated study objectives, as outlined below.

3.5.2.1. Objective 1 – Forensic anthropologist's ability to detect skeletal trauma

In order to achieve this objective, the radiological images of five of the piglets subjected to BFT were assessed by the radiologist, the primary investigator who is a novice forensic anthropologist (NFA) with approximately four years of forensic experience, and two additional observers. These observers were more experienced forensic anthropologists (EFAs), one with approximately 12 years of experience in the forensic field, and the other with approximately 30 years' experience and clinical training. Neither of the EFAs had any significant radiological training or experience, and, due to the availability of each observer, one performed the assessments of the CT and Lodox scans, and the other examined the X-rays. The EFAs did, however, receive very brief training on how to use RadiAnt DICOM viewer, and how to use the zoom, contrast, MPR and MIP functions in order to optimize the visualization of the bones. The NFA, who had brief radiological training, was also very familiar with piglet osteology while the radiologist and EFAs were not.

The level of agreement between each observer for detecting fractures was calculated using Cohen's kappa, and the sensitivity and specificity with which each observer detected these fractures in each body region was determined. Due to the highly fragmentary nature of the skulls following BFT, the skulls were not assessed in this sample.

3.5.2.2. Objective 2 – blunt force trauma in piglets

In addition to detecting the number of fractures present in each body region, the sensitivity and specificity of each imaging modality for identifying the specific type and location of skull fractures was determined.

The fracture type was classified according to descriptions by Hobbs (1984) and Bilo *et al.* (2010) and included simple linear, diastatic, complex, and depressed fractures. Simple linear fractures are identified as single, isolated fracture lines; fractures causing a widening of the sutures are diastatic fractures; and complex and depressed fractures consist of two or more fracture lines, including radiating and/or concentric fractures, which are frequently interconnected. The latter two fracture types are distinguished from each other as depressed fractures often have a distinct impression at the site of the impact, while this is absent in complex fractures. Individual radiating and concentric fracture lines associated with these two types of fractures were not counted, but only a single complex/depressed fracture was recorded.

The specific bone, suture or skull region where a fracture was present, which is outlined in detail in Table 1 of Paper 3 in Chapter 4 (Results), was classified as the location of the fracture. The bone on which the majority of a simple linear fracture was present was considered the fracture location, while for complex and depressed fractures, the location was the bone where the site of impact likely occurred.

When examining post-cranial fractures, specifically those of the ribs and limbs, the abilities of the radiological methods to determine the directionality of the trauma was assessed. This was done by locating osteological sites of tension and compression. While ribs tend to fail under compression first (Love & Symes, 2004), the long bones of the limbs initially fail under tension (Symes *et al.*, 2012; Reber & Simmons, 2015). The side of the bone subjected to compression forces is considered the location of the impact.

3.5.2.3. Objective 4 – sharp force trauma in adult-sized pigs

In addition to identifying the number and location of sharp force skeletal defects, the type of SFT was also recorded as either stabbing or hacking trauma. Following guidelines by numerous authors (Humphrey & Hutchinson, 2001; Lynn & Fairgrieve, 2009; Ferllini, 2012; İşcan & Steyn, 2013), several macroscopic characteristics were considered when distinguishing between the two types of SFT. These traits are outlined in Table 3.2. Bone wastage occurs when the sharp instrument is removed from the bone, resulting in bone fragments being separated from the main section of bone (Lynn & Fairgrieve, 2009; İşcan & Steyn, 2013). Chattering refers to the presence of bone chipping at the site of trauma (Humphrey & Hutchinson, 2001).

Table 3.2. Characteristics used to distinguish between stabbing trauma inflicted with a kitchen knife, and hacking trauma inflicted with a panga, as described by Humphrey & Hutchinson (2001), Lynn & Fairgrieve (2009), Ferllini (2012), and İşcan & Steyn (2013).

Stabbing trauma	Hacking trauma
Narrow defects	Wide defects
Cut marks and puncture wounds	Chop marks
Small nicks or notches in the bone cortex	Bisected and comminuted defects
Minimal bone wastage, chattering, flaking, crushing, and fracturing	Significant bone wastage, chattering, flaking, crushing, and fracturing
Hinge fractures	Sharp-blunt characteristics

3.6. Ethics

Ethical approval to conduct this research was granted by the Animal Research Ethics Committee at the University of the Witwatersrand (Clearance Certificate Number 2019/04/27/O) (Appendices 8.4.1 and 8.4.2), as well as the South African Department of Agriculture, Forestry and Fisheries (Appendix 8.5.1). Permission was also obtained by the Chief State Veterinarian (Pretoria) (Appendix 8.5.2), GHB Farms (Appendix 8.5.3), and the relevant institutions where radiological scanning was performed (Appendices 8.5.4 - 8.5.6).

3.7. Funding

Funding for the completion of this research was provided by the National Research Foundation (NRF) (grant number 118149, awarded to Associate Professor Desiré Brits) and the NRF/Deutscher Akademischer Austausch Dienst (DAAD) (grant number 117943, awarded to the primary investigator). Associate Professor Desiré Brits and Professor Maryna Steyn also contributed additional funding.

Chapter 4: Results

In line with the University of the Witwatersrand Faculty of Health Sciences' "Style Guide for Theses, Dissertations and Research Reports", the results of this thesis are presented in the divided block format and comprise a series of published and/or submitted research papers addressing the study objectives. At the time of this thesis being submitted for examination, three papers have been published, one has been submitted to a journal and is under review, and one has been written and is ready to submit to a journal. These papers are as follows:

- **Paper 1:** Can forensic anthropologists accurately detect skeletal trauma using radiological imaging? **(Published)**
- **Paper 2:** Forensic imaging: The sensitivities of various imaging modalities in detecting skeletal trauma in simulated cases of child abuse using a pig model **(Published)**
- **Paper 3:** A comparison of computed tomography, X-ray and Lodox® scans in assessing pediatric skull fractures using piglets **(Published)**
- **Paper 4:** Diagnostic accuracies of CTs, X-rays and Lodox to detect blunt force trauma in adults, using a pig model **(Submitted to journal and under review)**
- **Paper 5:** Radiological detection of sharp force skeletal trauma: implications for the accurate investigation of victims of violent crime **(Written and ready to submit)**

The student's contribution to each research paper, the agreement of each co-author to include these papers in this thesis, and copyright permission from the publishers to include these papers, are included in Appendices 8.2 and 8.3.

Each paper is formatted according to the author guidelines of the journal it has been published in/submitted to and, as a result, differs in format, spelling and reference style both from each other and from the rest of this thesis.

Paper 1

Can forensic anthropologists accurately detect skeletal trauma using radiological imaging?

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Declaration: The contents of this paper are the original work of the authors submitted to the Faculty of Health Sciences, University of the Witwatersrand, in fulfilment of the requirements for the degree of Doctor of Philosophy.

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Abstract

Radiological imaging is often used to aid in forensic anthropological examinations. While forensic anthropologists may need to detect skeletal trauma virtually, they generally have very little to no radiological training. The aim of this study was to assess the ability of forensic anthropologists to accurately detect fractures using radiology. Five piglets were struck with a mallet, post-mortem, and then scanned using CT, X-ray and Lodox®. The number of fractures detected on each modality was recorded by a senior radiology resident (SRR), a novice forensic anthropologist (NFA) with brief radiological training, and more experienced forensic anthropologists (EFA) with limited to no radiological training. The piglets were macerated and the number of fractures present on the dry bone were counted. The percentage of fractures detected by each observer using each method in comparison to the dry bone was calculated. Cohen's kappa revealed that agreement between the NFA and SRR was considered substantial to almost perfect (k=0.77-1.00), while agreement between the EFA and SRR was fair to almost perfect (k=0.21-1.00). However, while the SRR and NFA had comparable sensitivity (0.0-83.7% and 0.0-89.3% respectively), the EFA detected on average 22.0% less fractures than the NFA (0.0-62.4%). This indicates that even brief radiological training increases the sensitivity of fracture detection, and that the ability of forensic anthropologists to detect fractures virtually without training is not sufficient when evaluating cases with suspected trauma. It is therefore suggested that all forensic anthropologists, both novice and more experienced, should receive radiological training in order to accurately detect fractures.

Key words: Forensic imaging; forensic anthropology; skeletal trauma; fracture detection ability; Computed Tomography (CT); X-ray; Lodox®

Introduction

Both forensic pathologists and forensic anthropologists are involved in the examination and identification of deceased individuals. Forensic pathologists conduct autopsies in order to determine cause and manner of death and are also commonly relied upon to determine the identification of unknown decedents [1]. Forensic anthropology is concerned with the analysis and identification of decomposed or skeletal remains, which includes the construction of a biological profile and the evaluation of bone pathologies and trauma [2, 3]. In recent times, these disciplines have started to shift toward a more virtual approach, with examinations being conducted less invasively, using various radiographic tools [3].

Forensic odontologists, pathologists and anthropologists also rely on radiological methods to assist in the identification of unknown decedents by comparing ante- and post-mortem records of dentition [4-6], paranasal sinuses [1, 7-9] and unique skeletal variations, pathology or trauma [1, 3, 10, 11]. These methods of identification are particularly useful when dealing with decomposed [12], skeletonized [3] or burnt remains [13, 14], as well as during disaster victim identification [3, 5, 8], when DNA or fingerprint analysis is not possible or feasible.

Forensic imaging is being used more frequently in the construction of biological profiles during forensic anthropological analyses. Methods for the estimation of sex, age-at-death and living stature have been conducted using magnetic resonance imaging (MRI) scans [15-17], computed tomography (CT) scans [18-20], conventional X-rays [21-23] and low-dose full-body X-ray (Lodox®) scans [24, 25]. Skull radiographs have also been used to aid in the construction of craniofacial approximations [26].

Forensic pathologists increasingly rely on the use of imaging modalities as a complementary tool during traditional autopsy procedures and in some institutions, these modalities are even used to conduct virtual autopsies, or "VIRTOPSIES®" [27, 28]. Conventional autopsies are extremely time-consuming, labour-intensive, invasive, and have many cultural, religious and emotional implications, and the use of radiological imaging to conduct virtual autopsies have therefore garnered much interest [3, 27, 28]. The assessment of both soft tissue and the skeleton can be conducted using radiological methods such as CT and MRI scans, and is particularly important for the detection of skeletal trauma which is regularly assessed during autopsies and forensic anthropological examinations in order to establish the circumstances surrounding death, and to identify victims of abuse [3]. Fractures, which are common in victims of physical abuse and violent crime [29], and the detection of which is critical in these cases, are regularly missed during traditional autopsies, with between 9% and 69% of fractures going unnoticed [30, 31]. Fractures sustained peri-mortem and which have not yet begun to heal and form calluses are frequently undetected during autopsy procedures [30]. In addition, fractures in regions particularly difficult to assess during autopsy are also regularly undetected [31, 32]. While remains may be macerated so that forensic anthropologists can conduct skeletal analyses to detect trauma, this process is time-consuming, expensive and not always feasible [33]. Furthermore, in living individuals, skeletal trauma can only be visualized radiologically. The use of imaging tools aids in the rapid and accurate detection of bone fractures [3], which could assist in identifying both victims and perpetrators of abuse and violent crime.

Ali et al. [1] suggest that forensic pathologists with limited radiological experience can accurately compare ante- and post-mortem records of skull features in order to identify unknown decedents. However, the detection of trauma in the rest of the skeleton may be more challenging and may require the expertise of a radiologist, which is not always practical during forensic analyses where forensic anthropologists who typically have no to limited radiological training and experience, may be required to interpret radiological scans themselves [3]. Although many authors agree that the use of virtual methods to detect skeletal trauma is a critical part of modern forensic anthropology [3, 10, 11, 34], the ability of forensic anthropologists to accurately identify this trauma radiologically is not currently known. The aim of this study was therefore to determine the ability of both novice and experienced forensic anthropologists, in comparison to a radiologist, to accurately detect the number of skeletal fractures on CT, X-ray and Lodox® scans. For this purpose, a pig model was used.

Materials and methods

The Animal Research Ethics Committee at the University of the Witwatersrand (Clearance Certificate No 2019/04/27/O) and the South African Department of Agriculture, Forestry and Fisheries granted ethical permission for the completion of this study.

This paper forms part of a larger study by Spies et al. [35, 36] which investigated the abilities of various imaging modalities in detecting skeletal trauma. In order to assess whether forensic anthropologists can accurately detect skeletal trauma, the trunk (including the ribs and vertebrae), the anterior limbs and the posterior limbs of five piglets (5-15 kg each) were each hit between 1 and 10 times with a mallet post-mortem. Piglets were then radiographed. Helical computed tomography (CT) scans were taken at the Wits Donald Gordon Medical

Centre in Johannesburg using a 64 Slice Philips Brilliance CT scanner, with parameters of 120 kV, 150 mA, 3.0 mm slice thickness with a 1.5 mm slice increment, 0.391 pitch, and a reconstruction kernel C: 500 W: 1500 on a D filter (bone kernel). Conventional X-rays (58kV, 2.2-2.5mA) were taken at the Central Animal Services at the University of the Witwatersrand, and included ventrodorsal and left and right lateral views of each body region, as well as oblique views of both the left and right ribs Lodox® scans (80 kV, 160 mA) were taken at the Johannesburg Forensic Pathology Services and included ventrodorsal and right and left lateral views. Lodox® scanners are frequently used both in South Africa and worldwide, producing full-body X-ray images with very low doses of radiation and at very high speeds, and are therefore invaluable for performing initial trauma screening procedures [37]. For a more detailed description of the Lodox® scanner, the reader is referred to work by du Plessis et al. [37].

Four observers, including a fairly novice forensic anthropologist, more experienced forensic anthropologists, and a senior radiology resident read each scan. For the more experienced forensic anthropologists, one read the X-rays and another the CT and Lodox® scans. Two experienced forensic anthropologist observers, both with very limited radiological experience, were used due to the availability of each observer. While all forensic anthropologist observers had limited radiological experience, the novice received brief training in the basics of interpreting radiological images prior to the start of this study. This training amounted to approximately 10 hours, and included two workshops on detecting skeletal fractures and anomalies, as well as training by a radiologist on how to differentiate between anatomical and non-anatomical disruptions in bone cortex, and how to interpret CT scans using multiplanar reconstruction (MPR), maximum intensity projection (MIP) and volume rendering (3-dimensional reconstructions). The novice also had prior experience with sub-adult pig anatomy and osteology, which both the radiologist and experienced forensic anthropologists lacked.

Each observer recorded the exact number and location of fractures present in each body region as detectable on CT, X-ray and Lodox® scans. Fractures were detected based on non-anatomical linear radiolucencies and disruptions of the bone cortex. The skulls were not assessed as some were highly fragmented, and exact fracture numbers could not be determined as with the other body regions. All observers read the scans of each imaging modality using RadiAnt DICOM Viewer, and for CT scans, both 2-dimensional and 3-dimensional images were assessed.

The inter-observer repeatability between each of the observers for detecting the number and location of fractures was assessed using Cohen's kappa, where the level of agreement was considered slight with a kappa score of 0.00 - 0.20, fair with a score of 0.21 - 0.40, moderate with a score of 0.41 - 0.60, substantial with a score of 0.61 - 0.80, and almost perfect with a score >0.81 [38]. Intra-observer repeatability for the primary investigator, who was the novice forensic anthropologist, was also assessed using Cohen's kappa. As the aim of this study was specifically to assess inter-observer repeatability, the intra-observer repeatability for each other observer was not assessed.

The cleaned skeletons, which were considered as the standard of comparison in this study, were also assessed following maceration and skeletal reconstruction of each piglet, and the number of fractures present in the trunk, anterior and posterior limbs was determined. The sensitivity and specificity of each observer for detecting these fractures using each type of scanning method was calculated. Sensitivity is the correct radiological detection of a fracture which is also present on the dry bone, while specificity refers to detecting no fracture radiologically which is also not present osteologically [39]. Sensitivity is represented by the number of true-positive fractures divided by the total number of true-positives and false-negatives, whereas specificity is represented by dividing the number of true-negatives by the combined total of the number of true-negative and false-positive fractures [39]. IBM® SPSS® version 25.0 was used to perform all statistical analyses.

Results

A total of 279 post-cranial fractures were present on the dry bones, which included 178 rib fractures, 29 vertebral fractures, 31 anterior limb fractures and 41 posterior limb fractures. The overall sensitivity for the senior radiology resident (SRR) was 73.1% for CT, 51.3% for X-rays, and 45.9% for Lodox® scans. The novice forensic anthropologist (NFA) had a sensitivity of 77.4%, 54.5% and 47.7% for CT, X-rays and Lodox® scans respectively, while the sensitivity for the more experienced forensic anthropologists (EFA) was 53.4%, 28.3% and 31.5% respectively. Overall specificity ranged between 95.1% and 99.2% for all observers. Examples of frequently undetected fractures are presented in Figures 1-3.

The overall detection of fractures was highly repeatable between the SRR and NFA, with kappa values indicating almost perfect agreement between the two observers (CT 0.91; X-ray 0.86; Lodox® 0.89). Agreement between the SRR and the EFA (CT 0.64; X-ray 0.45; Lodox® 0.62) was similar to that between the NFA and EFA (CT 0.62; X-ray 0.48; Lodox® 0.62), and both were considered moderate to substantial agreement. Intra-observer repeatability for the NFA was considered substantial to almost perfect (CT 0.92; X-ray 0.78; Lodox® 0.86).

The kappa values indicating agreement levels between observers for each body region using each imaging modality are presented in Table 1. Repeatability between the SRR and NFA was consistently the highest, with substantial to almost perfect agreement for all regions and all radiological methods (kappa values between 0.77 and 1.00). Agreement between the SRR and EFA, and between the NFA and EFA, were comparable across all body regions and imaging modalities, with kappa values ranging between 0.21 for rib fractures detected using X-rays and 1.00 for vertebral fractures detected using both X-ray and Lodox® scans. In general, CT scans had the highest agreement between observers for all body regions, except the vertebrae, where X-rays and Lodox® had higher repeatabilities, and the anterior limbs for which repeatability was highest using X-rays. Repeatability using Lodox® scans was higher than X-rays for the ribs and posterior limbs, but repeatability using X-rays was higher than Lodox® scans for the anterior limbs. In general, regardless of imaging modality used, the highest agreement between all observers was for fractures of the vertebrae (k=0.70-1.00), while the lowest agreement between all observers was for the ribs (k=0.21-0.87).

The sensitivity for each observer in detecting fractures in each body region using each radiological method is presented in Table 2. The NFA had the highest sensitivity for all body regions using all diagnostic tools, with a range of 0.0% to 89.3%, and was comparable to the sensitivity of the SRR (0.0% to 83.7%). The EFA had the lowest sensitivity for detecting fractures across all regions and using all modalities, ranging between 0.0% and 62.4%. Sensitivity was highest for CT scans for all observers and all body regions (31.0-89.3%), and in general Lodox® scans had the lowest sensitivity (0.0-56.2%). In general, the ribs were the region with the highest sensitivity for all observers using all modalities (25.8-89.3%), while the spine had the lowest sensitivity (0.0-37.9%). For the SRR, NFA and EFA respectively, specificity ranged between 92.2-100.0%, 94.5-100.0% and 92.7-97.9% for CT scans; 83.0-

100.0%, 93.8-100.0% and 89.8-98.3% for X-rays; and 97.9-100.0%, 94.0-100.0% and 91.5-100.0% for Lodox® scans.

Table 1. Kappa values indicating level of agreement between the number of fractures detected by the senior radiology resident (SRR), novice forensic anthropologist (NFA) and experienced forensic anthropologist (EFA) in each body region using each imaging modality.

	Ribs			**Vertebrae**			**Anterior limbs**			**Posterior limbs**		
	CT	X-ray	Lodox	CT	X-ray	Lodox	CT	X-ray	Lodox	CT	X-ray	Lodox
SRR-NFA	0.87	0.77	0.83	0.97	1.00	1.00	0.86	1.00	0.95	0.97	0.90	0.88
SRR-EFA	0.54	0.21	0.53	0.70	1.00	1.00	0.59	0.69	0.53	0.67	0.56	0.66
NFA-EFA	0.52	0.28	0.54	0.72	1.00	1.00	0.60	0.69	0.49	0.64	0.57	0.63

A kappa value of 1.00 for vertebral fractures is likely because no observer identified any lesions in this region

Table 2. Sensitivity (%) of the senior radiology resident (SRR), novice forensic anthropologist (NFA) and experienced forensic anthropologist (EFA) in detecting fractures in each body region using each imaging modality.

	Ribs			**Vertebrae**			**Anterior limbs**			**Posterior limbs**		
	CT	X-ray	Lodox	CT	X-ray	Lodox	CT	X-ray	Lodox	CT	X-ray	Lodox
SRR	83.7	60.7	55.6	37.9	0.0	0.0	64.5	48.4	45.2	58.5	48.8	36.6
	(149/178)	(108/178)	(99/178)	(11/29)	(0/29)	(0/29)	(20/31)	(15/31)	(14/31)	(24/41)	(20/41)	(15/41)
NFA	89.3	64.6	56.2	37.9	0.0	0.0	67.8	48.4	48.4	61.0	53.7	43.9
	(159/178)	(115/178)	(100/178)	(11/29)	(0/29)	(0/29)	(21/31)	(15/31)	(15/31)	(25/41)	(22/41)	(18/41)
EFA	62.4	25.8	36.5	31.0	0.0	0.0	41.9	38.7	29.0	39.0	26.8	34.1
	(111/178)	(46/178)	(65/178)	(9/29)	(0/29)	(0/29)	(13/31)	(12/31)	(9/31)	(16/41)	(11/41)	(14/41)

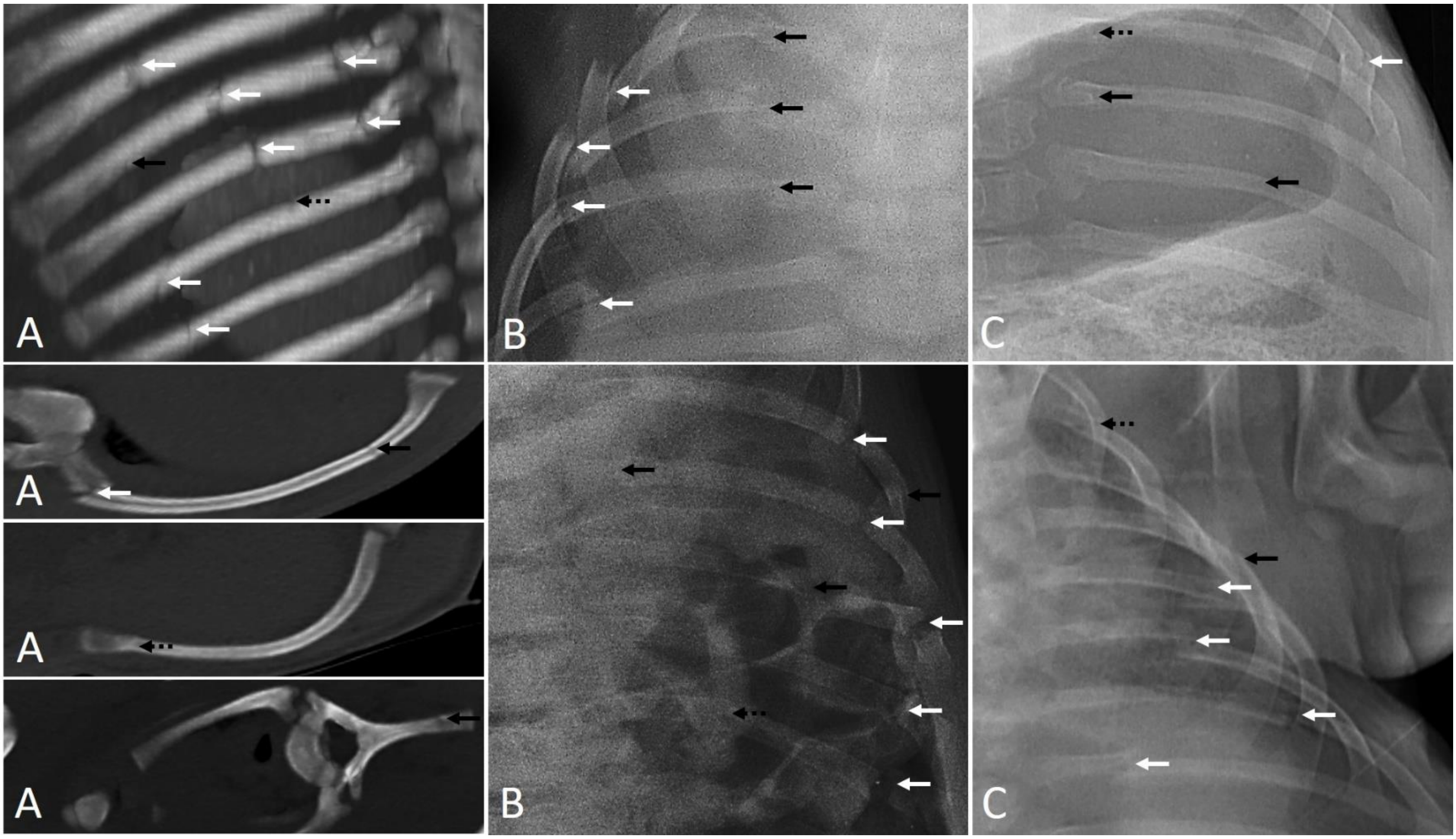

Figure 1. Frequently unidentified fractures of the ribs and vertebrae as shown with CT (A), X-ray (B) and Lodox® (C) scans. Solid white arrows indicate fractures identified by all observers; solid black arrows indicate fractures identified only by the SRR and NFA; dashed black arrows indicate fractures identified only by the NFA.

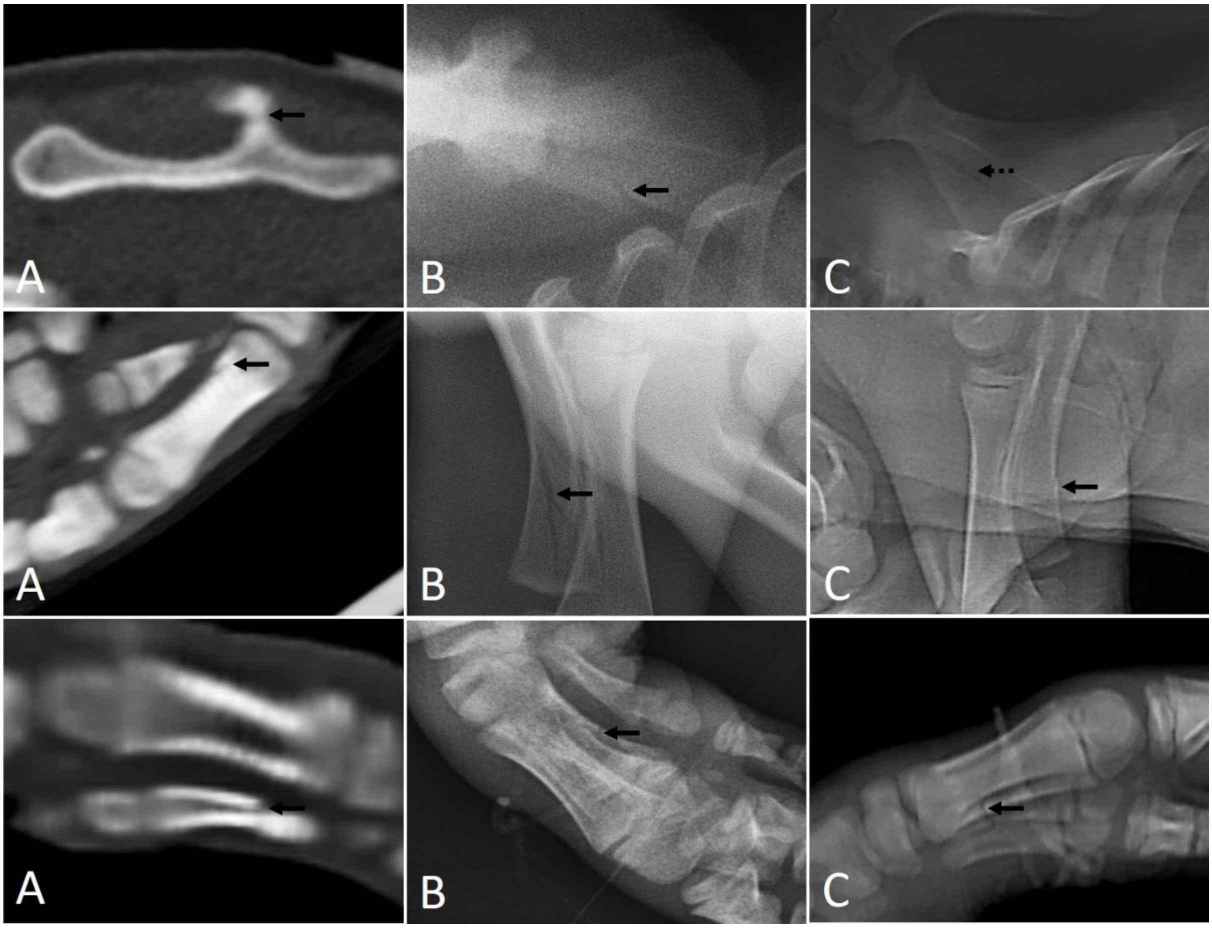

Figure 2. Frequently unidentified fractures of the anterior limb as shown by CT (A) (top: scapula; middle: metacarpal; bottom: metacarpal), X-ray (B) (top: scapula; middle: ulna; bottom: metacarpal) and Lodox® (C) (top: scapula; middle: ulna; bottom: metacarpal). Solid black arrows indicate fractures identified only by the SRR and NFA; dashed black arrows indicate fractures identified only by the NFA. A lack of white arrows indicates that none of the fractures were identified by all thee observers.

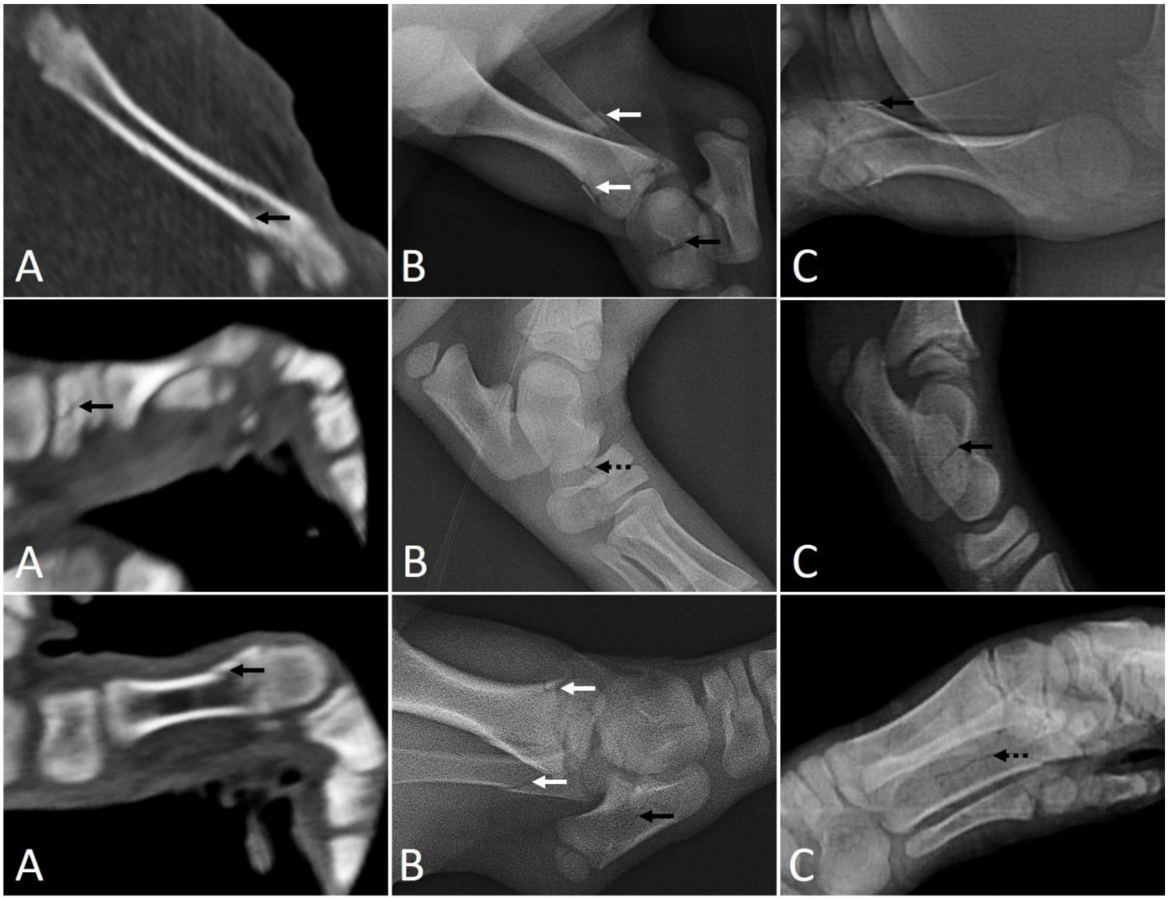

Figure 3. Frequently unidentified fractures of the posterior limb as shown by CT (A) (top: fibula; middle: tarsal; bottom: metatarsal), X-ray (B) (top: tibia, fibula and talus; middle: tarsal; bottom: tibia, fibula and calcaneus) and Lodox® (C) (top: fibula; middle: talus; bottom: metatarsal). Solid white arrows indicate fractures identified by all observers; solid black arrows indicate fractures identified only by the SRR and NFA; dashed black arrows indicate fractures identified only by the NFA.

Discussion

Radiological imaging is often used during forensic anthropological analyses, which includes the assessment of skeletal trauma. Two papers from the same larger study compared the abilities of CT, X-ray and Lodox® scans in detecting fractures of the skull, trunk, forelimbs and hindlimbs of piglets subjected to blunt force trauma [35, 36]. The results of these papers showed that many fractures were missed using all imaging modalities, but that CT consistently had the highest sensitivity while plain radiographs were insufficient in detecting fractures in these cases. The aim of the present study was therefore not to compare the abilities of the imaging modalities themselves or to assess how efficient they are, but to compare the ability of different observers, including forensic anthropologists, to detect fractures using these methods. While the use of a pig model is challenging in terms of the anatomy and osteology, and may have reduced the overall detection of fractures, the senior radiology resident used in the present study was as unfamiliar with pig anatomy as most forensic anthropologists, and therefore the results can still be considered accurate.

The number of fractures detected by the NFA was highly comparable to those detected by the SRR for all body regions using all radiological methods (k=0.77-1.00). The level of agreement between these two observers was substantial to almost perfect [38], indicating that the NFA was able to identify fractures visible radiologically at the same level as the SRR. The number of fractures detected by the more experienced forensic anthropologists (EFA) was less comparable with those identified by both the SRR (k=0.21-1.00) and the NFA (k=0.28-1.00). However, agreement between the EFA and SRR was still considered fair to almost perfect. The much higher repeatability of the NFA may be because this observer received brief radiological training prior to the start of this study, and therefore had slightly more experience with reading scans in comparison to the EFA. The NFA also had the highest sensitivity for detecting fractures in all body regions using all imaging modalities (0.0-89.3%). Sensitivity of the NFA was on average 3.0% higher than that of the SRR (0.0-83.7%) and 22.0% higher than that of the EFA (0.0-62.4%). The higher sensitivity of the NFA is, when compared with the EFA, likely due to the fact that the NFA had a slightly higher level of radiological experience. In addition, the NFA had a much more detailed knowledge of piglet osteology and anatomy, which explains why the NFA had a higher sensitivity than both the SRR and EFA who are less familiar with pig anatomy. It is therefore likely that the sensitivity for detecting fractures by both the SRR and the EFA may increase when reading scans of human infants and children, with which all observers are much more familiar.

These results, which indicate that observer experience does indeed affect the number of fractures detected using radiological scans, are similar to those of Hong et al. [40] who reported an increase in sensitivity of pediatric rib fracture detection from 29% to 46% for X-rays and 52% to 85% for CT scans when a more senior radiologist read the scans in comparison to a less experienced observer. However, Shelmerdine et al. [41] found that observer experience was not a significant predictor of sensitivity when detecting rib fractures in children, which did not differ between observers.

Both inter-observer repeatability as well as fracture detection sensitivity was generally highest for CT scans, for all observers and all body regions. This indicates that CT scans are not only more sensitive than both X-ray and Lodox® scans in detecting fractures, but that CT scans are also much easier to read and interpret regardless of observer experience or level of training, as was seen by Spies et al. [35, 36]. While the superimposition of bones in X-ray and Lodox® scans may cause the detection of fractures to be much more challenging, the three-dimensional renderings of each bone available with CT scans contributes to fractures being detected much more easily by observers of all levels of experience. Hong et al. [40] suggest that the use of CT scans in addition to X-rays may only be of benefit for observers with less radiological experience, as more senior observers may have a high enough diagnostic accuracy using X-rays alone. However, the results of this study, as well as the study by Shelmerdine et al. [41], show that all observers have a higher diagnostic accuracy using CT scans than when using plain radiographs. In addition to a higher sensitivity with CT scans, scanning times are also much quicker than conventional X-rays, and only one scan needs to be taken in comparison to three scans for Lodox®, and between 10 and 15 images for X-rays, depending on the size of the image cassettes. Furthermore, there is the added benefit of using 3-dimensional reconstructions, and even 3-dimensional printed models of the CT scans, which may be used as evidence in court during criminal trials [42]. Therefore, CT scans are preferred over X-ray or Lodox® scans regardless of observer experience.

Repeatability between all observers was lowest for the ribs using all imaging modalities. This is likely due to difficulties in counting the ribs, which range between 14 and 16 in pigs, as well as superimposition of the ribs in X-ray and Lodox® scans. In addition, abdominal gas often obscured the lower ribs, making fracture detection challenging. Sensitivity, however, was lowest for the spine, likely due to superimposition of the vertebrae in X-ray and Lodox® scans which makes it challenging to identify fractures of the transverse and spinous processes. Sensitivity was also relatively low for the limbs, which may be due to difficulty in detecting long bone metaphyseal fractures, as well as superimposition of some bones. While long bones such as the humerus and femur were easily visualised, smaller bones like the metacarpals and metatarsals were highly superimposed, making fractures difficult to detect. This is evident as 19.0-56.3% and 26.1-63.6% of all limb fractures undetected by observers using X-rays and Lodox® respectively, were those of the metacarpals/metatarsals. Again, increased radiological experience and training, as well as an increase in knowledge of piglet osteology may result in both improved inter-observer repeatability and sensitivity for these body regions. Furthermore, in human infants and children, where the bones of the hands and feet are not superimposed, sensitivity for detecting fractures in these regions are expected to be higher for all observers.

Specificity was extremely high for all observers (95.1-99.2%), indicating very few false-positive fracture identifications. This is significant since it suggests that all observers, irrespective of level of training, are not likely to incorrectly raise suspicion of abuse. For all observers, specificity was comparable between CT, X-ray and Lodox® scans, indicating that the level of observer experience does not affect the likelihood of making false-positive identifications using any imaging method. Hong et al. [40], however, suggest that limited radiological experience may result in lower specificity for CT in comparison to X-rays, and that with increased experience and training, the risk of false-positive identifications can be reduced. The results of the present study, however, contradict this.

The results of both inter-observer repeatability and fracture detection sensitivity in the present study show that an increase in observer experience results in an increase in the number of fractures detected using all imaging methods, as expected. The NFA received brief training in the basics of radiological imaging interpretation prior to the start of this study, while the EFA had little to no radiological experience. This training resulted in the NFA having a sensitivity for fracture detection comparable to that of the SRR, and which was on average 22.0% higher than the EFA. This indicates that even very brief radiological training and experience can result in a drastic increase in sensitivity, and that the ability of forensic anthropologists without this training to detect fractures is limited and not sufficient when evaluating cases with skeletal trauma such as in cases of physical child abuse.

A potential limitation of this study is the fact that a CT slice thickness of 3.0 mm with a slice increment of 1.5 mm is relatively thick and may have made the detection of very fine fractures more difficult, thus resulting in lower sensitivity. In addition, the fact that the NFA had a much more detailed knowledge of piglet anatomy and osteology may have resulted in higher fracture detection sensitivity and skewed the results in favour of the NFA. Therefore, including more observers familiar with piglet anatomy may improve results. Furthermore, including more observers of all levels of experience, including specialist pediatric radiologists, as well as increasing the sample size, may increase the validity of the results.

Conclusion

The field of forensic anthropology is becoming much more virtual in its approach and is making use of radiological tools to conduct forensic anthropological analyses, including the interpretation of trauma [3]. However, it was previously unknown whether forensic anthropologists, who generally have very limited to no radiological experience and training, are able to accurately identify skeletal trauma using various imaging modalities. Results of this study show that observer experience does indeed affect the number of fractures detected using CT, X-ray and Lodox® scans, with sensitivity increasing as level of experience increases. This indicates that even very brief radiological training, as was received by the NFA in this study, can drastically improve the ability of the observer to detect skeletal trauma. While forensic anthropologists do have fair to almost perfect agreement with the number of fractures detected by the SRR, fracture detection sensitivity of forensic anthropologists without radiological training are low and not sufficient for assessing cases of suspected trauma, such as physical child abuse or violent crime. The authors therefore suggest that all forensic anthropologists, both novice and experienced, should receive radiological training, either included in undergraduate courses or offered as professional courses for more advanced anthropologists before they comment on fractures observed on radiographic material.

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Paper 2

Forensic imaging: the sensitivities of various imaging modalities in detecting skeletal trauma in simulated cases of child abuse using a pig model

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Abstract

Physical child abuse is a major problem in South Africa and throughout the world, and the detection of skeletal trauma in victims of abuse may be critical in the accurate investigation of these cases. Since many of these fractures are not detected during traditional autopsy, the use of various diagnostic imaging tools is implemented in order to aid in the detection of trauma. In South Africa, Lodox (low-dose full-body X-ray) is commonly used in forensic mortuaries and the aim of this study was to assess the abilities of CT, X-ray and Lodox, in comparison to dry bone as the gold standard, in detecting both the number of fractures and impacts in piglets subjected to blunt force trauma. Ten piglets were beaten with a mallet post-mortem in every region of the body. CT, X-ray and Lodox scans were taken of each piglet, after which the piglets were macerated in order to conduct an osteological analysis of the remains. The number of fractures and impacts present in each scan and on the dry bone were recorded. CT scans were the most sensitive in identifying trauma in all regions of the body, detecting 73% of fractures and 79% of impacts. X-ray and Lodox scans were less sensitive in detecting both fractures (50% and 42% respectively) and impacts (59% and 54% respectively). An assessment of the directionality of trauma was possible using dry bone and CT scans, but not when using X-rays or Lodox scans. CT scans can be used to assess skeletal trauma in suspected victims of child abuse, but the use of X-ray and Lodox scans is not recommended other than for initial screening procedures. Osteological analysis, however, is still considered the gold standard and should be performed whenever possible.

Key words: Physical child abuse; fractures; imaging modalities; forensic anthropology

1. Introduction

Crimes against children are extremely prevalent in South Africa, and indeed throughout the world, and include sexual, psychological and physical abuse [1, 2]. In the 2017/2018 period in South Africa, a total of 43 540 crimes against children were reported [3]. Of these, 23 488 were victims of sexual assault, 10 211 of common assault, 7 562 of assault with the intent to inflict grievous bodily harm, 1 059 of attempted murder and 985 of murder. South Africa has a child homicide rate more than double the global average at 8 per 100 000 [4], and of these homicides, approximately 44.5% are the result of physical abuse [2].

One of the most common indicators of physical child abuse is the presence of fractures, which occur in approximately 30-55% of abused children [5-8]. In infants under the age of one year, between 50% and 69% of fractures are due to abuse [9, 10]. According to various authors [11-14], the probability of abuse given a skull fracture is 27-30%, while it ranges between 71 and 95% for rib fractures, 54 and 79% for humeral fractures, and 43 and 60% for femoral fractures. While accidents may also result in similar patterns of trauma, multiple skeletal injuries are more common in cases of abuse than in accidents. The minimum number of impact sites may also be informative and are regularly assessed during forensic anthropological analyses. An impact site is the location where a blow was inflicted, and knowledge of the number of impact sites can give insight into the minimum number of blows a victim was subjected to [15]. A single impact can cause more than one fracture, while multiple impacts may not cause any fractures. Multiple impacts are more likely to be the result of abuse than a single impact, and therefore it is important to be able to identify both the minimum number of impacts and the number of fractures when investigating cases of child abuse.

During an autopsy, which must be conducted in all cases of non-natural death according to the Inquest Act of South Africa (No. 58 of 1959), it can be difficult to locate and detect fractures. Calluses, which forensic pathologists often use to locate fracture sites, are not present in cases of peri-mortem trauma, and soft tissue damage, also often used to locate sites of trauma, may be extremely subtle or not even visible at all [16]. Furthermore, decomposition, which is much quicker in children, and other taphonomic processes may conceal both soft tissue and skeletal trauma [17, 18]. Fractures in locations difficult to assess such as the skull, particularly the base and facial skeleton, scapula, spine, posterior ribs, pelvis and long bones, as well as hairline fractures, are frequently undetected during autopsy [19-22]. Radiological methods are usually used to aid in the identification of trauma. These include computed tomography (CT) scans, conventional X-rays and, in South Africa, full body low-dose X-ray (Lodox®) scans. The Lodox scanner was developed in South Africa in order to perform full body low-dose scans of miners to prevent the theft of diamonds. These scanners are now often used in medicine and forensic pathology in order to detect both soft tissue and skeletal trauma [23], and has more recently been used in forensic anthropology in order to detect skeletal trauma and conduct forensic anthropological analyses [24]. The

Lodox scanner emits far less radiation than conventional X-rays and CT, and is thus much safer for both the living victim and the operator [23, 25]. It produces a full-body image in only 13 seconds which does not need to be "stitched", does not require the expertise of professional radiographers, and has very low running costs [23, 25].

The use of imaging modalities in both forensic pathology and anthropology may improve the detection of skeletal trauma or be used to perform virtual autopsies or "virtopsies" [26, 27]. This is particularly significant in countries like South Africa where conventional autopsies, especially of children, violate many cultural and religious beliefs [28], and may eliminate the need for bodies or specific body parts to be macerated and skeletonised in order to conduct forensic anthropological analyses. The importance of these imaging modalities goes without saying in the living, where the detection of trauma is based solely on these methods. These imaging tools are therefore vital, and the sensitivity of each method in detecting skeletal trauma needs to be explored.

Several researchers investigated the sensitivity of various modalities, including autopsy, to detect fractures. For example, both Williamson and Perrott [29] and McGraw et al. [30] found that radiological methods detected many fractures that were missed during autopsy, and Antúnez et al. [27] found that CT detected more fractures than X-rays in 39% of pediatric cases. Studies have found both autopsy and CT scans to be more sensitive than X-rays in detecting pediatric rib [31-34] and skull fractures [35]. Douglas et al. [36] reported that in children, fractures were detected by Lodox that would have been missed if only computed radiography were employed. Pitcher et al. [37] found that, when using computed radiography as the gold standard, Lodox detected 96% of fractures.

Most previous studies assessing the sensitivity of various diagnostic tools in paediatric trauma have either used autopsy results, CT or computed radiography as the reference standard against which to compare results. To the best of our knowledge, only one study [16] has compared the abilities of various imaging modalities in detecting fractures on control cases, using dry bone as the reference standard. In simulated cases of child abuse using a pig model, they found autopsy to be the most sensitive in detecting fractures of the ribs (65%) and forelimbs (91%), while CT, X-ray and autopsy all detected 100% of hindlimb fractures. For the skull, autopsy and X-rays detected only approximately a third of fractures, while CT scans incorrectly identified more fractures than were present osteologically.

To the best of our knowledge, the sensitivity of the Lodox scanner in detecting trauma in simulated cases of child abuse has not been assessed before. Furthermore, the minimum number of impacts identified by various imaging modalities has yet to be evaluated. The aim of the current study was therefore to compare the abilities of CT, X-ray and Lodox scans, which are commonly employed by forensic pathologists in South Africa, in detecting the number of fractures and minimum number of impacts in simulated cases of physical child abuse, using a pig model. The dry bone (macerated remains) were used as the gold standard.

2. Materials and methods

Ethical clearance for this study was obtained from the Animal Research Ethics Committee at the University of the Witwatersrand (Clearance Certificate No 2019/04/27/O), as well as from the Department of Agriculture, Forestry and Fisheries in South Africa.

2.1. Materials

Ten piglets which had died of natural causes were sourced from GHB Farms (Pty) Ltd in Bronkhorstspruit, South Africa. Piglets ranged between 5 and 15 kilograms, a weight range that was chosen since it is comparable to that of human infants and young children. Piglets with peri- or post-mortem trauma were excluded from the study. One additional piglet was used as a negative control in order to ensure that fractures detected radiologically were only the result of trauma and not confounding variables associated with the imaging methods.

2.2. Methods

2.2.1. Trauma

Piglets were subjected to blunt force trauma in order to simulate physical child abuse. Piglets were, post-mortem, subjected to blunt force trauma with a 55 mm x 55 mm, 500 g mallet in four major regions of the body: the skull, thorax, forelimbs and hindlimbs. This weapon was used in order to simulate a fist, which is one of the most common weapons of choice in cases of child abuse [38]. Between one and five blows were inflicted to the skull, and between one and 10 blows to each other body region. Trauma was inflicted by an independent observer so as to keep the principal investigator blind to the exact number of blows inflicted to each body region. The skull was struck on the superior and left and right lateral surfaces; the thorax was struck on the posterior and left and right lateral surfaces; and the limbs were struck on the left and right lateral surfaces. Piglets were then vacuum sealed and placed in body bags prior to scanning to prevent any leakage of fluid.

2.2.2. Radiological assessment

Full body helical CT scans (64 Slice CT Brilliance) were taken of each piglet at the Department of Radiology, Wits Donald Gordon Medical Centre in Johannesburg, South Africa. Scans were taken at 120 kV, 150 mA and a slice thickness of 1.5 mm. X-rays were taken at the Central Animal Services in the Faculty of Health Sciences at the University of the Witwatersrand, South Africa. Ventro-dorsal and lateral X-rays were taken of the skull, thorax, fore- and hindlimbs. Two additional views were taken of the thoracic region, including left 45° dorsal-right ventral oblique and right 45° dorsal-left ventral oblique images. Full body ventro-dorsal, lateral, and 7° and 15° oblique Lodox scans were taken at the Forensic Pathology Services Medicolegal Laboratory in Johannesburg, South Africa.

For each CT, X-ray and Lodox scan, the number and location of fractures visible in the thorax, forelimbs and hindlimbs was recorded. The minimum number of impacts visible on the skeleton was also assessed by determining which fractures were likely the result of the same blow. The minimum number of impacts takes into consideration that some impacts may not result in any fractures, and some fractures may be the result of more than one blow. For the skull, it was only documented whether the skull was fractured/impacted or not. This was done due to the heavily fragmented state of some of the skulls. Fractures were identified based on the presence of radiolucencies in the bone and cortical bone discontinuities. Where possible, the direction of the impact was also assessed by determining sites of compression and tension, with the impact located at the site of compression.

2.2.3. Osteological assessment

Piglets were macerated and skeletonized in the School of Anatomical Sciences at the University of the Witwatersrand, South Africa. Piglets were gently boiled in hot water for between one and two days, after which the soft tissue was carefully removed from the bone so as not to introduce any additional trauma. The cleaned skeletons were then rearticulated and the number and location of fractures, as well as the minimum number of impacts visible on the skeleton in each body region were recorded. The direction of impacts was also assessed where possible.

2.2.4. Repeatability

All assessments were done by the primary investigator, and intra-observer repeatability was assessed by this investigator on 5 pigs, by reading and then re-reading the same scans about two months later, in a different order to reduce recollection bias. Inter-observer repeatability was conducted by a professional radiologist on the same pigs. Both the number of fractures and minimum number of impacts detected in each body region, using each type of imaging modality, as well as on the cleaned skeletons, were counted.

2.2.5. Data analysis

The intra- and interobserver repeatability of detecting fractures on CT, X-ray and Lodox scans was tested using Cohen's kappa on 5 piglets. The percentage of both fractures and impacts detected by each method with respect to the number of fractures and minimum number of impacts detected on the bones was then calculated. In line with suggestions by Cattaneo et al. [16], differences between means were assessed using a two-way ANOVA, with body region (skull, thorax, forelimb, hindlimb) and imaging modality being the main factors. Logarithmic transformations were used when variances were not equal.

3. Results

Cohen's kappa tests revealed no significant differences for both intra- and inter-observer fracture counts (k=0.61-1.00) for any imaging modality or any body region. For the number of impacts, only the intra-observer thorax count using X-rays had a kappa value less than 0.61 (k=0.50), indicating some difficulty in repeatably scoring this region.

A total of 586 fractures were present on the skeletons, of which CT correctly detected 427 (73%), X-ray 294 (50%) and Lodox 245 (42%). All 10 piglets had fractured/impacted skulls, which were also detected by CT scans. X-rays and Lodox scans both only detected 9 fractured/impacted skulls (90%). There were therefore no significant differences in fracture/impact counts between dry bone and any of the imaging techniques for the skull ($p>0.05$).

Of 453 thoracic fractures (88 vertebral and 365 rib) identified osteologically, 346 (76%) were identified using CT, 220 (49%) using X-rays and 182 (40%) using Lodox (Fig. 1). X-ray and Lodox scans did not identify any vertebral fractures, while CT detected 38 (43%). When considering the ribs, there were 106 posterior fractures (CT 83%; X-ray 56%; Lodox 43%), 209 shaft fractures (CT 89%; X-ray 70%; Lodox 61%) and 50 sternal end fractures (CT 44%; X-ray 22%; Lodox 18%) (Fig 2). A large portion of the rib fractures that were missed were those of the lower ribs. Surprisingly, 10 healed rib fractures were also present in the current study. All 10 of these were seen on CT, 8 on X-ray and 6 on Lodox (Fig 2). Statistically, there were significant differences ($p<0.001$) in the number of fractures detected between dry bone and all imaging modalities for the thorax.

Osteological analysis showed 60 forelimb and 63 hindlimb fractures. Of these, CT scans detected 58% and 57% respectively, X-rays 52% and 54% respectively, and Lodox 45% and 43% respectively (Fig. 1). For all imaging modalities, the majority of fore- and hindlimb fractures missed were those of the metacarpals/metatarsals, hairline fractures and fractures of the proximal and distal metaphyses of long bones (Fig 3). Significant differences ($p<0.05$) existed between the number of fractures detected by dry bone and all imaging modalities for the forelimbs, while only CT did not differ from the osteological control ($p>0.05$) when considering the hindlimbs.

A minimum of 219 impacts were identified on the dry bone (10 skull, 126 thoracic, 42 forelimb and 41 hindlimb). CT detected 174 of these impacts (79%), X-rays 129 (59%) and Lodox 118 (54%). Minimum impact counts from all scanning methods were significantly different from dry bone for both limbs ($p<0.05$), while for the thorax, only counts from CT scans did not differ ($p>0.05$).

Fracture and minimum impact counts between CT, X-ray and Lodox scans did not differ significantly for the skull, fore- and hindlimbs ($p>0.05$) but were significantly different for the thorax ($p<0.05$).

For fractures of the ribs and limbs, it was possible to determine the direction of impact using dry bone and CT analysis, but not possible using X-ray and Lodox scans (Fig 4).

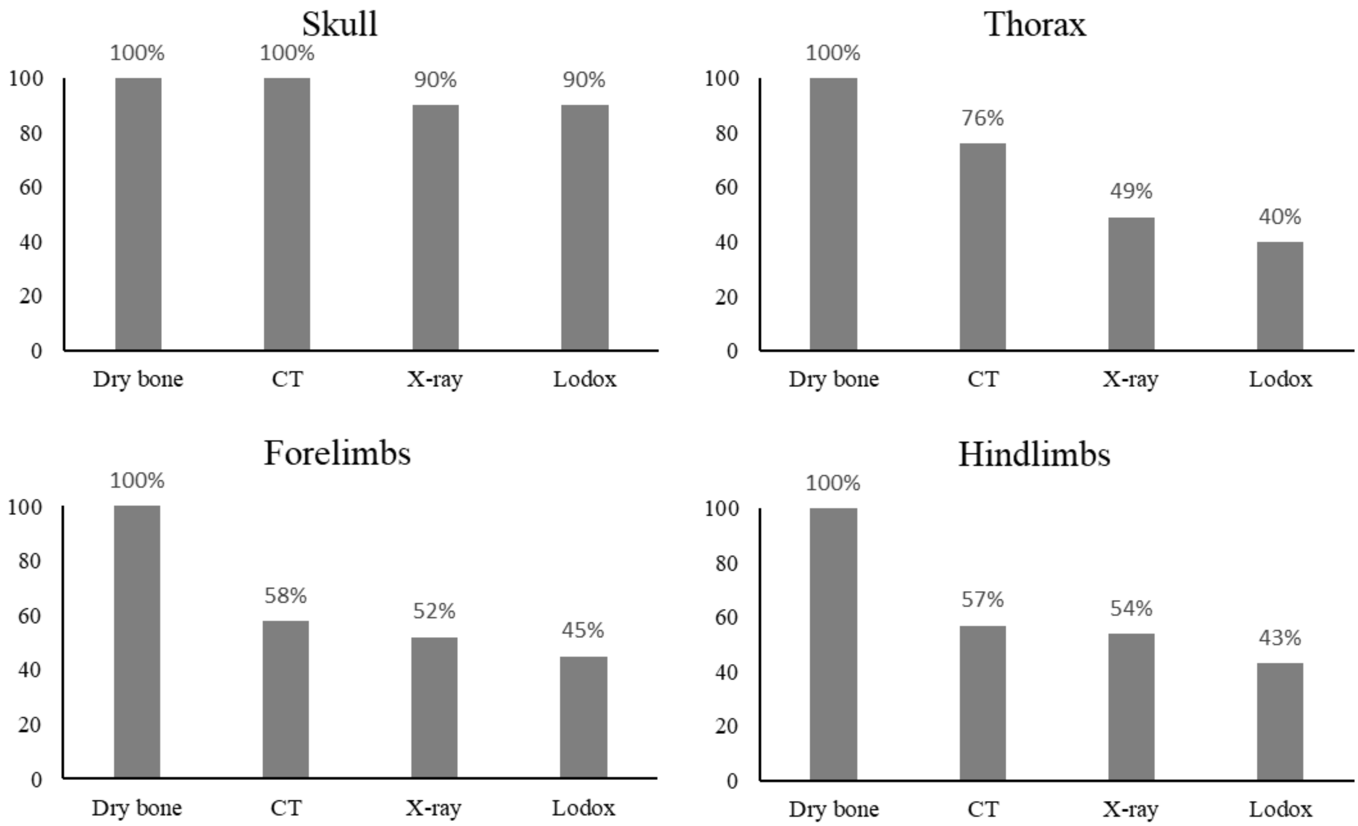

Figure 1. Comparison of percentage of fractures detected by dry bone, CT, X-rays and Lodox scans in each body region.

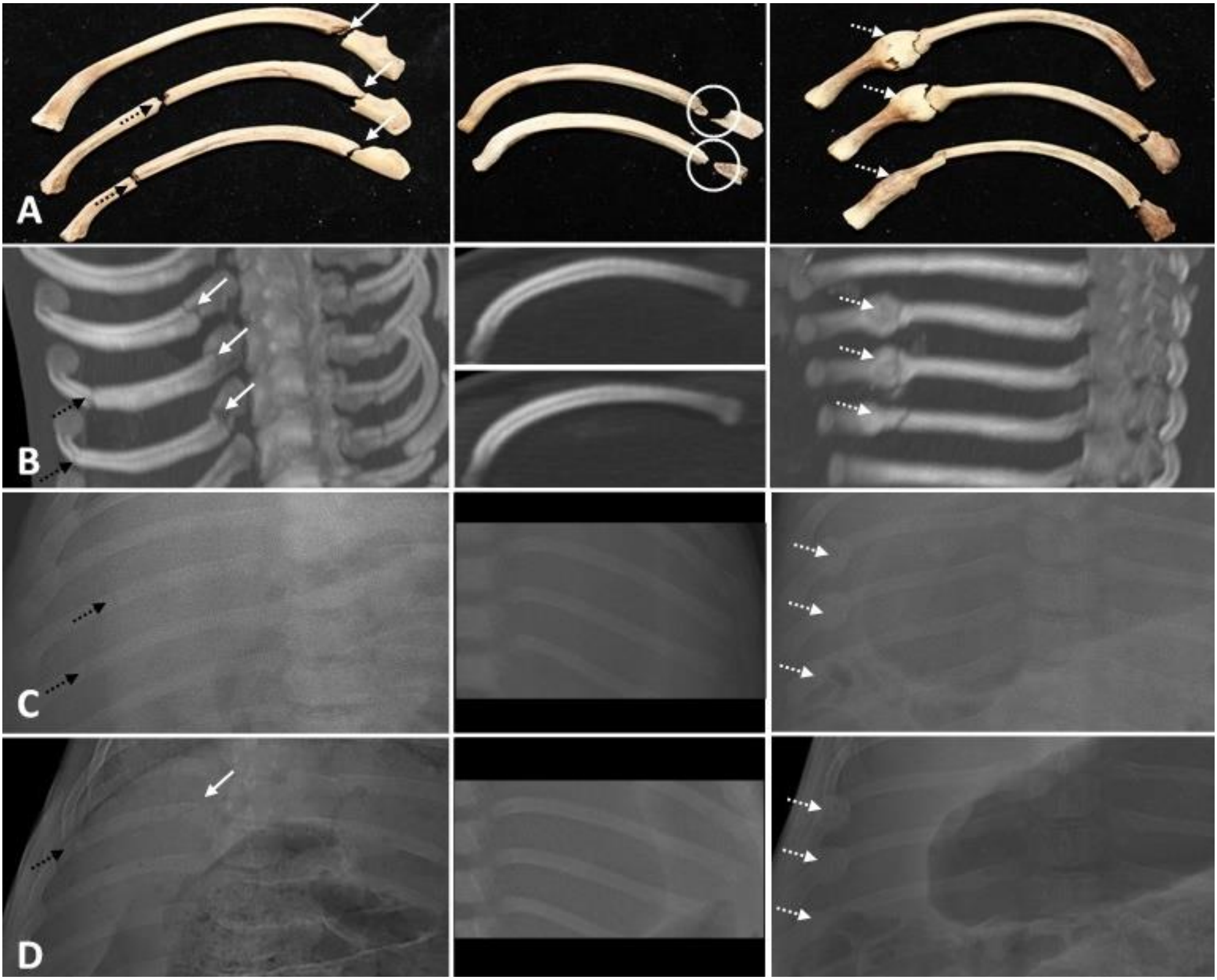

Figure 2. Posterior, sternal end and healed rib fractures (columns 1 – 3) of the same piglets as seen on dry bone (A), CT (B), X-ray (C) and Lodox (D). White arrows indicate posterior rib fractures, most of which were not observed on X-ray and Lodox scans. Note how gas obscures the lower ribs in X-ray and Lodox scans as seen in the first and third columns. Fractures of the shaft (dashed black arrows) are detected but fractures of the sternal end (white circle) are often missed by CT, X-rays and Lodox. Almost all healed fractures (dashed white arrows) are identified by all modalities. The absence of any arrows or circles indicates no fracture detected.

Figure 3. Metaphyseal fractures (black arrows) of the distal ulna (top) and distal tibia (bottom) as seen on dry bone (A), but missed by CT (B), X-ray (C) and Lodox scans (D) of the same piglets. The absence of any arrows indicates no fracture detected.

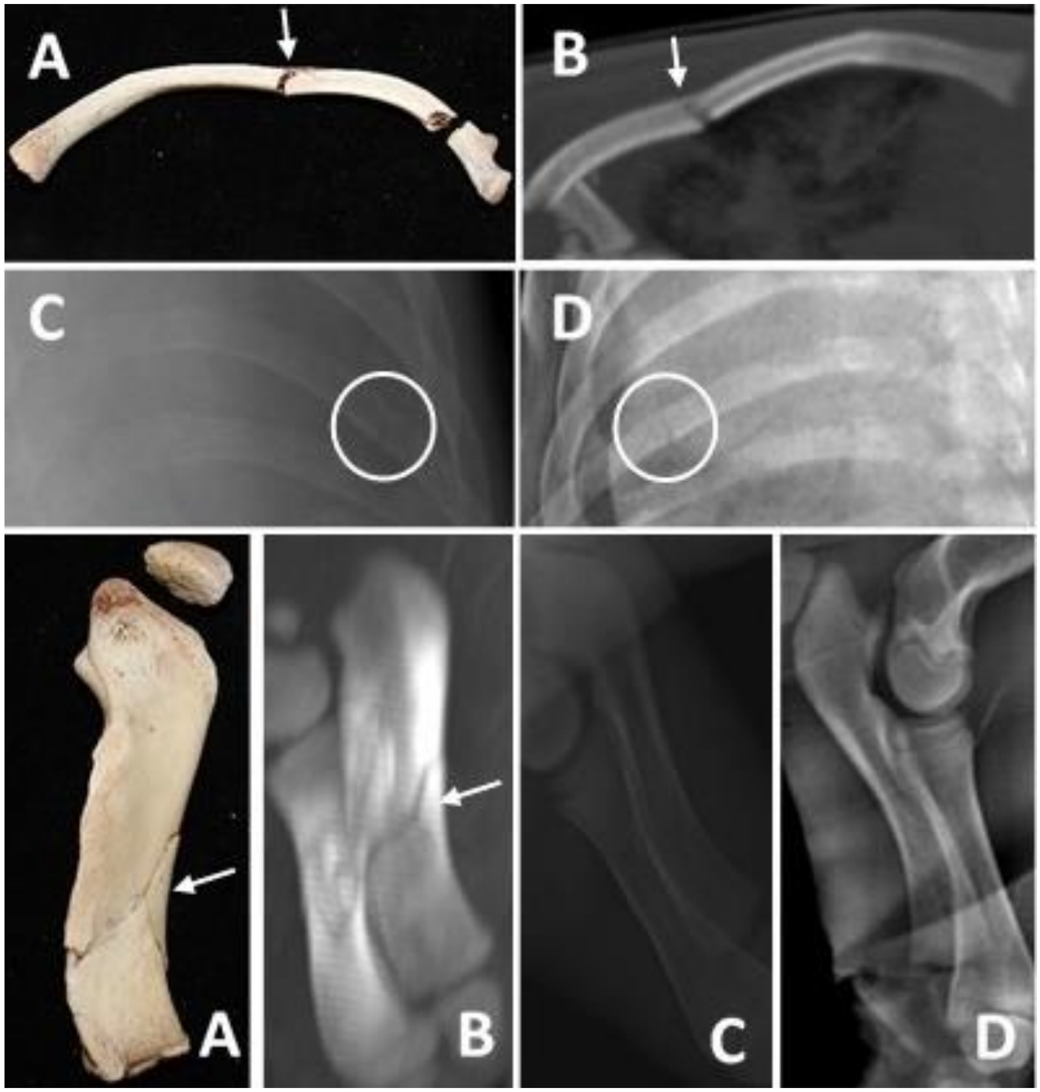

Figure 4. Direction of impact (white arrows) to the ribs (above) and ulna (below) of the same piglets as identified by dry bone (A) and CT (B), but not possible with X-ray (C) and Lodox scans (D). White circles show presence of fracture but no directional information.

Discussion

This study compared the abilities of CT, X-ray and Lodox scans in detecting bone fractures and impact sites in simulated cases of physical child abuse. Child abuse is a worldwide crisis, with child homicide rates (per 100 000) of 4 in the United States of America, 6 in Sudan, 8 in South Africa, 13 in Rwanda, 18 in Lesotho and 27 in El Salvador [4]. Of these child homicides, a large portion is the result of physical abuse [2]. One of the most common indicators of child abuse are skeletal fractures [11, 39], and the detection of these fractures both in the living and the dead are critical for the accurate investigation of these cases. Here, fractures present on the skeletons of 10 piglets exposed to blunt force trauma were compared to the number of fractures detected using various imaging modalities in order to assess their fracture detection abilities.

Cohen's kappa tests revealed moderate to almost perfect agreement [40] for both intra- and inter-observer fracture and impact counts. This indicates that all counts are highly repeatable, and that, due to substantial agreement with observations made by the professional radiologist, the results of this study can be considered accurate.

In paediatric skulls, the bones are much more elastic and more resistant to fracturing, and the presence of skull fractures may therefore suggest incidences of severe trauma or abuse [41]. Results from the present study indicate that CT, X-ray and Lodox scans are all highly sensitive in detecting impacted/fractured skulls. However, due to the highly fragmented nature of the skulls, it was only ascertained whether the skulls were impacted and/or fractured, and not precisely how many fractures or impacts were present. The complex anatomy of piglet crania makes them susceptible to extensive fracturing once they are compromised, in a sense making it easier to detect fracturing. Furthermore, distinguishing fractures from suture lines was challenging and has implications for the identification of trauma, thus requiring more research.

For the thorax, the number of fractures detected by all imaging modalities was significantly different from dry bone. While CT scans may have some sensitivity in detecting spinal fractures, X-rays and Lodox are particularly insensitive. This is significant since vertebral fractures have a high specificity for physical abuse [42, 43].

When considering the ribs, CT scans were the most sensitive (84%) and Lodox scans the least sensitive (50%) in detecting fractures in all locations. Sensitivity reported by Cattaneo et al. [16] was lower than those of the present study for both CT scans (34%) and X-rays (47%). It is interesting to note that in their study, X-rays fared better than CT. In the current study, CT scans detected almost all fractures of the posterior rib and shaft, but were only moderately sensitive in identifying fractures of the sternal end. Both X-rays and Lodox scans detected most shaft fractures, but were only moderately sensitive in detecting posterior fractures and had a very low sensitivity for sternal end fractures. These results are quite alarming since rib fractures, particularly those of the posterior and sternal ends, are highly indicative of physical abuse and account for between 5% and 27% of all abuse-related fractures [32, 34, 44, 45]. This low sensitivity means that many cases of physical child abuse may go undetected, especially if rib fractures are the only indicator of abuse which is often the case [14]. While there were instances where X-ray and Lodox did not detect fractures on certain ribs or rib locations that were identified by CT, there were no instances where X-ray or Lodox did not detect the presence of any rib fractures at all. Future research should include the use of antero-posterior and lateral chest compressions in order to better simulate rib fractures in children.

Between 60% (Lodox scans) and 100% (CT scans) of healed rib fractures were detected. This is important since healed fractures can be indicative of cases of repeated abuse and their detection is essential [16, 34]. However, callus formation only occurs within 11-14 days of injury, and therefore when these injuries occur peri-mortem, these fractures are difficult to detect [34], which is shown by the results for X-ray and Lodox scans in the present study. Most rib fractures missed by X-ray and Lodox scans were those of the lower ribs, which is likely due to the presence of gas in the abdomen which obscures these ribs (Fig 2).

For both the fore- and hindlimbs, CT was most sensitive and Lodox scans were least sensitive in detecting fractures. However, sensitivity was comparable between CT scans and X-rays, similar to results of Cattaneo et al. [16], who reported equal sensitivity for both CT and X-rays in these regions. However, sensitivity obtained in the present study was lower than that reported by Cattaneo et al. [16] for limb fractures. A large portion of limb fractures that were missed by all diagnostic tools were those of the proximal and distal metaphyses of long bones. These results are significant since metaphyseal fractures have a high specificity for abuse [42, 46-48]. While metaphyseal fractures with evidence of bone remodelling and healing can be detected radiographically [49], this is not the case when fractures are incurred peri-mortem and healing processes have not yet begun. Hairline fractures and fractures of the metacarpals and metatarsals were also often undetected, which again could result in cases of physical child abuse not being identified [50]. While the sensitivity of CT scans in detecting limb fractures may be adequate, especially for the hindlimbs where CT results did not differ significantly from dry bone, X-ray and Lodox scans have relatively low sensitivity and should not be relied upon solely for the detection of limb fractures.

This study also assessed the abilities of these diagnostic techniques in determining the minimum number of blows or impacts present in each body region. This is routinely estimated during forensic anthropological examinations of trauma, and knowledge of the minimum number of impacts may help to distinguish between abusive and accidental injury, and may also indicate repeated trauma over time [15]. Again, CT scans were most sensitive in detecting impacts in all body regions (79%), while Lodox scans were the least sensitive (54%). This indicates that none of the imaging techniques, apart from CT scans for the thorax which did not differ significantly from the dry bone, should be relied upon to determine the minimum number of impacts. However, all methods were still able to determine whether multiple impacts were incurred, regardless of the actual number of these impacts, information which may still contribute to evidence that an incident of trauma was abusive in nature.

An assessment of the direction of trauma, based on locating sites of compression and tension, was possible using dry bone and CT scans, but not when using X-ray and Lodox scans. Understanding the directionality of trauma may be important as it can help to reconstruct the event of injury, as well as corroborate cause and manner of death. For example, trauma directionality can aid in ascertaining whether an individual was impacted head on or from behind, giving an indication of the position of the perpetrator relative to the victim. As this is not possible using X-rays or Lodox scans, if an assessment of the direction of trauma is required in order to corroborate witness testimony, this should be performed using CT.

Although skeletal surveys using X-rays are common practice in hospitals and morgues in order to detect fractures in suspected victims of child abuse [51], results of the present study have shown X-ray and Lodox scans to not be sufficiently sensitive in identifying fractures in any body region. Their sole use in evaluating suspected child abuse cases is therefore not recommended, alarming results considering that they may sometimes be the only diagnostic tools used to detect skeletal trauma [52]. Their low sensitivity, as suggested by Cattaneo et al. [16] in the case of X-rays, may be the result of superimposition of bones on the scans or the small size of the bones. It is interesting to note that Lodox was consistently less sensitive than even conventional X-rays. While some authors have suggested that Lodox scans are of similar or even better quality than X-rays [25, 53, 54], the results of this study contradict that. Although Lodox scans are advantageous due to their low dose of radiation, as well as their speed and cost-effectiveness [52], the low sensitivity in detecting skeletal trauma does not promote their use when assessing cases of suspected child abuse. While Cattaneo et al. [16] suggest a combination of autopsy, CT scans, X-rays and osteological survey be used in cases where abuse is suspected, this is not practical in a real-life forensic setting such as in South Africa as it would be extremely time-consuming and expensive. The authors therefore suggest that osteological analysis, when practical and feasible, remain the method of choice when assessing suspected cases of child abuse. However, maceration of the entire skeleton is often not practical, and therefore specific bones or regions suspected to have trauma, either based on soft tissue findings or initial radiological findings, should be macerated and the dry bone assessed.

When skeletal analysis is not possible, such as in cases of the living or in cases where full-body maceration is not practical, CT should be used to detect skeletal trauma.

5. Conclusion

The detection of skeletal injuries may be critical in the accurate investigation of suspected cases of physical child abuse. Many of these fractures are undetected during autopsy procedures and therefore various imaging modalities are used to aid in the identification of this trauma. The present study found that X-ray and Lodox scans, which are commonly employed by both doctors and forensic pathologists in South Africa and around the world, are insensitive in identifying fractures and impacts in simulated cases of abuse. CT scans are the most sensitive in detecting trauma in all regions of the body and may therefore be used to diagnose victims of abuse when dry bone analysis is not a possibility, such as in living individuals. However, skeletal analysis is still considered the reference standard and the authors suggest conducting an osteological assessment whenever possible or practical in order to investigate cases of suspected physical child abuse.

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Paper 3

A comparison of computed tomography, X-ray and Lodox® scans in assessing pediatric skull fractures using piglets

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Abstract

Skull fractures are common in children both due to abuse and accidental incidences. The accurate detection of these fractures may therefore be critical. The aim of this study was to investigate the reliability of CT, X-ray and Lodox® scans, the latter which has not previously been evaluated and is commonly employed in South Africa, in detecting the number, location and type of pediatric skull fractures. Blunt force trauma was inflicted with a mallet on ten piglet skulls which were CT, X-ray and Lodox® scanned, and then macerated. The number, location and type of skull fractures visible using each imaging modality, and on the cleaned skulls, were recorded. Sensitivity and specificity of each method were calculated. For fracture number and location, CT had a sensitivity of 47.3%, X-rays 22.4% and Lodox® 23.3%. For fracture type, sensitivity was 46.1%, 16.6% and 17.8% for CT, X-ray and Lodox® respectively. Specificity was high (92.5% to 100%) which reduces the risk of incorrectly diagnosing fractures. However, low sensitivity increases the risk of failing to identify fractures and possible victims of abuse. Osteological analysis should preferably be the method of choice when evaluating pediatric skull trauma, and CT should be used when osteological analysis is not feasible. If CT scanners are not available, X-rays and Lodox® may have to be used. In these cases, additional radiographic views of the skull are imperative and may increase the sensitivity of these methods, although they are not recommended to detect exact pediatric skull fracture number, location and type.

Key words: Skeletal trauma; pediatric skull fractures; radiological tools; computed tomography; X-rays; Low-dose full-body X-rays and Lodox®; forensic anthropology

Introduction

Head injuries are extremely common in young children and infants, both as a result of accidents and abuse, and often result in skull fractures (1-3). It is imperative that pediatric skull fractures be accurately detected in order determine possible cause and manner of death, as fractures such as depressed, complex and diastatic skull fractures are more common in incidents of non-accidental trauma (3-8). In addition, it is important that all skull fractures are detected in order to identify potential victims of abuse, since failure to do so can put them at further risk of injury and allow perpetrators to go free (9). One study found that 54 of 173 children with abusive head trauma were not identified as victims of abuse, resulting in re-injuries of 15 children, and 4 deaths which may have been prevented (10). This demonstrates how difficult it can be to detect cranial fractures using radiological means.

Various imaging tools have been employed in order to accurately detect pediatric skull fractures, including Computed Tomography (CT) scans, X-rays and, particularly in South Africa, Lodox® scans. Lodox® scanners emit very low doses of radiation, produce full body X-ray images in a matter of seconds, and are very cost-effective, making them advantageous over CT and conventional X-rays (11). They are used widely in South African mortuaries, in fact, they are often the only radiological modality available in most Forensic Pathology Services.

Some studies have assessed the diagnostic accuracy of these imaging tools in detecting fractures in pediatric patients and have found that CT scans identified more fractures than X-rays, and that many fractures identified by X-rays were false-positives (3, 12). In a study of 85 pediatric patients with skull fractures, CT scans were found to be more sensitive than X-rays in identifying linear, depressed and diastatic skull fractures, which have a high specificity for abuse (4). Culotta et al. (5), however, reported no significant difference in the sensitivity for CT and X-ray scans when identifying skull fractures of 177 children. The CT scans of 76 children with skull fractures showed that a combination of 2-dimensional (2D) and 3-dimensional (3D) CT scans had a sensitivity of 83.1% while 2D scans alone had a sensitivity of 74.5% (6). In addition, the combination of 2D-3D scans yielded fewer false-negatives than 2D scans (6). Douglas et al. (13) and Pitcher et al. (14) both found that Lodox® scans were highly sensitive in detecting long bone fractures in pediatric patients, but information on the diagnostic accuracy of Lodox® scans in detecting skull fractures is limited.

Almost all previous studies used either autopsy results or CT scans as the reference standard, and very few have tested the sensitivity of these diagnostic modalities under controlled circumstances and using dry bone as the gold standard. Mulroy et al. (7) subjected six human pediatric cadaver skulls to blunt force trauma and found that CT scans had a sensitivity of 71% for identifying single skull fractures, while X-rays had a sensitivity of 63%. Results also showed that linear fractures were more easily detected compared to diastatic fractures but had a higher rate of false-positive identification. Cattaneo et al. (8) used piglets to compare the abilities of autopsy, CT and X-ray against dry bone, and found that autopsy detected 31% of skull fractures, while X-rays detected 35%. CT scans detected more fractures than were actually present (126%), indicating a high rate of false-positive identifications. In a previous study (15), the diagnostic accuracies of CT, X-ray and Lodox® scans in detecting blunt force trauma in piglet skeletons were compared. As far as the simple detection of cranial trauma was concerned, CT scans were found to be most sensitive (100%), while X-rays and Lodox® scans were somewhat less sensitive (90%). However, it was only recorded whether fractures were present, and the actual number of fractures, the types of fractures and their exact locations were not assessed. This was due to the highly fragmented nature of the skulls, and the difficulty in distinguishing fractures from unfused pediatric sutures, which required further exploration. During forensic anthropological examinations, the aim of trauma analysis is to document the location and characteristics of each skull fracture, which could aid in determining the minimum number of blows inflicted and to decide whether the trauma inflicted was accidental or abusive. The potential of various imaging modalities in performing these skeletal trauma assessments therefore needs to be evaluated as these may be the only tools available, such as is the case in South Africa where the Lodox® scanner is often the only radiological method available in Forensic Pathology laboratories. Therefore, the aim of this study was to compare the sensitivity and specificity of CT, X-ray and Lodox® scans in detecting the number, location and type of skull fractures in cases of piglets subjected to blunt force trauma, using the skeletonised remains as the reference standard.

Materials and methods

Ten piglets, each weighing between 5 and 15 kilograms and who had died of natural causes, were used in this study. The skull of each piglet was subjected to blunt force trauma and was struck between one and five times with a 500 g, 55x55 mm rubber mallet, post-mortem. Trauma was inflicted by an independent observer so that the principal investigator was blind to the number of blows inflicted to each skull. An additional piglet with no trauma was also included in this study as a negative control. Ethical clearance to conduct this study was obtained from the Animal Research Ethics Committee at the University of the

Witwatersrand (Clearance Certificate No 2019/04/27/O), and permission was also obtained from the South African Department of Agriculture, Forestry and Fisheries.

Following the infliction of blunt force trauma, piglets underwent CT, X-ray and Lodox® scanning. Helical CT scans (64 Slice CT Brilliance; 120 kV; 150 mA; 1.5 mm slice thickness) were taken at the Department of Radiology at the Wits Donald Gordon Medical Centre. Ventro-dorsal and left and right lateral X-rays of the skull were taken at the Central Animal Services at the University of the Witwatersrand, and ventro-dorsal and left and right lateral Lodox® scans were taken at the Johannesburg Forensic Pathology Services.

The number, location and type of fractures visible on each skull using each imaging modality was recorded. The number of fractures was counted as the overall number of fractures present on the skull, while the presence of a fracture on a specific bone or skull region was considered the fracture location. Fracture locations were scored according to the locations listed in Table 1. The location of simple linear fractures traversing two or more bones was scored as the bone where the majority of the fracture occurred. The location of complex and depressed fractures was scored as the bone where the impact site likely was. Fracture types were classified as either simple linear, complex, depressed or diastatic (1, 2) (Table 2). Simple linear fractures were determined as single, isolated, generally straight fractures. Both complex and depressed fractures were classified as having two or more, often interconnected, fracture lines likely associated with a single point of impact, and depressed fractures were distinguished as having an area of depression at the point of impact. Individual fracture lines were not counted but were only scored as one complex/depressed fracture. Diastatic fractures were those involving the sutures (outlined in Table 1), causing a widening of the suture. Fractures were identified as non-anatomical radiotransparencies and compact bone discontinuities, and all scans and images were read by the principal investigator, who had received training in the basics of radiology and interpreting radiological images prior to the start of this study. All images were read using RadiAnt DICOM Viewer, version 5.5.1, and when examining CT scans, both slice images and three-dimensional volume renderings of each bone were used to detect trauma.

The skulls of the piglets were then gently simmered and manually cleaned in the School of Anatomical Sciences, University of the Witwatersrand. The skeletonized skulls were carefully reconstructed by gluing them back together, being careful not to introduce additional trauma, and the sensitivity and specificity of each diagnostic method was then assessed by comparing the readings to the true locations and types of fractures present on the dry bone, which was the reference standard. Sensitivity refers to the imaging modality's ability to correctly identify fractures, and was calculated by dividing the number of true-positives (fracture seen both on both dry bone and radiologically) by the sum of the numbers of true-positives and false-negatives (fracture seen on dry bone but not radiologically) (7, 16). Specificity refers to the imaging modality's ability to not incorrectly diagnose the presence of a fracture, and was calculated by dividing the number of true-negatives (no fracture seen both on dry bone and radiologically) by the sum of the numbers of true-negatives and false-positives (no fracture seen on dry bone but seen radiologically) (7, 16). One-way ANOVA with number of fractures as the independent variable, and two-way ANOVA with imaging modality and location/type of fracture as the independent factors, were used to assess differences in the mean number of fractures detected. Differences were considered significant when $p<0.05$.

Intra- and inter-observer repeatability for detecting the number, location and type of fractures using CT, X-ray and Lodox® scans was assessed using Cohen's kappa. The principal investigator re-read the scans of 5 piglets to calculate the intra-observer repeatability, while a professional radiologist read the scans of the same 5 piglets to assess inter-observer repeatability. All statistical analyses were conducted using IBM® SPSS® version 25.0.

Results

Repeatability

Intra-observer repeatability for detecting the number, location and type of skull fracture was almost perfect for all imaging modalities, with kappa values ranging between 0.95 and 1.00. Kappa values were also high for inter-observer repeatability of fracture number, location and type using CT (0.75 for all three), X-ray (0.78, 0.78 and 0.74 respectively) and Lodox® scans (0.83, 0.83 and 0.78 respectively).

Number of fractures

A total of 241 fractures were present on the skulls of the piglets. There were 210 cranial fractures and 31 mandibular fractures. Cranial fractures included 106 fractures of the neurocranium and 104 facial fractures. Of the total 241 fractures, CT scans correctly identified 114 (sensitivity of 47.3%; specificity of 97.8%), while X-rays and Lodox® scans correctly detected 54 (sensitivity of 22.4%; specificity of 97.7%) and 56 (sensitivity of 23.2%; specificity of 100%) respectively. Results of the one-way ANOVA showed a significant difference in the overall number of fractures detected between dry bone and all imaging modalities ($p<0.05$). CT also differed significantly from both X-ray and Lodox® ($p<0.05$), but X-ray and Lodox® did not differ significantly ($p>0.05$).

Location of fractures

For identifying the correct location of a fracture, CT had a sensitivity of 47.3% (97.8% specificity), X-rays 22.4% (97.7% specificity), and Lodox® 23.2% (100% specificity) (Table 1). Since the overall number of fractures were classified according to location, which was necessary in order to determine the overall number of true-positive, false-positive, true-negative and false-negative fracture identifications, the sensitivity for correct location of a fracture is the same as that for overall number of fractures.

Sensitivity and specificity, respectively, for identifying fractures of the cranium were 43.3% and 100% for CT, 20.0% and 99.8% for X-rays, and 19.5% and 100% for Lodox®. The sensitivity of mandibular fracture detection was 74.2% (specificity: 99.2%) for CT scans, 38.7% (specificity: 100%) for X-rays, and 48.4% (specificity: 100%) for Lodox® scans. For CT scans, the sensitivity of detecting fractures of the neurocranium and face were 49.1% and 37.5% respectively, with a specificity of 100% for both regions. When considering X-rays, fracture detection sensitivity for the neurocranium was 24.5% with a specificity of 99.7%, and for the face 15.4% with a specificity of 100%. Lodox® scans had a sensitivity and specificity, respectively, of 26.4% and 100% for the neurocranium, and 12.5% and 100% for facial fractures.

The skull bone or region with the highest sensitivity was the mandibular body for all imaging modalities (90% for CT, 70% for X-rays and 80% for Lodox®), while all diagnostic tools had a 0% sensitivity for detecting diastatic fractures of the fronto-maxillary suture

(Table 1). X-rays and Lodox® scans also had a 0% sensitivity for detecting diastatic fractures of the sagittal suture, and X-rays had a 0% sensitivity for diastatic fractures of the mandibular symphysis (Table 1). CT scans had the highest sensitivity for almost all locations, and in general, Lodox® had a higher sensitivity compared to X-rays (Table 1). In one case with 17 fractures, both X-ray and Lodox® did not detect any fractures, all of which were fractures of the face and skull base, as well as diastatic fractures.

Two-way ANOVA tests showed that only parietal fractures, coronal suture diastatic fractures, mandibular body fractures and mandibular symphysis diastatic fractures did not differ significantly from dry bone for any radiological method ($p>0.05$). In addition, CT did not differ significantly from the dry bone for occipital and mandibular ramus fractures, while Lodox® also did not differ significantly for occipital fractures ($p<0.05$). CT only differed significantly from X-ray and Lodox® for nasal/maxillary, skull base and zygomatic arch fractures ($p<0.05$), and X-ray and Lodox® were not significantly different for any fracture location ($p>0.05$).

Type of fractures

A total of 115 simple linear, 84 complex, 11 depressed and 31 diastatic fractures were noted on the dry bones. For correctly detecting the type of fracture, CT had a sensitivity of 46.1% (99.4% specificity), X-rays a sensitivity of 16.6% (97.6% specificity), and Lodox® a sensitivity of 17.8% (97.9% specificity) (Table 2) (Figs 1-5). CT scans had the highest sensitivity for all fracture types, while X-rays had a higher sensitivity than Lodox® for complex and depressed fractures (Table 2). For CT scans, depressed fractures had the highest sensitivity (54.5%, with a specificity of 100%), while the lowest sensitivity was for diastatic fractures (29%, with a specificity of 100%). For X-rays, depressed fractures also had the highest sensitivity (27.3% sensitivity; 100% specificity), and complex fractures had the lowest (15.5% sensitivity; 97% specificity). For Lodox® scans, simple linear fractures had the highest sensitivity (22.6% with a 95.6% specificity), and depressed fractures had the lowest sensitivity (9.1% with a 100% specificity). For both X-ray and Lodox® scans, complex and depressed fractures were more likely to be classified as simple linear fractures (Figs. 2 & 5). Results of the two-way ANOVA revealed significant differences between the dry bone and all imaging methods for all fracture types ($p<0.05$), except for depressed fractures detected by CT scans (p>0.05). CT did not differ from X-ray and Lodox® for simple linear and depressed fractures (p>0.05), and X-rays and Lodox® scans did not differ significantly for any fracture type (p>0.05).

Table 1. Sensitivity and specificity of CT, X-ray and Lodox® scans in detecting the location of skull fractures. All fractures involving sutures are diastatic fractures.

Location of fracture	**Sensitivity (%) / Specificity (%)**		
	CT	**X-ray**	**Lodox®**
Neurocranium	**49.1 (52/106) / 100.0 (394/394)**	**24.5 (26/106) / 99.7 (393/394)**	**26.4 (28/106) / 100.0 (394/394)**
Frontal	45.5 (5/11) / 100.0 (39/39)	54.5 (6/11) / 100.0 (39/39)	54.5 (6/11) / 100.0 (39/39)
Parietal	66.7 (8/12) / 100.0 (38/38)	66.7 (8/12) / 100.0 (38/38)	58.3 (7/12) / 100.0 (38/38)
Occipital	62.5 (5/8) / 100.0 (42/42)	37.5 (3/8) / 100.0 (42/42)	62.5 (5/8) / 100.0 (42/42)
Temporal	61.5 (8/13) / 100.0 (37/37)	15.4 (2/13) / 100.0 (37/37)	15.4 (2/13) / 100.0 (37/37)
Skull base	54.5 (18/33) / 100.0 (67/67)	6.1 (2/33) / 98.5 (66/67)	12.1 (4/33) / 100.0 (67/67)
Coronal suture	60.0 (3/5) / 100.0 (45/45)	40.0 (2/5) / 100.0 (45/45)	60.0 (3/5) / 100.0 (45/45)
Sagittal suture	16.7 (1/6) / 100.0 (44/44)	0.0 (0/6) / 100.0 (44/44)	0.0 (0/6) / 100.0 (44/44)
Face	**37.5 (39/104) / 100.0 (75/75)**	**15.4 (16/104) / 100.0 (75/75)**	**12.5 (13/104) / 100.0 (75/75)**
Nasals/ maxilla	18.2 (6/33) / 100.0 (17/17)	6.1 (2/33) / 100.0 (17/17)	9.1 (3/33) / 100.0 (17/17)
Orbit	50.0 (8/16) / 100.0 (34/34)	37.5 (6/16)/ 100.0 (34/34)	12.5 (2/16) / 100.0 (34/34)
Zygomatic arch	45.5 (25/55) / 100.0 (24/24)	14.5 (8/55) / 100.0 (24/24)	14.5 (8/55) / 100.0 (24/24)
Fronto-nasal suture	44.4 (4/9) / 100.0 (41/41)	33.3 (3/9) / 100.0 (41/41)	11.1 (1/9) / 100.0 (41/41)
Fronto-maxillary suture	0.0 (0/9) / 100.0 (41/41)	0.0 (0/9) / 100.0 (41/41)	0.0 (0/9) / 100.0 (41/41)
Mandible	**74.2 (23/31) / 99.2 (118/119)**	**38.7 (12/31) / 100.0 (119/119)**	**48.4 (15/31) / 100.0 (119/119)**
Mandibular ramus	68.4 (13/19) / 96.8 (30/31)	26.3 (5/19) / 100.0 (31/31)	31.6 (6/19) / 100.0 (31/31)
Mandibular body	90.0 (9/10) / 100.0 (40/40)	70.0 (7/10) / 100.0 (40/40)	80.0 (8/10) / 100.0 (40/40)
Mandibular symphysis	50.0 (1/2) / 100.0 (48/48)	0.0 (0/2) / 100.0 (48/48)	50.0 (1/2) / 100.0 (48/48)
Total	**47.3 (114/241) / 97.8 (44/45)**	**22.4 (54/241) / 97.7 (43/44)**	**23.2 (56/241) / 100.0 (44/44)**

Table 2. Sensitivity and specificity of CT, X-ray and Lodox® scans in detecting the type of skull fracture.

Type of fracture	**Sensitivity (%) / Specificity (%)**		
	CT	**X-ray**	**Lodox®**
Simple linear	44.3 (51/115) / 98.4 (249/253)	16.5 (19/115) / 95.3 (242/254)	22.6 (26/115) / 95.6 (240/251)
Complex	51.2 (43/84) / 98.0 (99/101)	15.5 (13/84) / 97.0 (97/100)	13.1 (11/84) / 98.0 (98/100)
Depressed	54.5 (6/11) / 100.0 (151/151)	27.3 (3/11) / 100.0 (150/150)	9.1 (1/11) / 100.0 (150/150)
Diastatic	29.0 (9/31) / 100.0 (131/131)	16.1 (5/31) / 100.0 (132/132)	16.1 (5/31) / 100.0 (132/132)
Total	**46.1 (111/241) / 99.4 (631/635)**	**16.6 (40/241) / 97.6 (619/634)**	**17.8 (43/241) / 97.9 (620/633)**

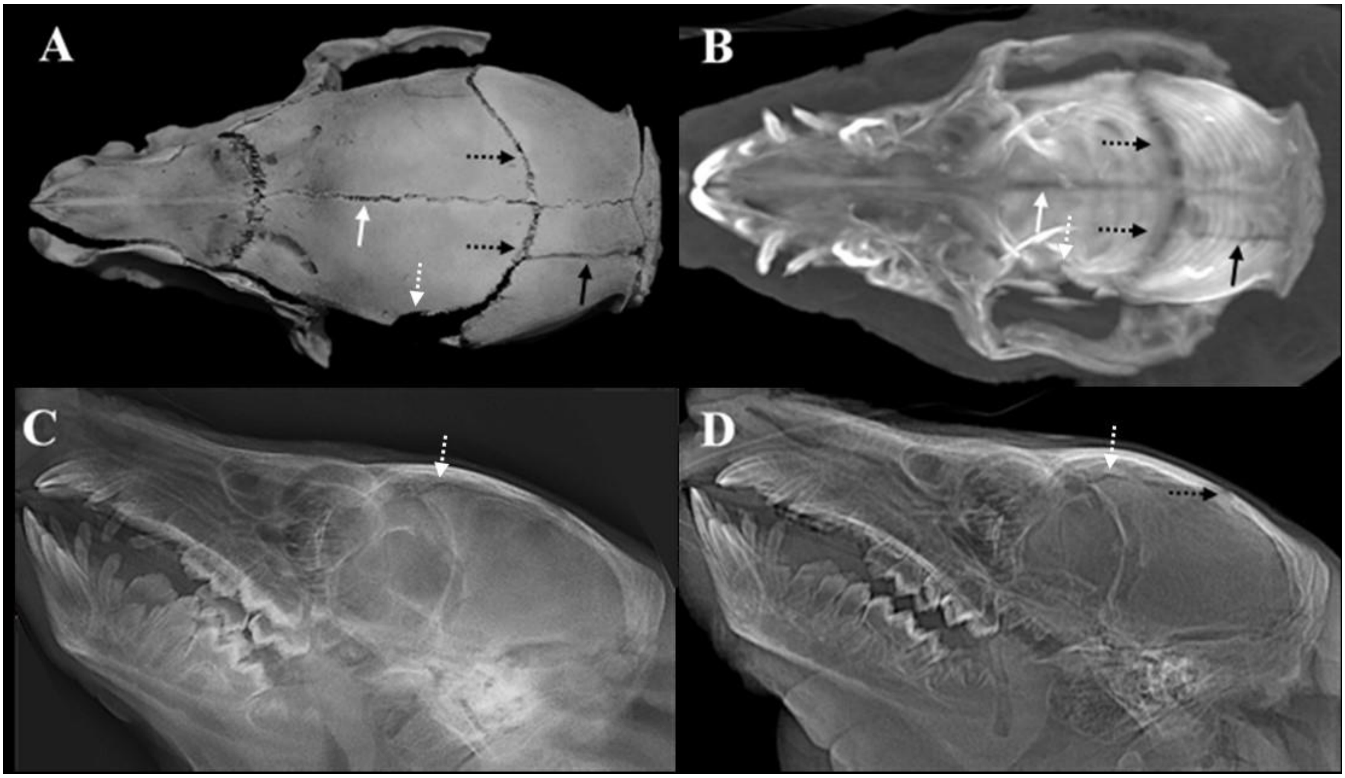

FIG. 1 – Parietal simple linear (solid black arrow) and sagittal diastatic fracture (solid white arrow) as seen on dry bone (A) and CT (B), but not visible on X-ray (C) or Lodox® (D) on any radiographic views. Frontal simple linear fracture (white dashed arrow) seen on dry bone (A) and all three imaging modalities (B-D), and coronal diastatic fracture (dashed black arrows) seen on dry bone (A), CT (B) and Lodox® (D), but not on X-ray (C).

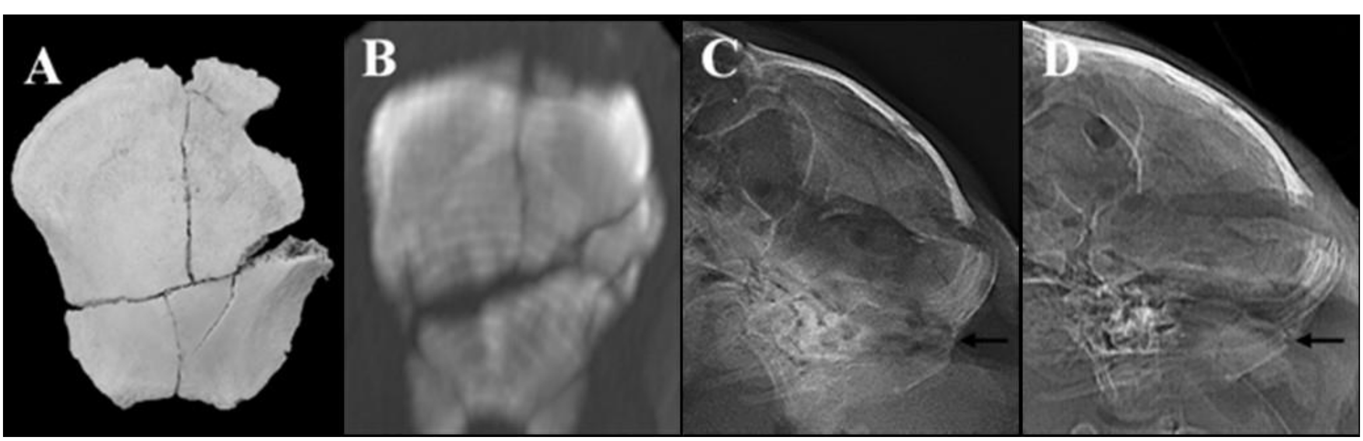

FIG. 2 – Complex occipital fracture as seen on dry bone (A) and CT (B) but classified as simple linear (solid black arrow) on X-ray (C) and Lodox® (D) on all radiographic views.

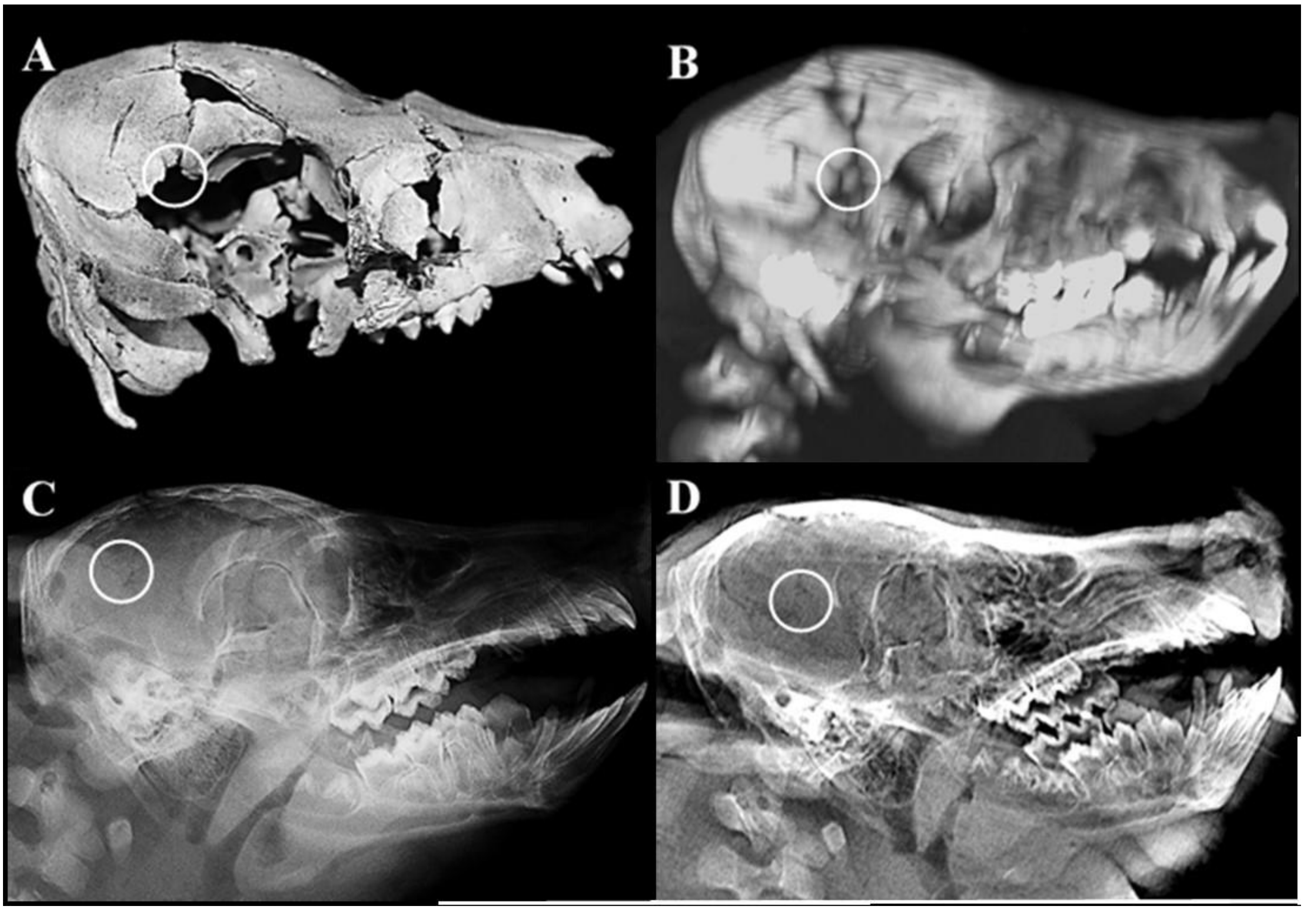

FIG. 3 – Depressed fracture of the parietal bone as seen on dry bone (A), CT (B), X-ray (C) and Lodox® (D), with central depressed part (white circle), and radiating and concentric fracture lines. Individual radiating and concentric fracture lines were not counted, and this was only scored as one depressed fracture.

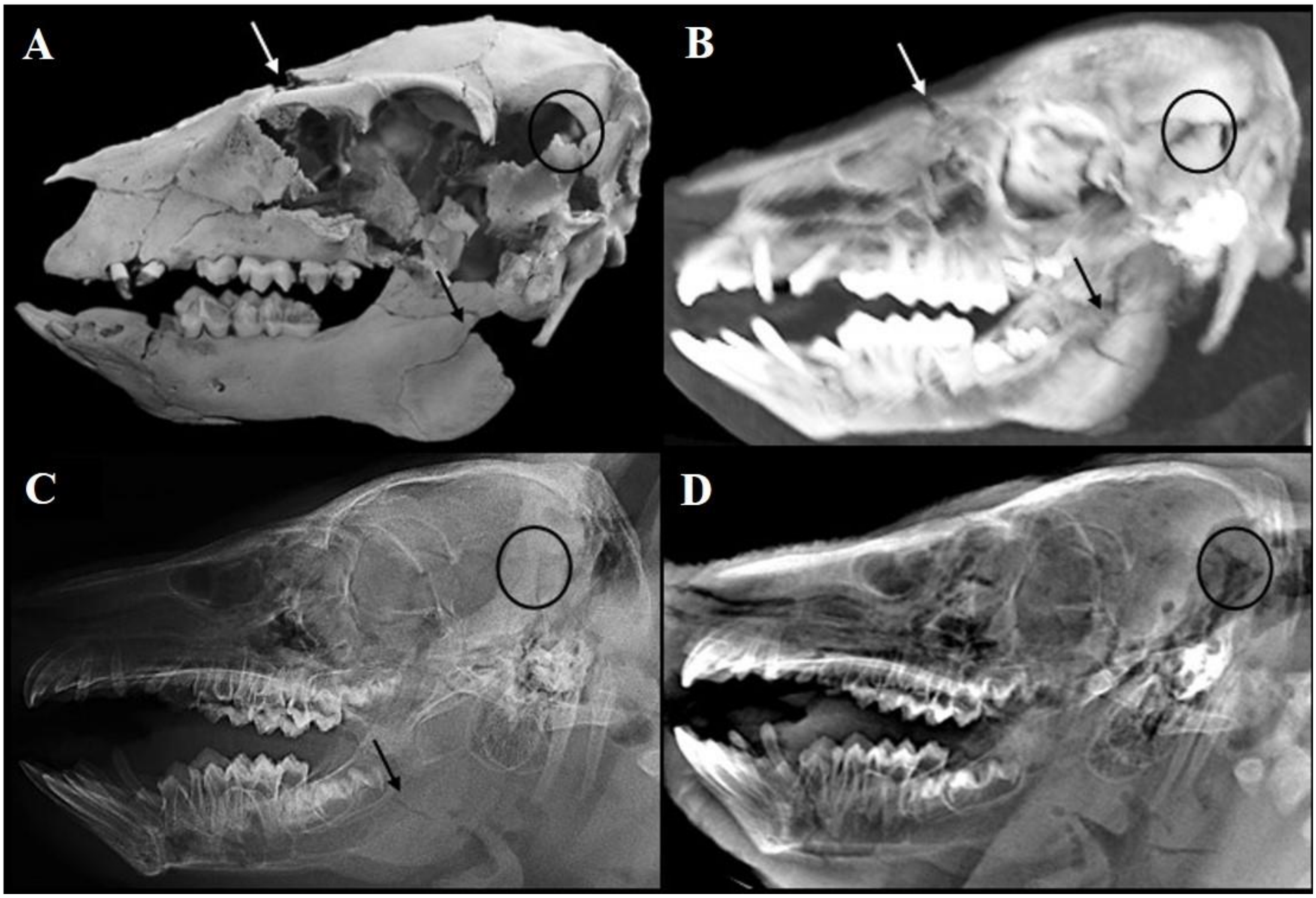

FIG. 4 – Parietal complex fracture (black circle) as seen on dry bone (A), CT (B), X-ray (C) and Lodox® (D). A fronto-nasal diastatic fracture (white arrow) is seen on dry bone (A) and CT (B), but not on X-ray (C) and Lodox® (D). A complex mandibular ramus fracture (black arrow) is also seen on dry bone (A) and CT (B), but is classified as simple linear on X-ray (C) and not visible on Lodox® (D).

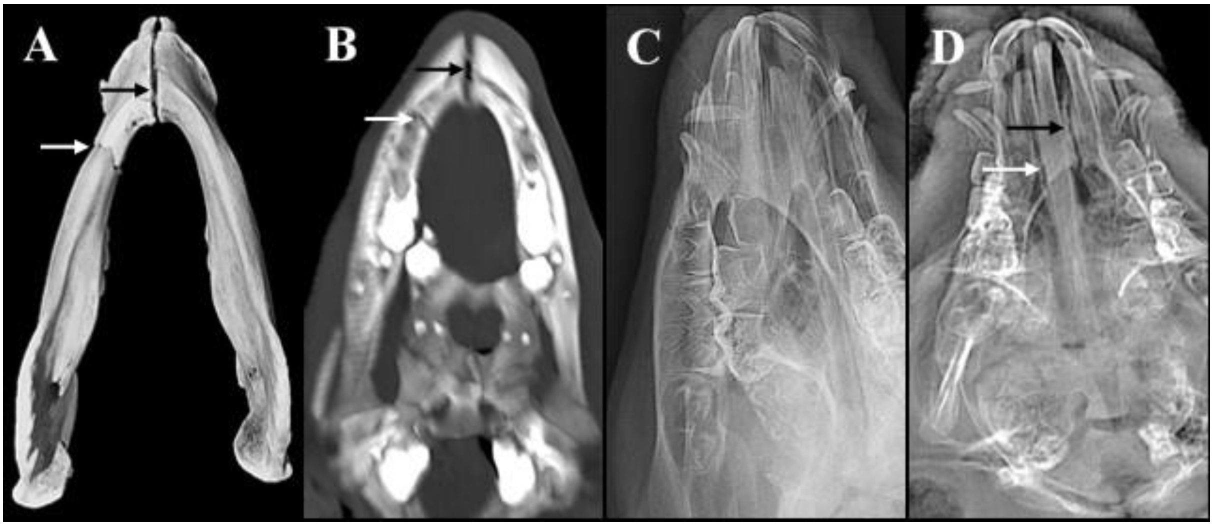

FIG. 5 – Simple linear fracture of the mandibular body (white arrow) and diastatic fracture of the mandibular symphysis (black arrow) as seen on dry bone (A), CT (B) and Lodox® (D), but not visible on X-ray (C)**.**

Discussion

Skull fractures are common in children, both as a result of accidental and abusive trauma (1-3). The accurate detection of these fractures is critical in order to determine possible cause and manner of death (3-8). Furthermore, as is common during forensic anthropological examinations, assessing the location and pattern of each skull fracture has implications for determining the minimum number of blows inflicted, as well as potentially distinguishing between accidental and abusive trauma. In this study, the abilities of CT, X-ray and Lodox® scans for detecting the number, location and type of pediatric skull fractures were assessed using a piglet model.

Both intra- and inter-observer agreement for detecting skull fractures was substantial to almost perfect for all imaging modalities (17). Agreement was slightly higher for detecting the location of fractures than for detecting the type of fractures for all imaging methods. While repeatability was similar for CT and X-ray scans, repeatability was highest for Lodox® scans for both fracture location and type. The substantial to almost perfect inter-observer agreement between the principle investigator and the professional radiologist indicates that the fractures detected using each imaging modality can be considered accurate.

The sensitivity for detecting the correct number of fractures at the correct location was 47.3% for CT scans, 22.4% for X-rays and 23.2% for Lodox® scans. While CT had the highest sensitivity for detecting fracture location, more than half of all fractures were undetected. These results are different from those reported by Cattaneo et al. (8) who found that CT scans had a high rate of false-positives and detected more fractures than were actually present. However, no attempt was made in the study by Cattaneo et al. (8) to distinguish between true- and false-positive fracture identifications, which may be the cause of this discrepancy. Even more alarming were the results for X-rays and Lodox® scans, the modalities generally used when conducting skeletal surveys in hospitals and morgues (18, 19), which only detected approximately 1/5th of all skull fractures. The sensitivity for X-rays was only slightly lower than that reported by Cattaneo et al. (8), where X-rays detected only a third of all pediatric skull fractures. Sensitivity for CT scans and X-rays in the present study was also lower than those reported by Martin et al. (12) who found a sensitivity of 81% for CT scans and 77-81% for X-rays, and Culotta et al. (5) who cited a 97% sensitivity for CT and 90% for X-rays. However, both authors used either CT or X-ray scans as the gold standard, not osteological analysis, which may have resulted in an increased, yet potentially unreliable sensitivity. Sensitivity for the detection of adult skull fractures appear to be better than those found in the present study, with a sensitivity of 85.4% reported for CT scans (20) and 71.4% for X-rays (21). The lower sensitivity found in the present study for pediatric compared to adult skull fractures is likely due to the presence of unfused sutures and incomplete fractures in pediatric skulls, which may make fracture detection more difficult (22).

All imaging modalities were more sensitive for identifying fractures of the mandible than fractures of the cranium. For the mandible, all radiological techniques detected almost all body fractures, while sensitivity for fractures of the ramus was much lower. This is significant since the ramus is often fractured as a result of blows to the face or jaw, which commonly occur during both accidents and incidences of abuse (1, 9, 23). Since most of these fractures are missed, many cases of abuse which involve blows to the face may go undiagnosed, especially when other facial fractures as a result of these blows are also not detected, as is the case in the present study. Only 37.5% of facial fractures were detected by CT, while 15.4% and 12.5% were detected using X-rays and Lodox® respectively. The anatomy of the piglet skull, which has a more elongated snout and face compared to the more orthognathic face of humans, may have contributed to the lower sensitivity for detecting facial fractures, particularly using X-rays and Lodox® scans. This is particularly true for diastatic fractures, which may have a very different appearance than what would be the case in a human skull. In addition, the presence of paranasal sinuses in facial structures may also pose a challenge for identifying fractures in these regions, as could the presence of unfused sutures in pediatric skulls.

All imaging methods also had low sensitivity for detecting fractures of the neurocranium, with CT scans only detecting half of all fractures and X-rays and Lodox® detecting only a quarter of fractures. The majority of fractures missed were those of the skull base and diastatic fractures. In addition, most temporal fractures, and many parietal and frontal fractures close to the vertex of the skull, such as the parietal fracture seen in Figure 1, were undetected using X-rays and Lodox®. The low sensitivity for detecting skull fractures in the correct locations may, in the case of CT, be the result of the orientation of the scan slice with respect to that of the fracture (8, 12). In the case of X-rays and Lodox® scans, superimposition of bones, very thin or incomplete fractures, and the limited three-views of the skull (antero-posterior and left and right lateral) may limit the detectability of fractures and cause the underestimation of the number of fractures present (4, 7, 8, 24). Since CT scans have the highest sensitivity for detecting fractures at the correct location, children with suspected cranial fractures should undergo CT scans where possible rather than X-rays and Lodox®, which are insensitive and add no diagnostic value over CT, a recommendation also made by a number of other authors (3, 4, 12). Moreover, CT scans have the additional advantage of visualizing intra-cranial injury and trauma (5, 12). However, the use of CT scans is not always feasible, especially in hospitals or morgues with limited resources and funding (25, 26). Although X-rays and Lodox® are not sufficiently sensitive for detecting skull fractures in piglets, results for human infants and children may be different and require some investigation. Additional views of the skull, such as the angled "Towne" and "Waters" views, may be beneficial and improve visualization of fractures of the neurocranium and face which may not be detected on the antero-posterior and lateral views. Many pediatric radiographic guidelines recommend using only these two-views of the skull, or only encourage additional views if fractures are already detected on the antero-posterior or lateral view (1, 24, 27-30).

The sensitivity for identifying the correct type of skull fracture was 46.1% for CT, 16.6% for X-rays and 17.8% for Lodox®. CT had the highest sensitivity for all fracture types, similar to results reported by Kim et al. (4), who found CT to be more sensitive in identifying both depressed and diastatic fractures compared to X-rays. For all imaging modalities, sensitivity was higher for simple linear fractures than for diastatic fractures, results also observed by Mulroy et al. (7), likely because diastatic fractures may be more difficult to distinguish from normal sutures, particularly the unfused sutures of infants and children. However, sensitivity for detecting simple linear fractures using X-rays and Lodox® scans was still low (16.5% and 22.6% respectively), which may be because very thin or incomplete linear fractures are not easily identifiable on plain radiographs (7). The very low sensitivity for detecting the type of skull fracture, particularly for X-rays and Lodox® scans, may prevent the accurate diagnosis of physical child abuse, since it is possible that some fracture types, such as complex, depressed and diastatic fractures, are more indicative of and have a high specificity for (1, 2, 31-33). Moreover, certain fracture types such as diastatic and depressed fractures may be more associated with intracranial trauma (4, 34), and thus the low sensitivity for detecting depressed and diastatic fractures (Table 2), specifically with X-rays and Lodox®, may mean that intracranial injuries are not suspected or detected, especially when CT scans are not available.

Specificity for all fracture locations and types for all imaging modalities was extremely high, ranging between 92.5% and 100.0% (Tables 1 & 2), comparable to those of other studies (5, 7, 12). This indicates that very few false-positive fracture identifications were made, which is significant since it reduces the risk of incorrectly diagnosing physical child abuse, which could result in unwarranted and potentially traumatic investigations in non-abusive situations (1, 35). However, the very low sensitivity for all radiological methods in detecting pediatric skull fractures means that many cases of physical child abuse may be undetected and undiagnosed, which may increase the risk that a child is returned to an abusive situation and subsequently re-injured (1, 10, 35). In postmortem cases, osteological analysis should always be the method of choice when evaluating pediatric skull trauma and can be used in conjunction with CT scans which have the highest sensitivity. However, when dry bone analysis or even autopsy is not possible, as with living children, CT scans should be the radiological method employed. However, while X-ray and Lodox® should not be used to replace autopsy, dry bone or CT evaluations, they are often the only radiological resource available. Therefore, despite their low sensitivity, they may have to be relied upon to detect pediatric skull fracture locations and types.

A potential limitation of this study, as is with all forensic anthropological examinations, is that the maceration and manual reconstruction of the skulls may have introduced additional damage or trauma not present during the scanning process, despite how carefully the skulls were handled. Furthermore, the radiologist employed to perform the inter-observer repeatability was not specifically trained in pig anatomy, and therefore the detection of fractures may have been more difficult and may have resulted in some fractures not being detected. Future research should consider the use of a radiologist trained in comparative anatomy and osteology.

In summary, the results of this study are a stark reminder that no radiological technique is infallible, and no matter what technique is used there is always the possibility that trauma can be missed. This reiterates the fact that clinicians and forensic experts should always have a high index of suspicion and realize that it is relatively easy to miss fractures on imaging modalities. Therefore, the clinical picture and associated information should always be kept in mind.

Conclusion

The detection of pediatric skull fractures is critical in diagnosing victims of abuse and may also have implications for determining cause and manner of death. This study assessed the abiltiies of CT, X-ray and Lodox® scans for detecting the number, location and type of pediatric skull fractures. While specificity for all imaging modalities was high, sensitivity was very low, which may increase the risk of fractures and potential victims of abuse being unidentified. Osteological analysis therefore remains the gold standard and is the best method of choice to assess skull trauma in children whenever possible or practical. However, when this is not possible, CT scans should be used to detect skull fractures. In cases when even CT is not feasible or available, and X-rays and Lodox® have to be used, although not recommended, additional radiographic views of the skull may improve the detection of skull fractures.

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Paper 4

Diagnostic accuracies of CTs, X-rays and Lodox to detect blunt force trauma in adults, using a pig model

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Abstract

The accurate radiological detection of skeletal trauma is crucial for the investigation of blunt force trauma (BFT) cases. The abilities of CT, X-ray and Lodox scans in identifying BFT fractures and minimum number of impacts in pigs, used as proxies for adult humans, were assessed. Ten human sized pigs were struck with a mallet and scanned, after which the number of fractures and minimum number of impacts detected radiologically was recorded. All pigs were then macerated, and the skeletonized remains were considered the gold standard as far as number and location of fractures were concerned. CT was most sensitive in identifying fractures and impacts in all body regions, with an overall sensitivity of 55.2% and 71.5% respectively, while X-rays and Lodox had a sensitivity of 25.8% and 29.3% for fractures, and 43.5% and 41.1% for impacts, respectively. All modalities were highly specific for identifying fractures (CT: 99.1%; X-ray: 98.9%; Lodox: 99.4%). CT should be used to analyze blunt force skeletal trauma in the living where possible, while an examination of the dry bones remains the gold standard for the deceased where feasible. X-rays and Lodox have limited diagnostic value in these cases and relying on them to detect fractures may compromise patient care and the accurate forensic investigation of blunt trauma victims. However, the use of Lodox for initial screening of major trauma is still of value. Sensitivity is generally higher for detecting fractures in pigs compared to published studies on piglets, indicating that increased diagnostic value is achieved when imaging pigs compared to piglets.

Key words: Blunt force skeletal trauma; Radiological imaging; Diagnostic accuracies; CT; X-ray; Lodox

Introduction

The use of radiology in the clinical and medicolegal examination of individuals has become common practice [1-9]. Whether in the hospital, morgue, or forensic anthropology laboratory, numerous individuals subjected to injuries have blunt force trauma (BFT) [10-14], and the use of radiology can be crucial in accurately investigating this trauma.

In South Africa in 2019, 21 325 murders, 18 635 attempted murders, and 332 214 physical assaults were reported [15], while there was a global estimate of 478 000 homicides in 2017 [16]. Blunt instruments are among the most commonly used weapons during physical assaults [15], and BFT is one of the most common causes of death in homicides [12, 13, 17]. Accidents and mass disasters also result in BFT [16, 18, 19]. Skeletal fractures are common in BFT and need to be rapidly and accurately identified, both in the living and the deceased [20, 21, 22].

In emergency settings, radiology is utilized to rapidly detect trauma, and triage patients accordingly [5, 6, 23]. While computed tomography (CT) and conventional X-rays have generally been used for this purpose, the value of the low-dose X-ray ("Lodox") [24] has more recently been realized, as it provides full-body X-ray images in ±13 seconds, drastically reducing the time until clinical management can be given [25, 26]. In addition, the amount of radiation emitted by the Lodox is considerably less than CT and conventional X-rays, making it ideal for the imaging of living patients [27]. The use of radiology contributes to the accurate planning of surgical procedures in patients with orthopedic trauma [28] and is commonly used to perform skeletal surveys in suspected victims of physical child abuse [29].

During forensic examinations, post-mortem imaging of skeletal trauma may assist in ascertaining cause and manner of death [30-33, 35] and determining the minimum number of blows inflicted [30, 34]. CT scanning is the most commonly used method in most forensic institutions but is expensive and requires highly trained personnel [36-38]. Therefore, in institutions with limited resources, less expensive conventional X-ray imaging may more commonly be employed [39]. Lodox has therefore become the preferred method in many forensic institutions in South Africa as it is less expensive, does not require highly trained professionals to operate, and its rapid speed means less time scanning, potentially resulting in a higher throughput of autopsies [40]. Whether skeletal trauma as a result of BFT is being assessed in the hospital or during post-mortem forensic analyses, the diagnostic accuracies of the radiological methods used need to be known to ensure this trauma is detected as accurately as possible.

Many studies have assessed the abiltiies of imaging techniques in the detection of skeletal BFT. Chawla et al. [41, 42] found that CT detected 85.4% of skull fractures, and X-rays 71.4%. Makino et al. [43] reported that CT identified 77.0% of cervical spine fractures that were not detected during autopsy, and autopsy only identified 26.1% of fractures not detected by CT. For rib fractures, it was found that CT had a sensitivity of only 63.0% [44], and that conventional X-rays missed 74.5% of fractures identified by CT [45]. Lodox has also been assessed, reporting a sensitivity of 73.0% for peripheral skeletal fractures [46], 96.0% for pelvic fractures [47], 37.8% for rib fractures [47], 100.0% for thoracolumbar fractures [48], and 100.0% for long bone fractures [49]. However, most studies have evaluated the diagnostic accuracies of imaging modalities by comparing them to results from autopsy, CT, or computed radiography examinations. Only a handful of researchers compared results against the actual number of fractures present on the dry bones following skeletonization.

Mulroy et al. [50] found that CT detected 71.0% of cranial fractures in human infants, while X-rays detected 63.0%. Cattaneo et al. [51] reported that, in piglets, CT detected 126.0% of skull fractures (many were incorrectly diagnosed) and 34.0% of rib fractures, while X-rays detected 35.0% and 47.0% respectively. Both CT and X-rays identified 73.0% of forelimb fractures and 100.0% of hindlimb fractures. In a comparison of CT, X-ray and Lodox in piglets, Spies et al. [52] found that CT detected 47.3% of skull fractures while X-rays and Lodox only detected 22.4% and 23.2% respectively. CT identified 72.0% of all postcranial fractures, with X-rays and Lodox identifying only 49.0% and 41.0% respectively [34]. Spies et al. [34] also assessed the ability of these methods to detect the minimum number of blows incurred, with CT detecting 79.0%, X-rays 59.0% and Lodox 54.0%. However, all of these studies using the skeletonized remains as the gold standard were performed on human infants or piglets, and to the best of our knowledge, no such study has included adults or adult proxies. It is important to include adults in such assessments since bones fracture differently in adults and children, and therefore the radiological detection of these fractures may be different [53]. Pediatric bones are more elastic and the periosteum thicker than in adult bones, resulting in non-displaced, greenstick fractures in children, while adults tend to have a higher incidence of comminuted fractures [53]. The radiological detection of displaced, comminuted fractures is easier than non-displaced, greenstick fractures, and it is likely that sensitivity for detecting fractures in adults would be higher.

The aim of this study was therefore to determine the BFT fracture detection abilities of CT, X-ray and Lodox scans in pigs as proxies for human adults, with the cleaned skeletons considered the gold standard. An assessment of the abiltiies of these methods in determining the minimum number of impacts was also conducted.

Materials and methods

To assess the abilities of imaging methods in detecting skeletal trauma, this trauma must be performed on deceased bodies or animal models so that results can be compared against the cleaned skeletons. Pigs (Animal Research Ethics Committee, University of the Witwatersrand, Ethical Clearance No 2019/04/27/O) were used in this study as they are commonly used as proxies for humans in forensic research [54]. Ten pigs that had died of natural causes were used, each weighing between 49 and 82 kilograms, with age ranges of 16-20 weeks. While these pigs were still technically sub-adult as epiphyseal closure had yet to occur, they were much larger and slightly older than piglets used in previous studies (5-15 kg; 3-6 weeks old) [34, 52], and their weight ranges are comparable to that of the average adult human. They were therefore considered suitable proxies for human adults.

BFT using a 1.1 kg, 50 mm x 50 mm steel mallet was inflicted upon the head (1-5 blows), ribs and vertebrae (1-10 blows total), anterior limbs (1-10 blows) and posterior limbs (1-10 blows) of each pig. A mallet was chosen since it is one of the most commonly used weapons in cases of violent crime involving BFT [15, 55] and causes trauma similar to what is the case with other BFT instruments. Pigs were then CT, X-ray and Lodox scanned, the parameters of which are presented in Table 1. An additional pig not subjected to trauma was used as a negative control, ensuring that any skeletal anomalies were the result of trauma and could in fact be considered fractures. Pigs were then gently simmered in boiling water for between one and two days in order to macerate the remains and assess the cleaned skeletons.

Table 1. Scanning parameters used for CT, X-ray and Lodox scans.

Imaging modality	Milliampere-seconds (mAs)	Kilovoltage (kV)	Slice thickness (mm)	Scans taken
CT	150-300	120	3	Full-body helical scan (64 Slice CT Brilliance) (1 scan each)
X-ray	2-45	45-91	-	Ventro-dorsal and lateral views of each body region (24 scans each)
Lodox	200	120	-	Full-body ventro-dorsal and lateral views (2 scans each)

The number of fractures present in each body region of the cleaned skeletons, as well as on each radiograph, was documented. For the skull, it was noted whether the fracture was present on the cranium or mandible, while for the ribs, location was recorded either as vertebral end, shaft, or sternal end. For the limbs, the exact bones on which fractures were present were recorded, and for long bones, it was noted whether fractures were proximal, distal, or on the shaft. Both 2-dimensional and 3-dimensional images were examined when reading CT scans. In comparison to fractures detected on the dry bones, the number of true-positive, false-positive, true-negative, and false-negative fractures detected using each radiological method was counted. From these values, the sensitivity, specificity, positive predictive value (PPV) and negative predictive value (NPV) of each modality was calculated. Sensitivity is an imaging method’s ability to detect true-positive fractures; specificity is the ability to detect true-negative fractures; PPV is the probability that a fracture detected is indeed a true-positive identification; NPV is the probability that a fracture not detected is indeed a true-negative identification. These were calculated as follows:

$$Sensitivity = \frac{number\ of\ true-positives}{number\ of\ true-positives\ +\ number\ of\ false-negatives}\ x\ 100$$

$$Specificty = \frac{number\ of\ true-negatives}{number\ of\ true-negatives + number\ of\ false-positives}\ x\ 100$$

$$PPV = \frac{number\ of\ true-positives}{number\ of\ true-positives + number\ of\ false-positives}\ x\ 100$$

$$NPV = \frac{number\ of\ true-negatives}{number\ of\ true-negatives + number\ of\ false-negatives}\ x\ 100$$

A two-way ANOVA test was used to determine whether the number of fractures detected by each method in each body region differed significantly from the number of fractures present osteologically.

In keeping with a previous study using piglets [34], the minimum number of impacts in each body region was estimated based on the number and location of fractures present both radiologically and osteologically. The sensitivity of each modality for estimating the minimum number of impacts was calculated.

Cohen's kappa was used to evaluate intra- and inter-observer agreement for detecting fractures and estimating minimum number of impacts. The scans of the same five pigs were read by the principal investigator two months apart in order to determine intra-observer agreement, and the radiographs of these five pigs were read by a radiologist so that inter-observer agreement could be calculated. Statistical tests were done using IBM® SPSS® version 26.0, and all radiographs were viewed using RadiAnt DICOM Viewer (version 2020.2).

Results

Osteological analysis revealed a total of 543 fractures, with CT detecting 301 (55.2% sensitivity), X-ray 140 (25.8% sensitivity) and Lodox 159 (29.3% sensitivity). False-positive fracture identifications were minimal, with a specificity of 99.1% for CT, 98.9% for X-ray and 99.4% for Lodox. PPVs were high for all methods (CT: 98.0%; X-ray: 95.2%; Lodox: 97.5%), and NPVs were moderate (CT: 72.4%; X-ray: 61.3%; Lodox: 62.4%).

The sensitivity, specificity, PPVs and NPVs of each method for detecting fractures in each body region are presented in Table 2, along with the two-way ANOVA results. The number of true-positive fracture identifications made were consistently highest using CT across all regions, detecting on average 25.6% more fractures than X-rays and 23.3% more than Lodox. X-rays generally had the lowest sensitivity. When using CT, the anterior limbs and ribs had the highest sensitivity, while when using X-rays and Lodox, the highest sensitivity was achieved for the limbs. All modalities were least sensitive for fractures of the vertebrae. Specificity and PPVs were high for all modalities across all regions, while NPVs had much larger ranges. Due to no true-positive or false-positive vertebral fracture identifications made using X-rays or Lodox, PPVs could not be calculated for the vertebrae using these methods.

Of the 134 fractures of the skull, 109 were cranial and 25 were mandibular. CT scans had the highest sensitivity for both cranial and mandibular fractures, detecting more than half of all cranial fractures and almost all mandibular fractures (Table 2) (Figure 1). Sensitivity for Lodox was slightly higher than X-rays, and while both detected more than half of all mandibular fractures, only 10.1% and 13.8% of cranial fractures were detected by X-rays and Lodox respectively (Table 2) (Figure 1). Specificity and PPVs were comparable across all modalities for both cranial and mandibular fractures, while CT scans had NPVs higher than both X-rays and Lodox, which were similar (Table 2).

A total of 215 rib fractures were present, including 68 vertebral end, 56 shaft, and 91 sternal end fractures. CT resulted in the highest number of true-positive fracture identifications for all rib locations, while X-rays generally had the least (Table 2) (Figure 2). All modalities were most sensitive for fractures of the rib shaft, and least sensitive for sternal end fractures (Table 2) (Figure 2). All radiological methods had very high specificity and PPVs for all rib locations (all above 90.0%). CT had NPVs above 85.0% for all locations, while only the NPVs for sternal end fractures were below 80.0% for X-rays and Lodox (Table 2).

Vertebral fractures (120 in total) consisted of 75 spinous process and 45 transverse process fractures. CT detected only a fifth of both vertebral spine and transverse process fractures, while X-rays and Lodox did not detect any (Table 2) (Figure 3). Specificity and NPVs were high for both types of fractures using all modalities, and while PPVs were 100.0% for CT, PPVs could not be calculated for X-rays or Lodox (Table 2).

A total of 30 anterior limb and 44 posterior limb fractures were present osteologically. Of the total number of anterior limb fractures that were not detected using CT, X-ray and Lodox, respectively, 13.3%, 33.3% and 26.7% were fractures of the scapula, while the bones with the next highest number of false-negative identifications were the metacarpals (6.7% using all methods) (Figure 4). For the posterior limbs, 16.0% of all fractures missed using CT, and 25.0% using both X-rays and Lodox, were distal fractures of the long bones (Figure 5).

The analysis of the dry bones revealed a minimum number of 207 impacts (64 to the skull; 91 to the ribs and vertebrae combined; 25 to the anterior limbs; 27 to the posterior limbs). Using CT scans, 148 (71.5%) of overall impacts (56.3% skull; 79.1% rib and vertebral; 84.0% anterior limb; 70.4% posterior limb) were estimated. Corresponding figures for X-rays were 90 (43.5%) for overall impacts, including 31.3% skull, 44.0% rib and vertebral, and 60.0% and 55.6% anterior and posterior limb, respectively. A minimum number of 85 (41.1%)

impacts were estimated using Lodox (skull: 32.8%; ribs and vertebrae: 38.5%; anterior limbs: 64.0%; posterior limbs: 48.1%).

The intra-observer agreement for detecting fractures and impacts was almost perfect [56], with kappa values ranging between 0.93-1.00 for CT, 0.89-1.00 for X-rays, and 0.88-1.00 for Lodox. Inter-observer agreement for fracture and impact counts was substantial to almost perfect [56] (CT: 0.66-0.88; X-ray: 0.85-1.00; Lodox: 0.79-0.94).

Table 2. Sensitivity, specificity, positive predictive values (PPVs) and negative predictive values (NPVs) of CT, X-ray and Lodox scans for detecting fractures in the various body regions.

	CT				X-ray				Lodox			
	Sens	**Spec**	**PPV**	**NPV**	**Sens**	**Spec**	**PPV**	**NPV**	**Sens**	**Spec**	**PPV**	**NPV**
Skull	***58.2 (78/134)**	**100.0 (44/44)**	**100.0 (78/78)**	**44.0 (44/100)**	***18.7 (25/134)**	**97.8 (43/44)**	**96.2 (25/26)**	**28.3 (43/152)**	***22.4 (30/134)**	**100.0 (44/44)**	**100.0 (30/30)**	**29.7 (104/148)**
Cranium	*51.4 (56/109)	100.0 (40/40)	100.0 (56/56)	43.0 (40/93)	*10.1 (11/109)	100.0 (40/40)	100.0 (11/11)	29.0 (40/138)	*13.8 (15/109)	100.0 (40/40)	100.0 (15/15)	29.9 (40/134)
Mandible	88.0 (22/25)	100.0 (4/4)	100.0 (22/22)	57.1 (4/7)	*56.0 (14/25)	75.0 (3/4)	93.3 (14/15)	21.4 (3/11)	*60.0 (15/25)	100.0 (4/4)	100.0 (15/15)	28.6 (4/14)
Ribs	***69.3 (149/215)**	**98.1 (153/156)**	**98.0 (149/152)**	**69.9 (153/219)**	***37.2 (80/215)**	**98.1 (153/156)**	**96.4 (80/83)**	**53.1 (153/288)**	***43.3 (93/215)**	**99.3 (151/152)**	**97.9 (93/94)**	**55.3 (151/273)**
Vertebral end	*66.2 (45/68)	99.6 (235/236)	97.8 (45/46)	91.1 (235/258)	*41.2 (28/68)	100.0 (236/236)	100.0 (28/28)	85.5 (236/306)	*38.2 (26/68)	100.0 (236/236)	100.0 (26/26)	84.9 (236/308)
Shaft	*82.1 (46/56)	100.0 (246/246)	100.0 (46/46)	96.1 (246/256)	*57.1 (32/56)	99.6 (245/246)	97.0 (32/33)	91.1 (245/269)	*64.3 (36/56)	100.0 (246/246)	100.0 (36/36)	92.5 (246/266)
Sternal end	*63.7 (58/91)	99.1 (210/212)	96.7 (58/60)	86.4 (210/243)	*22.0 (20/91)	99.1 (210/212)	90.9 (20/2)	74.7 (210/281)	*34.1 (31/91)	99.5 (211/212)	96.9 (31/32)	77.9 (211/271)
Vertebrae	***20.8 (25/120)**	**100.0 (184/184)**	**100.0 (25/25)**	**65.9 (184/279)**	***0.0 (0/120)**	**100.0 (184/184)**	**-**	**60.5 (184/304)**	***0.0 (0/120)**	**100.0 (184/184)**	**-**	**60.5 (184/304)**
Spinous process	*21.3 (16/75)	100.0 (214/214)	100.0 (16/16)	78.4 (214/273)	*0.0 (0/75)	100.0 (214/214)	-	84.6 (214/289)	*0.0 (0/75)	100.0 (214/214)	-	84.6 (214/289)
Transverse process	*20.0 (9/45)	100.0 (248/248)	100.0 (9/9)	87.3 (248/284)	*0.0 (0/45)	100.0 (248/248)	-	70.4 (248/293)	*0.0 (0/45)	100.0 (248/248)	-	70.4 (248/293)
Anterior limbs	**70.0 (21/30)**	**98.3 (113/115)**	**91.3 (21/23)**	**92.6 (113/122)**	***43.3 (13/30)**	**97.4 (112/115)**	**81.3 (13//16)**	**86.8 (112/129)**	***50.0 (15/30)**	**97.4 (112/115)**	**83.3 (15/18)**	**88.2 (112/127)**
Posterior limbs	***63.6 (28/44)**	**99.3 (144/145)**	**96.4 (28/29)**	**90.0 (144/160)**	***52.3 (23/44)**	**100.0 (145/145)**	**100.0 (23/23)**	**87.3 (145/166)**	***47.7 (21/44)**	**100.0 (145/145)**	**100.0 (21/21)**	**86.3 (145/168)**

*Indicates a significant difference ($p<0.01$) between the mean number of true-positive fractures detected radiologically and the actual number of fractures present osteologically (tested by two-way ANOVA). Sens: Sensitivity; Spec: Specificity.

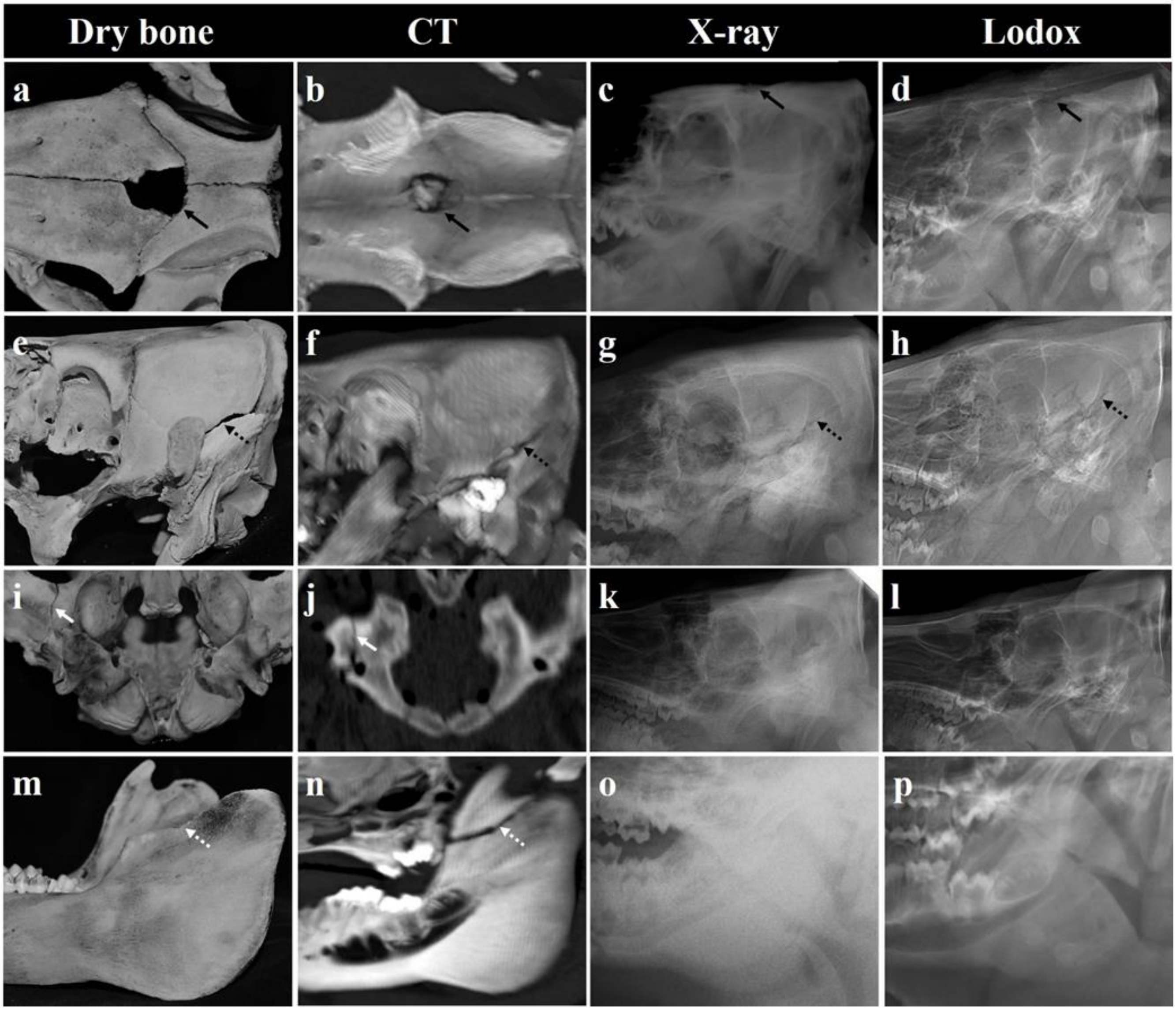

Fig. 1 Some of the very large, wide fractures present on the dry bone, such as the depressed frontal fracture (solid black arrows) (images a-d) and wide temporal fracture (dashed black arrows) (images e-h), were detected using CT, X-ray and Lodox. However, many of the smaller fractures, or fractures in areas of superimposition on X-rays and Lodox, such as the small temporal fracture (solid white arrows) (images i-l) and fracture of the mandibular coronoid process (dashed white arrows) (images m-p), were detected using CT but not X-ray or Lodox in any radiographic view. A lack of arrows indicates no fracture detected

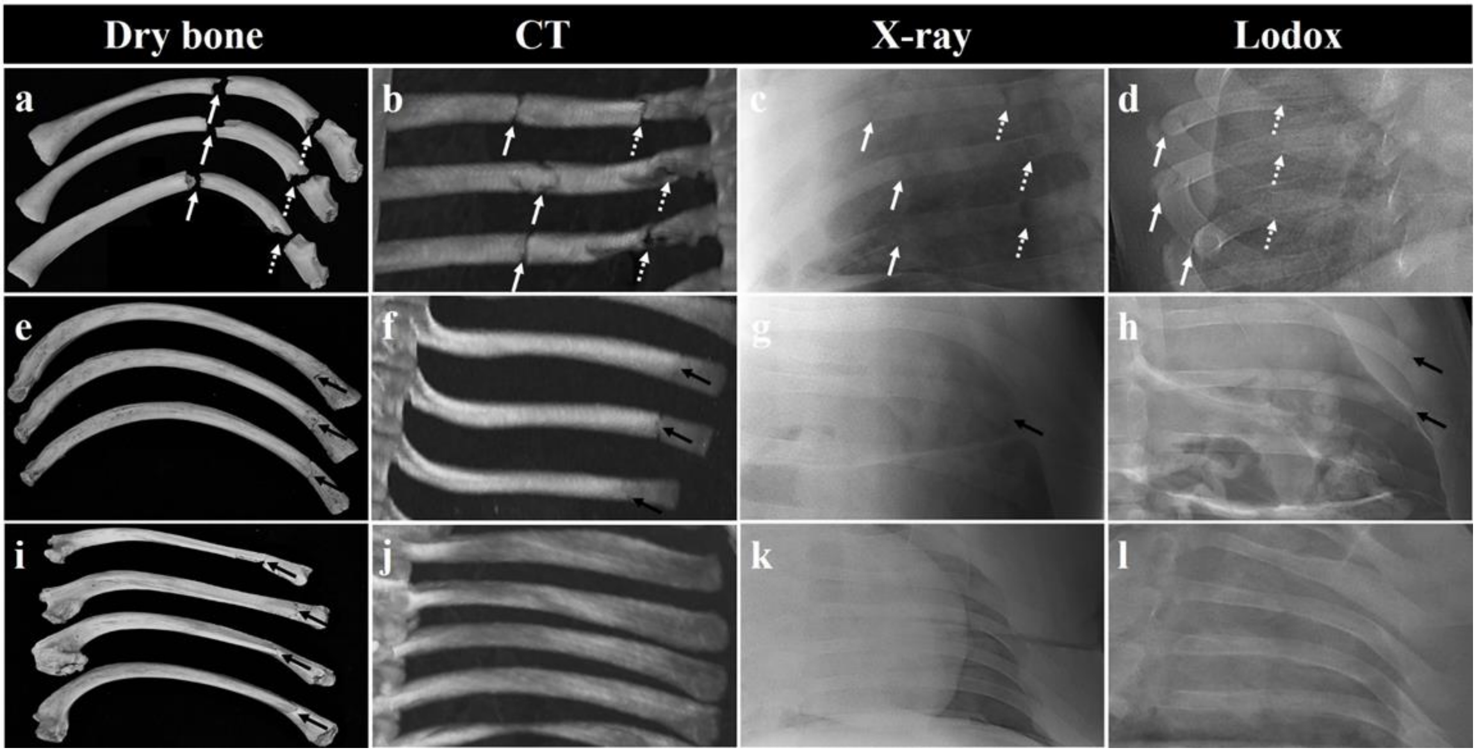

Fig. 2 Rib shaft (solid white arrows) and vertebral end rib fractures (dashed white arrows) (images a-d) as seen on dry bone, CT, X-ray and Lodox. Many sternal end rib fractures (black arrows) (images e-l) present on dry bone were not identified by CT, X-ray or Lodox in any radiographic view. A lack of arrows indicates no fracture detected

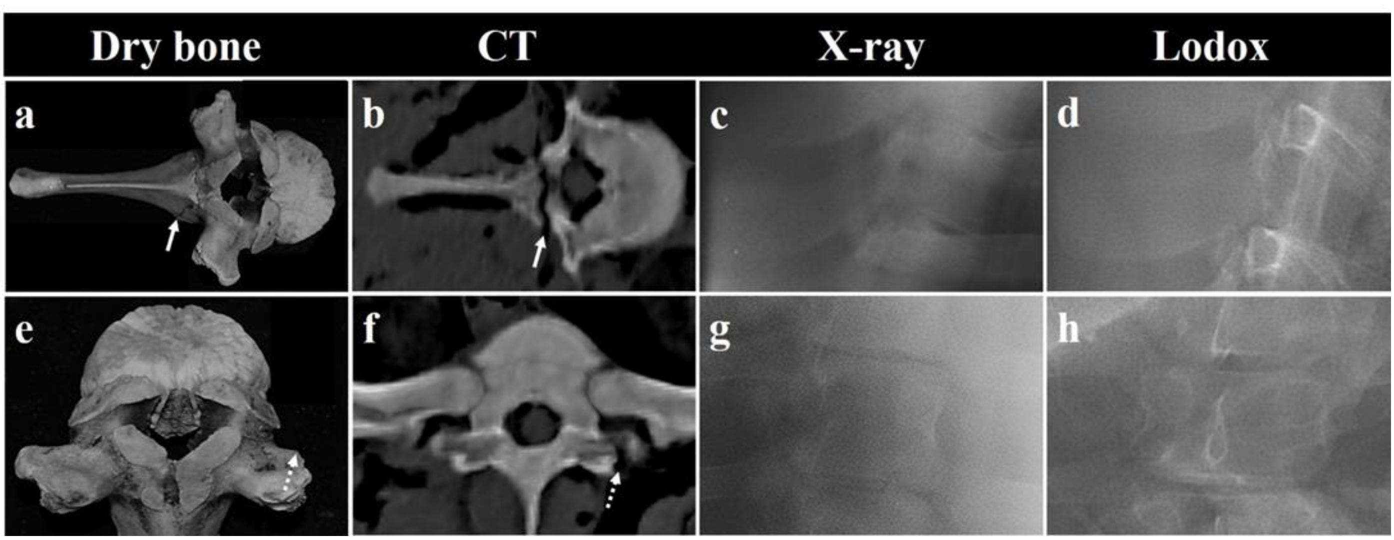

Fig. 3 Vertebral spine (solid white arrows) (images a-d) and transverse process fractures (dashed white arrows) (images e-h) as seen on dry bone and CT, but not detected on X-ray or Lodox in any radiographic view. A lack of arrows indicates no fracture detected

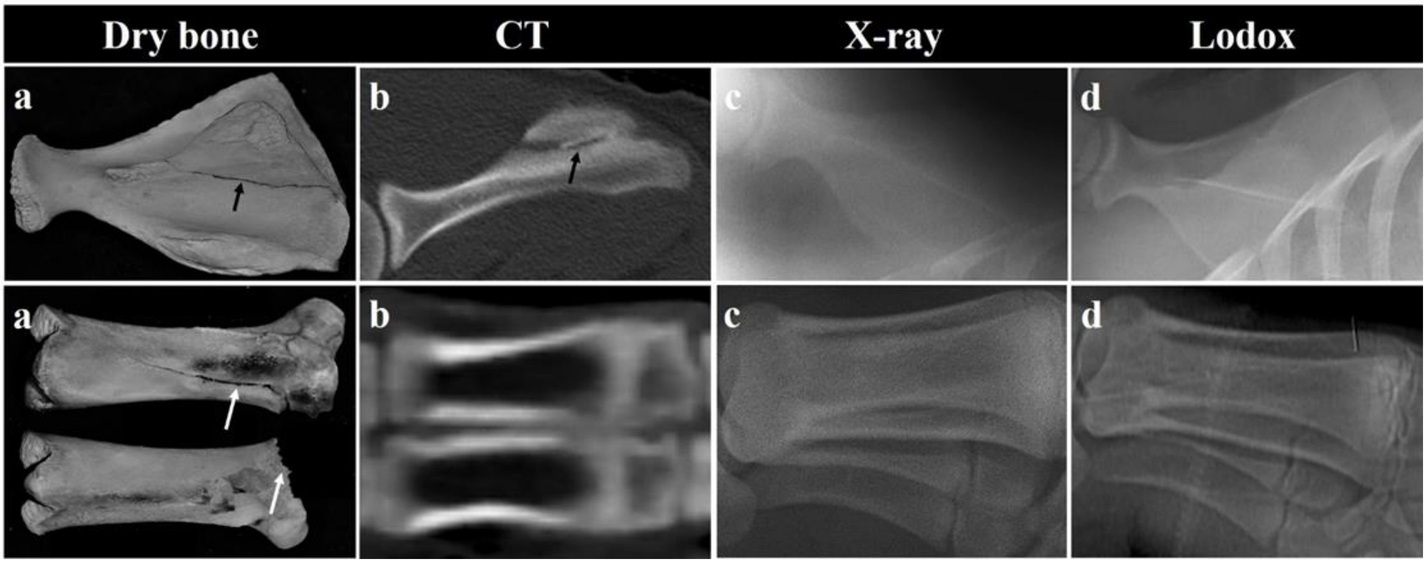

Fig. 4 Scapular fractures (black arrows) (images a-d) as seen on dry bone and CT, but not detected on X-ray or Lodox. Metacarpal fractures (white arrows) (images e-h) as seen on dry bone, but not detected on CT, X-ray or Lodox in any radiographic view. A lack of arrows indicates no fracture detected

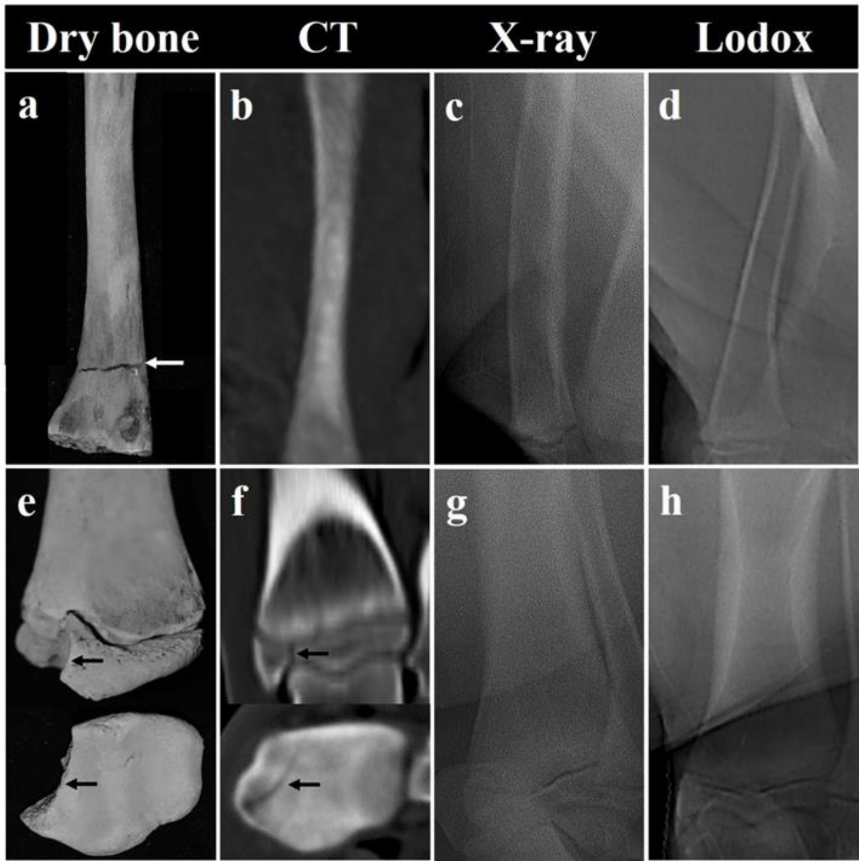

Fig. 5 Fracture of the distal fibular shaft (white arrow) (images a-d) as seen on dry bone but not on CT, X-ray or Lodox. Fracture of the distal epiphysis of the tibia (black arrows) (images e-h) as seen on dry bone and CT but not detected by X-ray or Lodox in any radiographic view. A lack of arrows indicates no fracture detected

Discussion

Skeletal trauma is often evaluated using radiological means, and knowledge of the diagnostic capabilities of these methods in detecting fractures is essential. While some studies have compared the abilities of various imaging modalities against the number of fractures detected on the cleaned skeletons [34, 50-52], these studies all assessed BFT in human infants or piglets as proxies for human children. However, the bones of adults and children differ in size, composition, elasticity, and strength [53], and the radiological detection of skeletal trauma may differ between them. This study therefore investigated the diagnostic accuracies of CT, X-ray and Lodox scans in identifying skeletal BFT in pigs as proxies for human adults.

CT scans are more sensitive than X-rays (18.7%) and Lodox (22.4%) in detecting skull fractures, with a diagnostic accuracy of 58.2%. These are lower than those reported by Chawla et al. [41, 42] for skull fractures in adults (85.4% for CT [41] and 71.4% for X-rays [42]). However, CT and X-ray results in those studies were compared against autopsy results and an osteological examination of the skulls was not performed. Consequently, these results should be interpreted with caution as it is likely that if dry bone were used as the gold standard in these studies, results would be much more comparable to those of the present study. When compared to piglets, CT scans are more sensitive in larger, older pigs, detecting 58.2% of skull fractures in pigs compared to only 47.3% in piglets [52]. However, sensitivity for X-rays and Lodox are comparable between pigs and piglets, both detecting approximately 1/5th of fractures in both models [52]. CT therefore appears to add more diagnostic value in adults compared to children when evaluating skull fractures.

While X-rays and Lodox are moderately sensitive in detecting mandibular fractures, they are both insensitive for fractures of the cranium (10.1% and 13.8% respectively). This is cause for concern, since blows to the skull are extremely common in incidences of violent crime, domestic abuse, and accidents, with between 6.3% and 68.3% of patients in emergency trauma units presenting with skull trauma [10, 11], and up to 93.0% of homicide victims having evidence of BFT to the skull [12]. The inability of X-rays and Lodox to detect fractures of the skull, and the fact that CT scans fail to identify approximately 40.0% of these fractures, is concerning and could compromise the clinical or forensic examination of these individuals.

CT scans are most sensitive in identifying the overall number of rib fractures, with a true-positive detection rate of 69.3%, which is slightly higher than reported in previous studies (62.4% [57] and 63.0% [44]). X-rays and Lodox, however, detected only 37.2% and 43.3% of rib fractures respectively, which is still higher than previous studies reporting a sensitivity of 25.5% for X-rays [45] and 37.8% for Lodox [47]. A potential reason for the sensitivity being slightly higher in the present study compared to previous research may be due to differences in scanning technologies or specific parameters used. Sensitivity is, however, lower than that reported for piglets [34], which is 84.0% using CT, 60.0% using X-ray, and 50.0% using Lodox. CT scans also have the highest diagnostic accuracies for detecting rib fractures in all locations. Similar to results for piglets [34], all modalities are most sensitive for shaft fractures and least sensitive for sternal end fractures. However, CT and Lodox are more sensitive in detecting sternal end fractures in older pigs (63.7% and 34.1% respectively) compared to piglets (44.0% and 18.0% respectively) [34], while X-rays have equal sensitivity for both (22.0%) [34]. All modalities, however, are more sensitive in detecting vertebral end and shaft fractures in piglets compared to older pigs, except for shaft fractures detected using Lodox (64.3% for pigs and 61.0% for piglets) [34]. Greater diagnostic value is therefore achieved when using CT and Lodox to detect shaft (Lodox only) and sternal end fractures in adults compared to children. Rib shaft and vertebral end fractures may have a significant effect on mortality [58] and the moderate to high sensitivity of these radiological methods for these fractures is therefore significant. However, the lower sensitivity of X-rays and Lodox in detecting all rib fractures indicate that CTs should be the method of choice when evaluating chest trauma.

Vertebral fractures are most commonly identified by CT (20.8%), while X-rays and Lodox are completely insensitive (0.0% each). This sensitivity is much lower than the 98.7% reported for CT scans [59], 70.0% for X-rays [60], and 16.7% [47] and 100.0% [48] for Lodox, which may because these studies used autopsy or other imaging modalities as the standard of comparison. Sensitivity using CT scans is also lower than those reported when assessing piglets (43.0%) [34], but sensitivity for X-rays and Lodox are the same (0.0%) [34]. While X-rays and Lodox do not differ between pigs and piglets for vertebral fractures, greater diagnostic value is achieved when assessing piglets compared to older pigs when using CT. CT scans identified 21.3% and 20.0% of spinous and transverse process fractures respectively, whereas X-ray and Lodox did not detect any of either type of fracture. This low sensitivity is significant since vertebral fractures, such as those of the transverse processes of lumbar vertebrae, are often associated with abdominal injury [61], information which could aid in medicolegal investigations. The low sensitivity may be due to the very intricate anatomy and structure of vertebrae, which makes fractures in these regions difficult to visualize. In addition, superimposition of the transverse processes of the vertebrae with the posterior aspects of the ribs may obscure lesions to these skeletal elements on X-ray and Lodox scans.

CT is more sensitive than both X-rays and Lodox in detecting anterior and posterior limb fractures. Both CT and Lodox are more sensitive for fractures of the anterior limb

(70.0% and 50.0% respectively) compared to the posterior limb (63.6% and 47.7% respectively), but X-rays are more sensitive for posterior limb fractures (52.3%; anterior limbs: 43.0%). The sensitivity of CT for detecting limb fractures in the present study is comparable to that reported by Cabarrus et al. [62], with a sensitivity of 69.0%. However, sensitivity for X-rays and Lodox in the present study is lower than previously reported (70.0% for X-rays [63] and 100.0% for Lodox [49]). Again, differences in the gold standard used in these previous studies may be the result of these discrepancies. Sensitivity is, however, higher than that reported for piglets using all modalities (43.0% - 58.0%) [34], except for the posterior limbs using X-rays. The moderate to high sensitivity for detecting limb fractures using all modalities is important since long bone fractures are common in instances of violent crime [64]. Many of the limb fractures missed included those of the distal epiphyses of the long bones, and it is possible that these fractures were mistaken as epiphyseal fusion lines since pigs were still sub-adult and fusion was not yet complete. This would not be of concern in adult humans where epiphyseal closure is complete, and it is likely that the sensitivity for detecting limb fractures may therefore improve when radiologically assessing the skeletons of adult humans.

Specificity is extremely high for all modalities and all body regions, ranging between 98.1% and 100.0% for CT, 80.0% and 100.0% for X-rays, and 97.4% and 100.0% for Lodox. This indicates that false-positive fracture detection is uncommon using all modalities, making unnecessary surgical interventions or forensic-related skeletal dissections unlikely. Specificity is similar to that reported for adults in previous studies [41, 42, 44, 47, 49], and similar to those reported for skull fractures in piglets (97.7% - 100.0%) [52]. PPVs are high for all modalities and all regions (all above 80.0%) which indicates that a fracture detected by any modality is highly likely to indeed be a true-positive identification. NPVs are much more variable, indicating highly variable probabilities that a fracture not detected by a radiological method is indeed a true-negative identification. Caution should therefore be used when a fracture is not detected by an imaging modality, particularly for the skull which has the lowest NPVs.

When it comes to estimating the minimum number of impacts, CT scans are most sensitive in all body regions, while the sensitivity of X-rays and Lodox is lower but comparable to each other. These results indicate that CT can be used to estimate the minimum number of blows, but X-rays and Lodox should not be used for this purpose. This is significant since assessing the minimum number of blows incurred during a traumatic incident may aid in distinguishing between whether this trauma was accidental or intentionally inflicted.

Sensitivity is highest using CT scans for all body regions, which may be due to superimposition of structures in X-rays and Lodox, which increases the difficulty of detecting fractures in these regions. The low to moderate sensitivity of X-rays and Lodox in detecting skeletal BFT, and the fact that CT scans do not detect nearly a half of all fractures, is concerning, as failing to correctly identify fractures means that an accurate establishment of cause and manner of death may not be possible. However, Lodox outperformed X-rays in detecting fractures in pigs, and therefore forensic institutions which employ Lodox technology as opposed to conventional X-rays are not at a disadvantage. In fact, the use of Lodox for fast, initial screening procedures to detect major trauma is still of value. It is likely that sensitivity using all methods will be higher when evaluating trauma in humans, as both radiologists and forensic professionals are much more familiar with human osteology and anatomy. While CT therefore remains the gold standard for evaluating skeletal trauma in the living, an osteological assessment of the cleaned remains should be considered the gold standard in post-mortem investigations of BFT.

Many of the sensitivity differences reported in this study and previous studies may be due to the use of different methods as the gold standard, as well as different scanning technologies and parameters used.

In general, diagnostic accuracies of all modalities are higher in larger, older pigs compared to piglets. This may be due to an increased incidence of displaced and comminuted fractures in older bones [53], which may be easier to detect radiologically. This suggests that, in general, greater diagnostic value is achieved when imaging adults, particularly when using CT scans. Results also suggest that radiographic techniques used for adults may not be sufficient for children. For example, while sensitivity was generally higher for Lodox compared to X-rays in pigs in the current study, X-rays outperformed Lodox in piglets [34]. This suggests that, when CT or dry bone examinations are not possible, Lodox should be used to detect trauma in adults, but conventional X-rays are preferred when imaging children.

Conclusion

The present study found CT to be more sensitive than both X-rays and Lodox in detecting fractures and estimating the minimum number of impacts in all body regions. However, CT scans still fail to detect nearly half of all fractures. Assessments of skeletal trauma in the living should therefore be conducted using CT, but dry bone examinations, whenever possible, are the gold standard for investigations of the deceased. Lodox is slightly more sensitive than X-rays, but both are generally insufficient in detecting skeletal BFT and, where possible, should be used in conjunction with CT or a dry bone analysis. Using X-rays and Lodox exclusively could compromise patient care and the investigation of cause and manner of death. However, the use of Lodox in the initial screening of major trauma is still of value. Increased diagnostic value is generally achieved when imaging adults compared to children, particularly using CT scans. When CT or osteological assessments are not possible, Lodox should be used when imaging adults, but imaging of children should be performed using conventional X-rays.

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Paper 5

Radiological detection of sharp force skeletal trauma: implications for the accurate investigation of victims of violent crime

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Abstract

Victims of violent crime often have evidence of sharp force trauma (SFT) which needs to be examined to accurately investigate these cases. The abilities of CT, X-ray and Lodox to detect skeletal SFT defects and the minimum number of impacts were assessed, as were their abilities to macroscopically interpret SFT with the aim of identifying the class of weapon used. Ten pigs were, post-mortem, stabbed using a kitchen knife on one side of the body, and chopped using a panga on the other side. They were then scanned and macerated. The number of SFT defects, type of SFT, and minimum number of impacts identifiable osteologically were recorded, as well as when using each imaging modality. CT was most sensitive for detecting stab and chop defects (56.7% and 78.3% respectively) and the minimum number of impacts (82.8%), while X-rays were least sensitive (17.2% for stab wounds, 46.5% for chop marks, and 43.5% for impacts). Lodox detected 9.6% more stab defects (26.8%), 12.8% more chop marks (59.3%), and 14.9% more impacts (58.4%) than X-rays. The type of SFT for more than 70.0% of identified defects was correctly classified using all methods, while only Lodox had moderate sensitivity for stab wounds (52.4%). When radiological assessments of skeletal SFT are required, CT should be performed, but Lodox can be used as an alternative. However, dry bone analyses still produce the best results and should be performed whenever possible. Macroscopic interpretations of skeletal SFT to broadly determine the class of weapon used is possible radiologically.

Key words: sharp force trauma; radiological sensitivity; computed tomography (CT); X-ray; low-dose full-body X-ray (Lodox)

Introduction

Individuals with evidence of sharp force trauma (SFT) are relatively common in both clinical and forensic settings. SFT is trauma produced as a result of bevelled, edged or pointed instruments [1], resulting in incisions, punctures, or clefts on bone [2]. Of the 21 325 murders reported in South Africa in 2019/2020, 6 354 (29.8%) were the result of SFT, while 17.2% of all attempted murders and assaults were committed using sharp instruments [3]. Between 2015 and 2017, 7.1% of all cases at the Johannesburg Forensic Pathology Services involved sharp force injuries (C. Keyes, personal communication), and from 2016 to 2020, 10.7% of forensic anthropological analyses conducted at the Human Variation and Identification Research Unit at the University of the Witwatersrand had evidence of SFT. Between 18.9% [4] and 20.9% [5] of patients presenting in South African emergency trauma centres have sharp force injuries. The detection and analysis of these injuries, specifically to the skeletal system, is crucial in optimising patient care or establishing the circumstances surrounding death.

The examination of the specific characteristics of the SFT can add further information regarding the traumatic event, such as the class of weapon used, which could aid in identifying the murder weapon or the instrument used in post-mortem dismemberment cases [6]. For example, narrow defects such as cuts, incisions or punctures in the bone are generally a result of stabbing trauma with weapons such as knives [2, 7], while wide defects with bone wastage and chattering, and other sharp-blunt characteristics such as fracturing and crushing of the bone, are often the result of hacking trauma with weapons such as axes, hatchets, or machetes [2, 8, 9,]. Saws are often used in cases of post-mortem dismemberment and analysing the characteristics of the kerf wall and floor, such as the striations made by the instrument, can assist in determining the class of saw used [6, 10, 11].

Soft tissue injuries resulting from SFT are generally easy to detect during clinical and forensic examinations and are often used to help locate sites of osteological trauma. As an alternative to dissecting or macerating the remains to examine SFT, which is time-consuming and labour-intensive and which cannot be performed in living individuals, radiological imaging can be used. In cases of burning, where skeletal remains are charred and therefore extremely fragile, conducting a dry bone analysis is not always appropriate as the bones may fragment and crumble [12]. In these cases, soft tissue may also become charred and adhere to the bone surface, which could obscure any trauma beneath this tissue [12, 13]. The virtual examination of skeletal trauma in these cases is therefore invaluable.

While the radiological examination of soft tissue injuries as a result of SFT has been widely assessed [14-19], as has the use of micro-computed tomography (micro-CT) to analyse SFT characteristics on bone [20-24], only a handful of studies have evaluated the use of imaging methods to detect and macroscopically interpret SFT to bone. Schnider et al. [15] assessed SFT in 12 individuals using both autopsy and radiological means and found that CT detected 100% of SFT osseous lesions detected during autopsy, whereas Thomsen et al. [16]

noted that CT scans were more sensitive than autopsy in detecting skeletal fractures in cases of sharp-blunt trauma. Ampanozi et al. [25] used CT and magnetic resonance imaging (MRI) scans to virtually analyse SFT to the skull using a hatchet and found that many of the macroscopic features characteristic of the bone trauma caused by this type of weapon were easily identifiable radiologically, including bone crushing and fracturing. Furthermore, CT was found to be superior to autopsy in determining the exact number of bone fragments as a result of the SFT, as well as the presence of bone flaking at sites of trauma [25]. Other authors [26; 27] used 3-dimensional CT imaging to assess SFT to the skulls of surviving victims and reported that the weapons used to inflict the trauma, an axe and a hatchet, respectively, could be confirmed based on the characteristics of trauma visualized radiologically.

Previous studies [15, 16] evaluating the radiological detection of sharp force injuries to bone, however, have used autopsy results as the gold standard, while no study using the dry bone as the gold standard has been performed. In addition, the studies that have radiologically assessed the macroscopic characteristics of skeletal SFT were case studies [25-27], where the exact weapon used to inflict trauma was known prior to radiological imaging, and imaging was used to confirm the use of this weapon. No study, to the best of our knowledge, has aimed to distinguish between two or more possible classes of weapons based on these characteristics. Moreover, the sensitivity of conventional X-rays in the detection and interpretation of SFT has rarely been evaluated, while low-dose full-body X-rays (commonly referred to as Lodox scans) have yet to be assessed. Lodox are commonly used in South African hospitals [28, 29] and medico-legal laboratories [30] as a result of their fast scanning times and low maintenance costs.

The aim of this study was therefore to compare the abilities of CT, conventional X-rays, and Lodox scans in detecting skeletal defects as a result of SFT. Their suitability to determine the type of SFT inflicted and, as a result, the class of weapon used, was also assessed by analysing the macroscopic characteristics of the trauma. This was done by comparing the results of the radiological examinations to what was observed on the dry bones.

Materials and methods

In South Africa, kitchen knives and pangas, which are weapons similar to machetes, are among the most commonly used sharp instruments during incidences of violent crime [3]. These two weapons result in different types of osteological SFT; knives are generally used during incidences of stabbing, resulting in puncture or incision defects on bone [2, 7], while pangas are used to inflict hacking trauma, which causes sharp-blunt, chop defects on bone [2, 8, 9]. In order to accurately simulate these types of injuries, a non-serrated kitchen knife and a panga were used to inflict SFT on ten deceased pigs (47-79 kg each), with one side of the body being subjected to stabbing trauma using the kitchen knife, and the other side hacking trauma using the panga (Animal Research Ethics Committee at the University of the Witwatersrand, Clearance Certificate Number 2019/04/27/O). The kitchen knife was single-edged and non-serrated, with a stainless-steel blade measuring 163 mm in length and 28 mm in width. The panga had a curved carbon steel blade, measuring 652 mm in length and 112 mm in width. The side of the body on which each instrument was used to inflict trauma, as well as the number of strikes inflicted, were not kept consistent in order to reduce bias, but were recorded independently for each pig.

Each weapon was used to inflict between 1 and 10 strikes to each of the four body regions: the skull, the trunk (including the ribs and vertebrae), the forelimbs, and the hindlimbs. Pigs were used since research has shown that pig bones are acceptable proxies for humans when studying sharp force skeletal trauma [31].

The radiological methods used to detect SFT included full-body helical CT scans, conventional X-rays of each body region, and full-body Lodox scans. Ventro-dorsal and left and right lateral images were taken using both conventional X-rays and Lodox. Milliampere-seconds (mAs) and kilovoltage (kV) were, respectively, 150-300 and 120 for CT scans, 2-45 and 45-91 for X-rays, and 200 and 120 for Lodox. Slice thickness and slice increment were 3.0 mm and 1.5 mm respectively for CT scans. Following scanning of the pigs, the pigs were skeletonized so that the dry bones could be examined as the gold standard. Cleaning of the remains during the maceration procedure was done extremely carefully, especially when using scalpels to remove the soft tissue, to ensure that no additional SFT was introduced to the remains.

CT (both 2-dimensional and 3-dimensional), X-ray and Lodox images were analysed using RadiAnt DICOM Viewer (version 2020.2.2). The number and location of skeletal sharp force defects evident in each body region was recorded for each type of radiological method, as well as for the dry bones.

The type of SFT was also recorded as either stabbing or hacking trauma. Following guidelines by numerous authors [2, 7-9], several macroscopic characteristics were considered when distinguishing between the two types of SFT. These traits are outlined in Table 1 [2, 7-9] and are illustrated in Figures 1-7. Bone wastage occurs when the sharp instrument is removed from the bone, resulting in bone fragments being separated from the main section of bone [2, 9]. Chattering refers to the presence of bone chipping at the site of trauma [8]. Based on the type of SFT, stabbing vs hacking, the class of weapon was assessed. The minimum number of strikes inflicted was also estimated by ascertaining which sharp force skeletal defects were likely the result of the same impact (Figs. 4 and 6). A minimum number was determined as some strikes may not have resulted in any osteological lesions.

In line with previous papers assessing the radiological detection of blunt force trauma (BFT) [32, 33], the sensitivity, specificity, positive predictive value (PPV) and negative predictive value (NPV) of each imaging method in identifying the overall number and location of sharp force defects, as well as the number and location of each type of SFT, was calculated by comparing these results against the results from the dry bone assessments. A radiological method's sensitivity is its ability to detect fractures that are also present osteologically, while its specificity is its ability to correctly determine that a bone does not have a fracture. PPV refers to the probability that a radiologically identified fracture is actually present osteologically, while NPV refers to the probability that a bone not determined to have a fracture virtually is indeed fracture-free osteologically. The sensitivity for estimating the minimum number of impacts was also calculated for each imaging method. A sensitivity between 0.0% and 39.0% was considered low, between 40.0% and 69.0% was considered moderate, and between 70.0% and 100.0% was considered high.

Radiological examinations were only conducted three months after the infliction of trauma, scanning and maceration, in order to reduce memory bias regarding the exact number of strikes inflicted to each pig, as well as which weapon was used on each side of the body. Dry bone examinations were only conducted after the radiological assessments had been completed. Two-way ANOVA tests were used to determine if the number of defects detected and the minimum number of strikes estimated using each radiological tool differed significantly from those recorded during the osteological examinations.

A radiologist read the CT, X-ray and Lodox scans of five pigs to perform an assessment of inter-observer repeatability, while the primary investigator performed an intra-observer repeatability assessment by reading the scans of the same five pigs one month apart. The level of inter- and intra-observer agreement was evaluated using Cohen's kappa. The two-way ANOVA and Cohen's kappa tests were performed using SPSS (version 26).

Table 1. Characteristics used to distinguish between stabbing trauma inflicted with a kitchen knife, and hacking trauma inflicted with a panga [2, 7-9].

Stabbing trauma	Hacking trauma
Narrow defects	Wide defects
Cut marks and puncture wounds	Chop marks
Small nicks or notches in the bone cortex	Bisected and comminuted defects
Minimal bone wastage, chattering, flaking, crushing, and fracturing	Significant bone wastage, chattering, flaking, crushing, and fracturing
Hinge fractures	Sharp-blunt characteristics

Results

Agreement between the number of defects and impacts detected by the primary investigator and the radiologist was substantial to almost perfect [34], ranging between 0.84 and 0.98 for CT, 0.72 and 1.0 for X-rays, and 0.65 and 1.0 for Lodox. Intra-observer agreement was almost perfect, ranging between 0.81-0.93 for CT, 0.89-1.00 for X-rays, and 0.92-1.00 for Lodox.

The highest sensitivity for detecting sharp force defects was achieved when using CT scans, which detected 292 (70.4%) of the 415 defects detected during the dry bone analyses, including 89 (56.7%) of the 157 stab wounds and 202 (78.3%) of the 258 chop marks. The lowest sensitivity was attained when using X-rays, which identified 35.4% of the total number of defects, 17.2% of stab wounds and 46.5% of chop marks. Sensitivity for Lodox was 47.0%, 26.8% and 59.3% for all defects, stab wounds and chop marks, respectively. All methods were far more sensitive in detecting chop marks compared to stab wounds. Of the stab wounds detected by CT, 76 (85.4%) were correctly classified as stab wounds, while the remaining 14.6% were incorrectly classified as chop marks, and 165 (81.6%) of chop marks identified by CT were correctly classified as such. When using X-rays, 74.1% of stab wounds were correctly identified as stab defects, and 80.8% of chop marks were indeed classified as chop marks. For Lodox, only 52.4% of stab wounds were correctly classified, while the remaining 47.6% were indeterminate or incorrectly classified as chop marks. However, 85.0% of chop marks detected by Lodox were correctly classified as such.

Overall specificity was high for all radiological methods, ranging between 92.9% and 97.2% for CT, 97.5% and 99.1% for X-rays, and 92.9% and 97.6% for Lodox. PPVs and NPVs were also generally high (CT: PPVs 77.4-97.6% and NPVs 82.9-92.9%; X-rays: PPVs 79.4-93.0% and NPVs 69.8-85.9%; Lodox: PPVs 68.9-85.0% and NPVs 73.2-87.4%).

The sensitivity of each imaging modality for detecting sharp force defects in each body region is presented in Figure 8, together with the two-way ANOVA results. CT consistently had the highest sensitivity for detecting both stab wounds and chop marks in all body regions, while X-rays were consistently the least sensitive (Figs. 1-7). When considering the overall number of sharp force defects, as well as chop marks, sensitivity was highest for the fore- and hindlimbs for all methods, while sensitivity for detecting stab wounds was highest for the ribs for CT and Lodox, and highest for the hindlimbs using X-rays. The lowest sensitivity for all types of sharp force defects was noted for the vertebral region, except when detecting stab wounds using CT, for which the hindlimbs had the lowest sensitivity. In general, sensitivity for all methods in all body regions was higher for detecting chop marks compared to stab wounds (Fig. 8).

Skull defects were considered as either cranial or mandibular defects. CT was most sensitive, detecting 69.6% of all cranial defects (50.0% of stab wounds and 78.1% of chop marks) and 58.1% of all mandibular defects (52.9% of stab wounds and 64.3% of chop marks). Sensitivity was lowest for X-rays, which detected 30.4% of cranial defects (14.3% stab and 37.5% chop) and 25.8% of mandibular defects (0.0% stab and 57.1% chop). Lodox detected 50.0% of cranial defects (35.7% stab and 56.3% chop), and 35.5% of mandibular defects (17.6% stab and 57.1% chop). Specificity for skull defects was above 87.0%, PPVs above 76.0%, and NPVs above 50.0% for all methods.

Rib defects were classified either as vertebral end, shaft, or sternal end. CT had the highest sensitivity for all rib locations, identifying 64.0% of all vertebral end defects (60.0%

of stab wounds and 66.7% of chop marks), 72.6% of shaft defects (74.1% of stab wounds and 71.4% of chop marks), and 52.2% of sternal end defects (25.0% of stab wounds and 57.9% of chop marks). X-rays had the lowest sensitivity, with only 16.0% vertebral end (0.0% stab and 26.7% chop), 37.1% shaft (37.0 stab and 37.1% chop), and 34.8% sternal end defects (0.0% stab and 42.1% chops) being identified. Lodox detected 32.0% of vertebral end defects (20.0% of stab wounds and 40.0% of chop marks), 48.4% of shaft defects (44.4% of stab wounds and 51.4% of chop marks), and 39.1% of sternal end defects (25.0% of stab wounds and 42.1% of chop marks). All modalities had a specificity above 93.0% for rib defects, and NPVs were above 84.0% for all modalities, except when using X-rays and Lodox to detect the overall number of rib defects (73.0% and 76.0% respectively). PPVs for rib defects were much more variable, ranging between 50.0% and 91.8% for CT, 0.0% and 100.0% for X-rays, and 33.3% and 90.0% for Lodox.

For vertebral defects, specificity was above 96.0% and NPVs above 87.0% for all radiological tools. PPVs for vertebral defects ranged between 50.0% and 88.9% for CT, and between 25.0% and 50.0% for Lodox. PPVs could not be calculated for X-rays as no true-positive or false-positive identifications were made using this method.

For forelimb defects, specificity was above 79.0% and PPVs above 66.0% for all imaging techniques. NPVs ranged between 66.7% and 94.2% for CT, 48.0 % and 80.8% for X-rays, and 49.6% and 83.0% for Lodox. For the hindlimbs, specificity was above 93.0% and PPVs above 75.0% for all modalities. NPVs for hindlimbs ranged between 84.3% and 93.8% for CT, 70.4% and 90.2% for X-rays, and 77.4% and 90.3% for Lodox.

Of the 308 impacts (154 stab and 154 chop) that were found during the dry bone analyses, 82.8% (70.8% stab and 94.8% chop) were correctly identified using CT, 43.5% (21.4% stab and 65.6% chop) using X-rays, and 58.4% (35.1% stab and 81.8% chop) using Lodox.

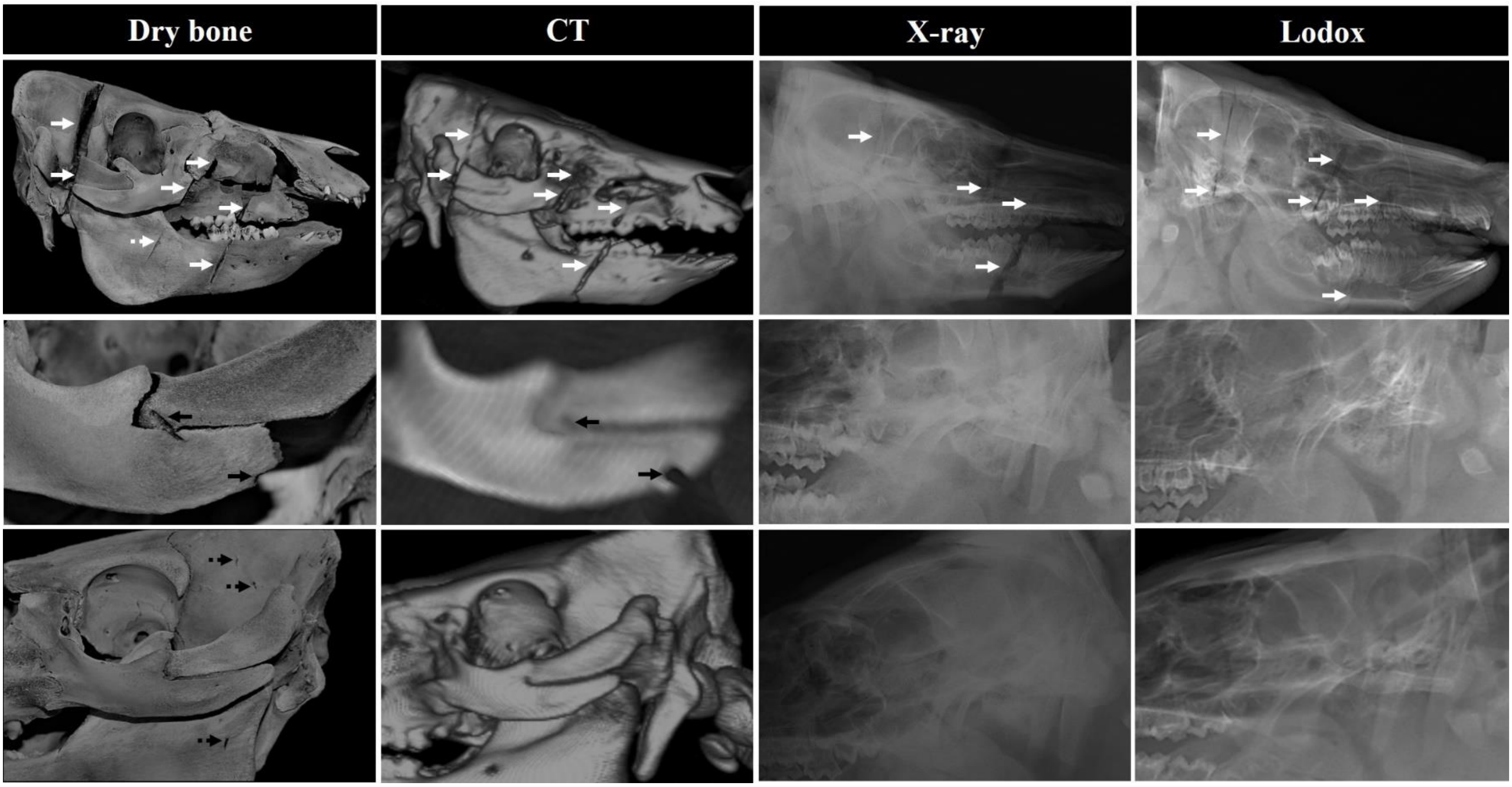

Fig 1. SFT defects to the skull, as seen on dry bone, CT, X-ray and Lodox. Many of the wide chop marks (solid white arrows) were identified by all imaging modalities, but some of the narrower, shallower chop defects (dashed white arrow) were only detectable on dry bone. Some of the small, puncture defects as a result of stabbing trauma (solid black arrows) were identified by CT, but not X-ray or Lodox in any radiographic view. However, other much smaller stabbing defects (dashed black arrows) were not identified by any radiographic method.

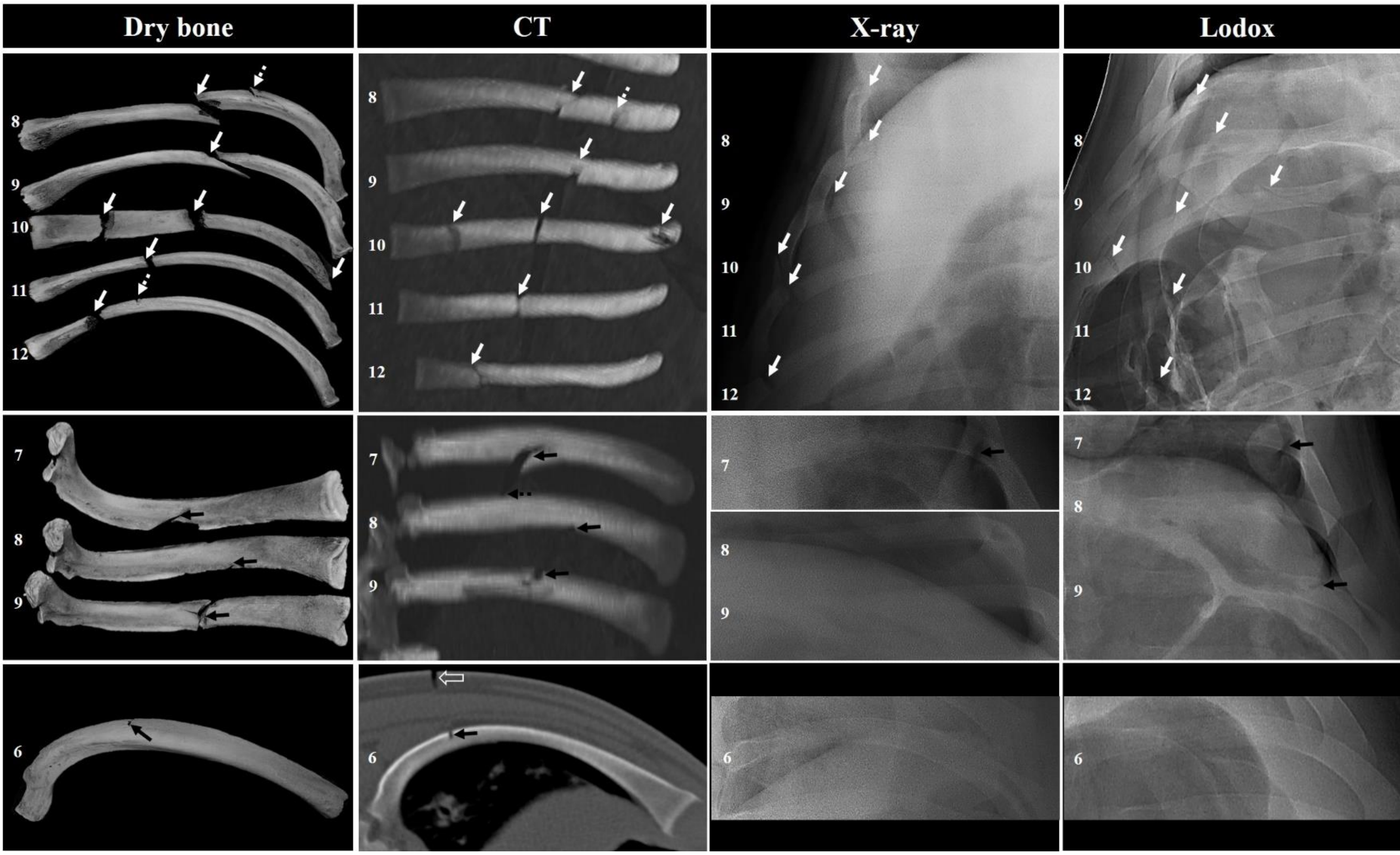

Fig 2. SFT defects to the ribs, as seen on dry bone, CT, X-ray and Lodox. Many chop marks (solid white arrows) were easily identifiable by all radiological techniques, while some of the smaller chop marks (dashed white arrows) were either only detectable using CT or on the dry bones only. Note the chattering, crushing and fracturing of bone associated with the chop defects on ribs 8, 9 and 10 in row 1, which is visible using CT. Many stab defects (solid black arrows), especially those with associated hinge fractures and bone chipping (ribs 7 and 9, row 2), were identifiable using CT, X-ray and Lodox. However, many of the smaller defects, visible as small nicks or notches in the bone cortex (rib 8 in row 2 and rib 6 in row 3) were only detectable radiologically using CT. Note how skin incisions/lacerations (white arrow outline) often assisted in locating sites of underlying bone trauma (rib 6, row 3), but soft tissue injuries may also result in false-positive identifications (dashed black arrow) by creating radiolucent, linear lesions which can mimic fractures on the scans, but which is not present on the dry bone (rib 8, row 2).

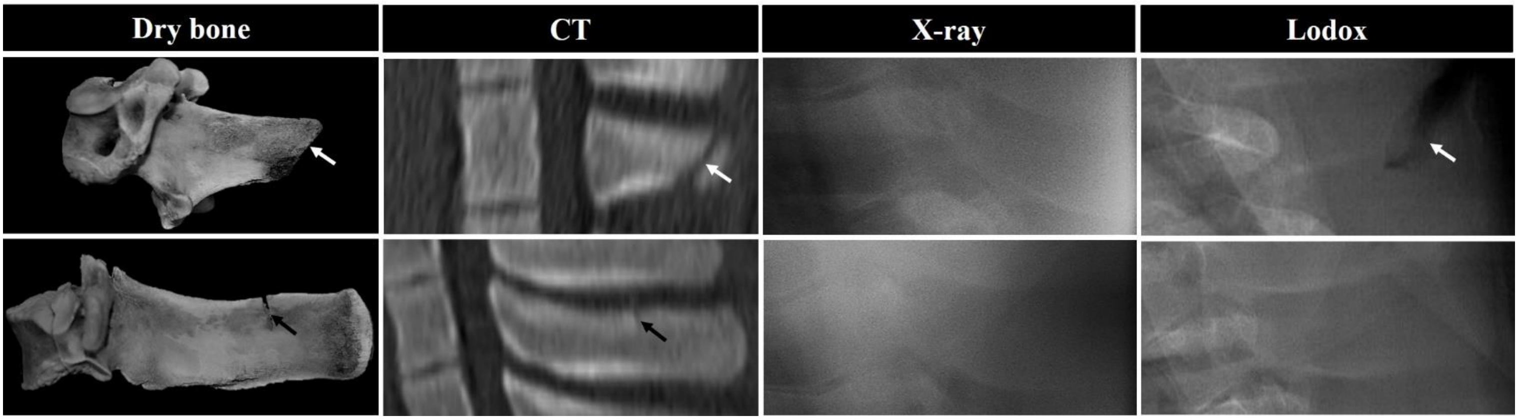

Fig 3. SFT defects to the vertebrae, as seen on dry bone, CT, X-ray and Lodox. Chop marks (solid white arrows) could be identified using CT and Lodox, but not using X-rays, while small incision defects as a result of stabbing trauma (solid black arrows) were often only identifiable using CT.

Fig 4. Hacking trauma defects to the forelimb, as seen on dry bone, CT, X-ray and Lodox. Most chop marks as a result of hacking trauma (solid black and white arrows) were easily

identifiable using all imaging modalities. However, some of the smaller chop defects (dashed black arrow) were only detectable on dry bone. The solid black arrows show two separate defects, one to the distal epiphysis of the ulna and one to the distal shaft of the radius, that are the result of only one impact. Note bone wastage, chattering and fracturing associated with the chop defect to the ulna (solid white arrows). Also note how soft tissue lesions (dashed white arrows) could result in false-negative fracture identifications using X-rays and Lodox, as skeletal defects could be mistaken as only soft tissue defects.

Fig 5. Stabbing trauma defects to the forelimbs, as seen on dry bone, CT, X-ray and Lodox. Many puncture and incision defects as a result of stabbing trauma were detectable using all imaging methods (solid white arrows), while some were only identifiable using CT and Lodox (solid black arrows). Note how soft tissue lesions assist in locating sites of bone trauma in X-ray and Lodox scans (solid white arrows).

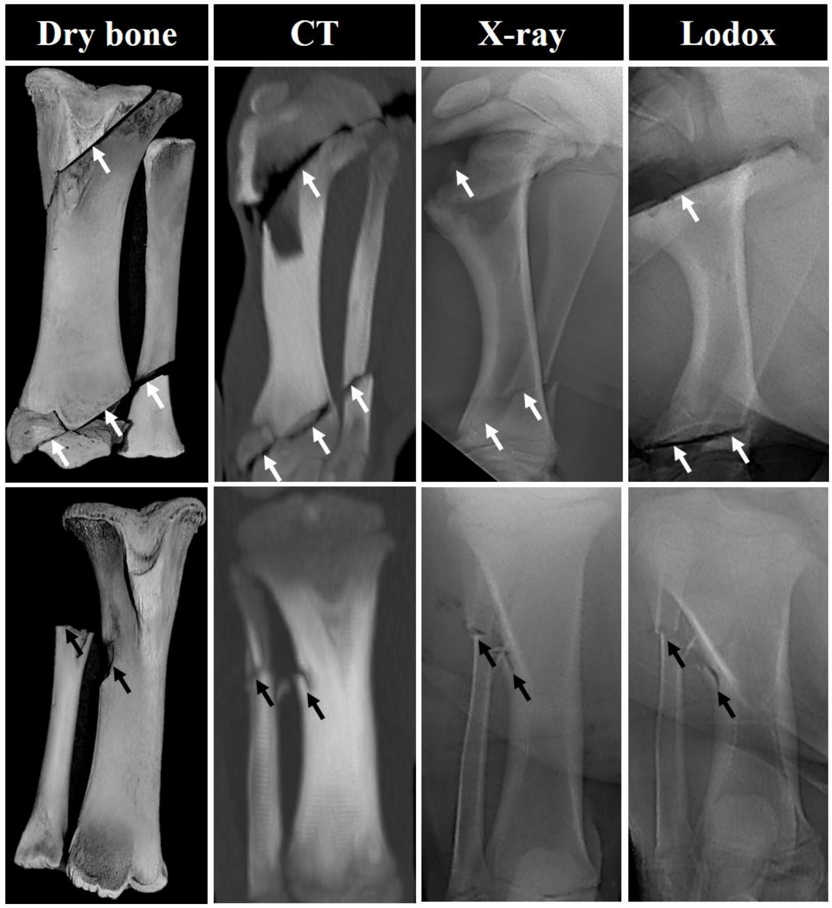

Fig 6. Hacking trauma defects to the hindlimbs, as seen on dry bone, CT, X-ray and Lodox. Most chop marks from hacking trauma (solid white and black arrows) were identifiable using all imaging modalities. The solid white arrows show four separate defects (one proximally and three distally), that are the result of two impacts (one proximally and one distally). The solid black arrows show two separate defects that are likely the result of the same impact. Note complete bone bisection of the proximal tibia and distal fibula (solid white arrows), as well as bone chattering associated with the chop defects to the tibia and fibula (solid black arrows).

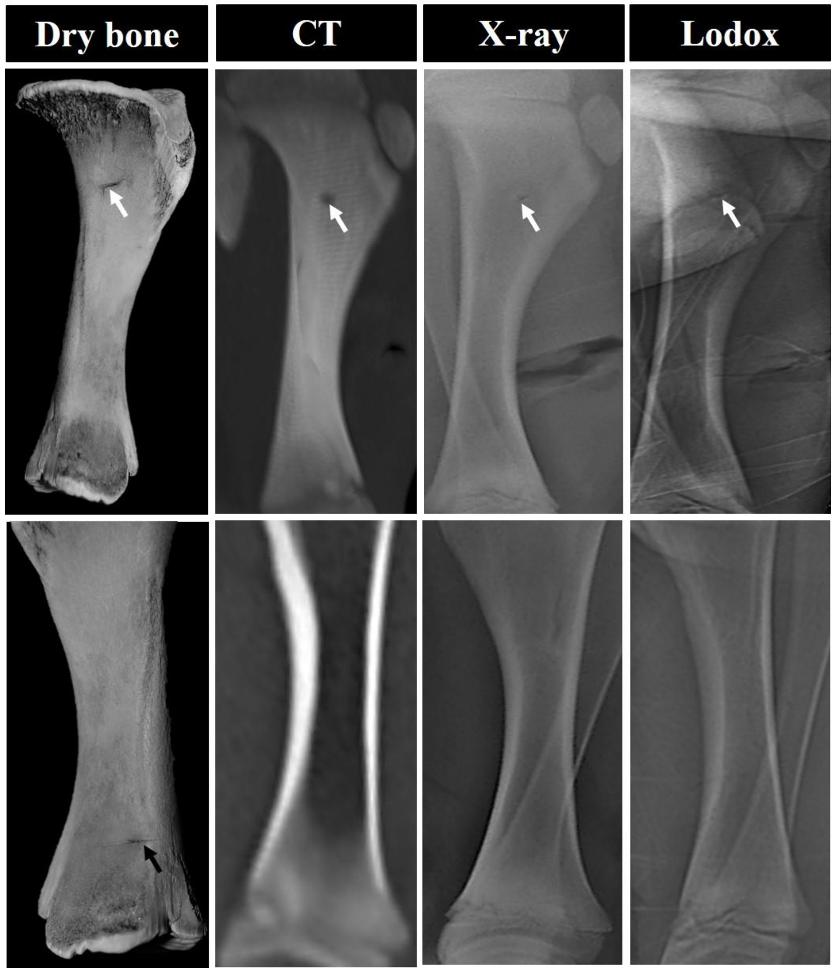

Fig 7. Stabbing trauma defects to the hindlimbs, as seen on dry bone, CT, X-ray and Lodox. Some puncture defects as a result of stabbing trauma were detectable using all imaging methods (solid white arrows), while some of the shallower cut marks (solid black arrow) were not detectable radiologically using any imaging method.

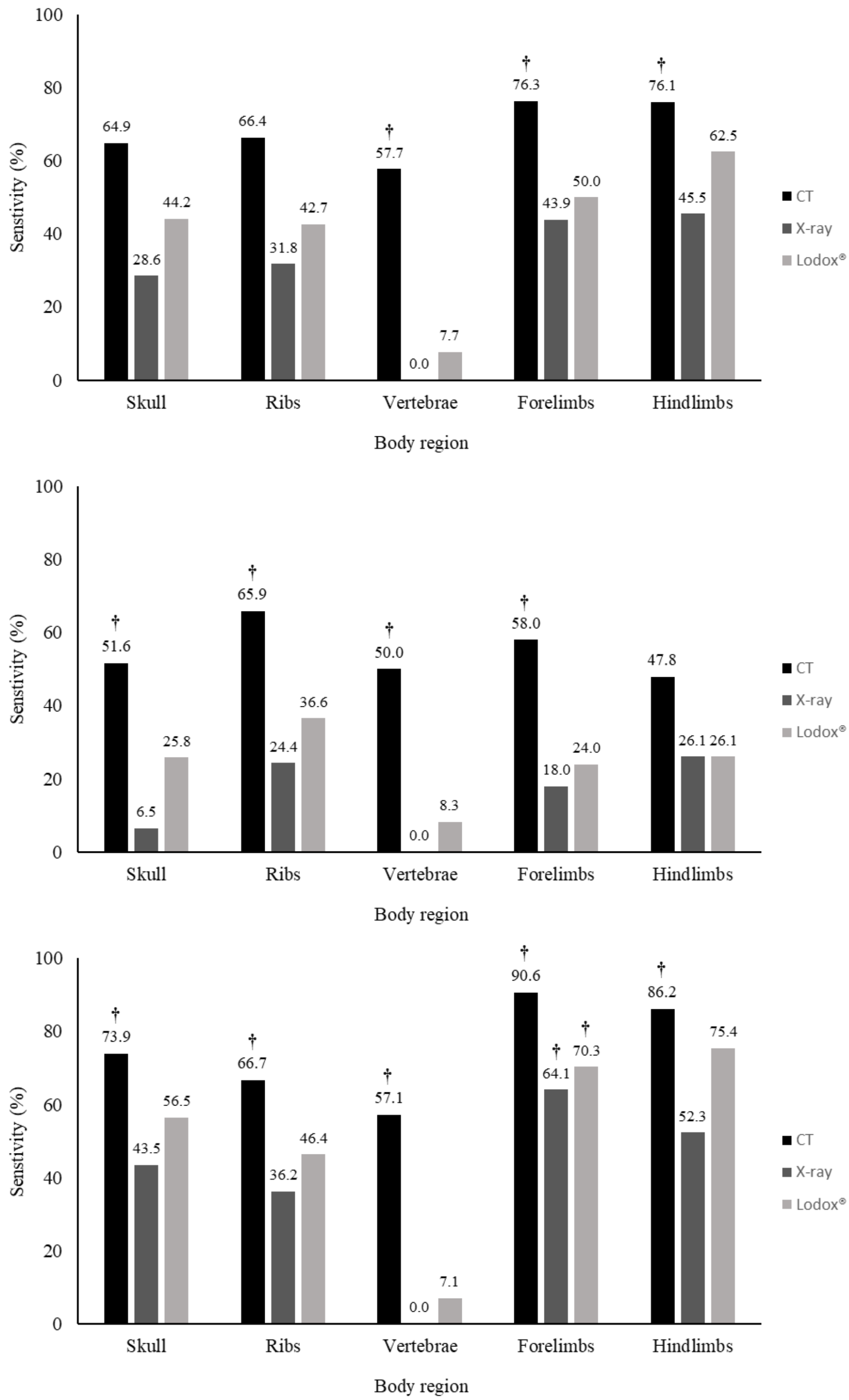

Fig 8. Sensitivity of CT, X-ray and Lodox scans for detecting all sharp force defects (top), stab wounds (middle) and chop marks (bottom) in each body region. † indicates no significant difference from the dry bone results ($p>0.01$). As dry bone was the gold standard, the number of fractures observed on dry bone was considered as 100.0% of fractures.

Discussion

The accurate detection and interpretation of skeletal defects as a result of SFT has both clinical and forensic implications. This study assessed the abilities of CT, X-ray and Lodox scans to detect sharp force skeletal defects in pig carcasses subjected to SFT, as well as the possibility to interpret the macroscopic characteristics of these defects in order to determine the type of SFT and, as a result, the class of weapon used. A similar study assessing the abilities of these radiological methods in detecting fractures as a result of blunt force trauma (BFT) was previously performed also on adult-sized pigs [33], and therefore sensitivity for detecting SFT and BFT in the various body regions is compared.

The highest sensitivity for detecting the overall number of sharp force skeletal defects was achieved using CT (70.4%), which detected on average 35 more percentage points than X-rays (35.4%) and 23.4 more than Lodox (47.0%). The sensitivity achieved using CT is lower compared to that reported by Schnider et al. [15], who found CT scans to have a sensitivity of 100.0% for detecting skeletal SFT. However, CT results in that study were compared against autopsy findings as the gold standard, rather than an analysis of the cleaned skeletal remains as in the present study. Since it has been shown that autopsy is sometimes insensitive for detecting skeletal trauma [16, 35, 36], a 100.0% detection rate using CT as reported by Schnider et al. [15] should be treated with caution and may be the cause of the discrepancy in sensitivity between the Schnider et al. [15] study and the present study. The overall sensitivity in the present study is much higher than those for detecting fractures in pigs as a result of BFT, with a sensitivity of 55.2% reported for CT, 25.8% for X-rays and 29.3% for Lodox [33].

Two types of SFT were inflicted in the present study – stabbing trauma and hacking trauma. CT scans have the highest sensitivity for detecting sharp force defects as a result of both types of trauma, while X-rays have the lowest. All imaging modalities are much more sensitive for detecting chop marks as a result of hacking trauma compared to defects as a result of stabbing trauma. This is likely because hacking trauma often results in much larger, wider defects with significant trauma to the bone, including bone wastage, chattering, crushing, flaking, and fracturing (Figs. 1-3, 5 and 7). In contrast, defects associated with stabbing trauma are often narrow, small punctures or cut marks in bone, resulting in very small nicks or notches in the bone cortex (Figs. 1-4 and 6). The detection of these small defects is difficult and depends on the resolution and settings of the radiological tool used [37]. Using thinner CT slices may therefore increase these detection rates. However, difficulties in identifying very small SFT defects has also been found to be the case during examinations of dry bone specimens [38].

However, CT is still moderately sensitive for detecting stab defects (56.7%), whereas X-rays and Lodox have very low sensitivity (17.2% and 26.8% respectively). This has specific implications for decomposed remains whereby the soft tissues may be too decomposed for stab wounds to be visible on the surface and would obscure the stab defects on the underlying bone. In such cases, where only radiological imaging is used, these wounds may be easily overlooked.

Based on the macroscopic characteristics outlined in Table 1, almost all (>80.0%) of the chop marks that were detected were indeed correctly classified as chop marks by all radiological methods. This was also true for stab wounds detected using CT (85.4%) and X-rays (74.1). However, for Lodox, nearly half of all stab wounds detected were classified either as indeterminate or incorrectly as chop marks. This indicates that CT and X-ray are highly sensitive for correctly determining the type of SFT inflicted and, therefore, the broad class of weapon used (in this case, a kitchen knife for inflicting stabbing trauma, and a panga for inflicting hacking trauma). However, Lodox is only moderately sensitive for distinguishing stabbing trauma. This may be due to superimposition of structures, as well as the presence of post-mortem gas, which makes small defects like stab wounds difficult to detect. Several other researchers also found that hacking trauma was easy to distinguish using CT scans, which could therefore be used to confirm the class of weapon involved (i.e. an axe or hatchet) [25-27].

For sharp force defects of the skull, CT is most sensitive in identifying both cranial and mandibular defects (69.6% and 58.1% respectively), while X-rays are the least sensitive (30.4% and 25.8% respectively) (Fig. 8). When compared to the detection of cranial fractures as a result of BFT (CT: 51.4%; X-ray: 10.1%; Lodox: 13.8%) [33], sensitivity for detecting sharp force cranial defects is much higher. However, sensitivity for mandibular defects is much lower than those reported for BFT (CT: 88.0%; X-ray: 56.0%; Lodox: 60.0%) [33]. While sensitivity for detecting cranial defects in the present study is higher than for mandibular defects using all imaging methods, the opposite is true for analyses of BFT [33].

Although CT is moderately sensitive for detecting sharp force defects of the skull and should be the preferred method for imaging of this region, sensitivity for X-rays and Lodox is low. This is true for both stabbing and hacking trauma, as CT scans are most sensitive for both types of SFT (Fig. 8). Lodox, however, is more sensitive than X-ray for skull defects, detecting 19.3% more stab wounds and 13.0% more chop marks (Fig. 8). When a CT scan of the skull is not an option, Lodox should therefore be used for imaging of this region.

Low sensitivity for skull defects is concerning since during incidences of violent crime, the head is the most common target for attackers and may be the only region with evidence of trauma [39]. Furthermore, sharp weapons, especially those such as knives during incidences of stabbing, may not penetrate the skull and injure the brain [40], and in the absence of any other soft tissue injury, skeletal trauma may be the only evidence of SFT.

Similar to results for the skull, CT is also most sensitive for detecting both stab and chop defects of the ribs, while X-rays are least sensitive (Fig. 8). Sensitivity for rib defects using CT (66.4%) and X-ray (31.8%) is lower than reported for BFT analyses, which have a sensitivity of 69.3% for CT scans and 37.2% for X-rays [33]. Sensitivity using Lodox, however, is comparable for SFT and BFT (42.7% and 43.3% respectively) [33]. CT also had the highest sensitivity for all rib locations for both stab wounds and chop marks, while X-rays have the lowest. All imaging methods are most sensitive for identifying defects of the rib shaft, similar to what was the case for BFT [33]. Sensitivity for BFT, however, is higher using all imaging methods for all rib locations [33], except the sternal end using X-rays and Lodox, for which sensitivity is higher when detecting SFT. All imaging methods have a much higher sensitivity for detecting chop marks to the ribs compared to stab wounds (Fig. 8), likely because chop defects are much larger and result in more bone trauma and deformation and are therefore easier to detect (Fig. 2). These results indicate that CT should be used for imaging of the rib cage since sharp force defects are less likely to be missed, and injury to the underlying organs and vasculature can be sought during clinical examinations or included as possible causes of death during post-mortem investigations. In the absence of a CT scanner, a Lodox scan should be taken to detect SFT to the chest.

Sensitivity for detecting sharp force defects of the vertebrae as a result of both stabbing and hacking trauma is highest using CT and lowest using X-rays (Fig. 8). In fact, X-rays are completely insensitive, not detecting any vertebral defects, and Lodox are only slightly more sensitive, detecting 7.7% of all defects. Sensitivity using CT and Lodox in the present study is higher than those reported for BFT examinations (CT: 20.8%; Lodox: 0.0%), while sensitivity using X-rays is the same (0.0%) [33]. The sensitivity for chop marks using CT was higher than for stab wounds, but Lodox was slightly more sensitive for stab defects. This may be because many of the chop marks involved the transverse processes, which are highly superimposed in Lodox scans and therefore difficult to detect. The vertebral column is the region for which all imaging modalities are least sensitive for detecting sharp force defects, which is alarming since SFT to the vertebrae may be associated with injury to the spinal cord [41], and SFT particularly to the cervical vertebrae may be an indication of a slit throat or decapitation [2, 6, 42, 43], critical information to have during clinical and forensic investigations.

For both the fore- and hindlimbs, most sharp force defects (both stab and chop defects) were detected using CT, while the least were identified using X-rays (Fig. 8). Forelimb sensitivity is comparable to those for BFT fracture detection using X-rays (43.3%) and Lodox (50.0%), but higher for SFT defects using CT (76.3%), which is 70.0% for BFT fractures [33]. For the hindlimbs, sensitivity for CT and Lodox is higher for SFT defects compared to BFT fractures (63.6% using CT and 47.7% using Lodox), but lower using X-rays (52.3% for BFT) [33]. The limbs are the regions with the highest overall sensitivity using all imaging methods, likely because superimposition in these regions is limited and trauma is therefore easier to detect. This is also true when chop marks as a result of hacking trauma are considered (Figs. 5 and 7). However, when defects as a result of stabbing trauma are considered, sensitivity is low to moderate. In fact, sensitivity for the hindlimbs using CT is lower than all other regions for detecting stab wounds. This may be because stabbing trauma to the limbs, because of their sturdy nature, often result in puncture defects or small cut marks which are difficult to detect (Figs. 4 and 6), while stab wounds of the ribs, for example, more often result in hinge fractures which are easily identifiable (Fig. 2). Sensitivity for detecting stab defects to the limbs using CT is still, however, considered moderate (58.0% for the forelimbs and 47.8% for the hindlimbs). The moderate to high sensitivity for detecting limb defects using CT, and the moderate sensitivity using X-rays and Lodox, is significant since SFT to the limbs is often associated with defensive wounds [44] and can also be indicative of attempted dismemberment [6, 42, 43], information which aids in determining the circumstances surrounding the traumatic event.

Specificity is high for all body regions using all radiological tools, indicating that the likelihood of making a false-positive identification in cases of SFT is low for all methods. However, PPVs and NPVs are much more variable, and therefore the probability of a radiologically identified defect truly being a defect is variable, as is the probability that a bone not considered to have trauma radiologically is indeed trauma-free. These results are similar to those reported for BFT analyses [33].

This study also assessed the ability of these imaging methods to estimate the minimum number of strikes inflicted with each sharp instrument. This is an important aspect of forensic pathological and anthropological investigations, and has implications for determining whether witness testimony regarding the circumstances of the traumatic event is accurate. Results showed that CT scans are highly sensitive for estimating the minimum number of impacts, while X-rays and Lodox are moderately sensitive. This is similar to what was found for BFTs [33]. CT scans are highly sensitive for estimating impacts as a result of both stabbing and hacking trauma, while X-rays and Lodox are highly sensitive for hacking impacts but have low sensitivity for impacts due to stabbing. CT should therefore be the preferred method for estimating the minimum number of impacts inflicted during a traumatic event involving SFT.

Overall, in this study, CT was found to be more sensitive than X-rays and Lodox in detecting both stab wounds and chop marks in all body regions, likely because the challenge of superimposition is overcome when using CT scans, as bones can be viewed 3-dimensionally. Therefore, when radiological imaging is needed to examine skeletal defects as a result of SFT, CT should be the method of choice. Lodox scans are more sensitive than X-rays and should be used for the purpose of conducting radiological analyses of skeletal SFT when a CT scan is not available or in very time-sensitive instances, as it only takes approximately 13 seconds to generate a Lodox scan [28]. It is possible that in some cases of X-rays, the ribs or limbs were oriented or positioned in a way that may have obscured the trauma. This is likely to be less of an issue when imaging humans, where radiographers trained in forensic imaging would perform standard X-ray views on more familiar subjects, and sensitivity is therefore expected to increase slightly. Best results, however, are still achieved from dry bone analyses which should therefore be performed whenever possible.

In general, sensitivity achieved in the present study for detecting SFT is higher than that for detecting BFT [33]. There are a few potential reasons for this. SFT such as hacking trauma often results in complete bone discontinuities or bisections which are much easier to detect in comparison to hairline or incomplete fractures which are often the result of BFT. In addition, soft tissue lesions as a result of the SFT, which are visible radiologically, may help to locate sites of bone trauma (Figs. 2 and 5), although not specifically used as a guide. This, however, is not the case in analyses of BFT. Sensitivity for detecting SFT may therefore decrease when remains are partially fleshed, decomposed or charred. However, while soft tissue lesions may aid in locating and detecting true-positive skeletal defects, they may also result in a higher incidence of false-negative and false-positive identifications, as soft tissue injury may obscure underlying bone trauma (Fig. 4) or may be mistaken for skeletal trauma when in fact only the soft tissue is injured (Fig. 2). It is possible that a lack of soft tissue may therefore in fact improve results. Further research involving partially fleshed, decomposed, or charred remains is therefore needed.

A potential limitation of this study is that, even though the side of the body on which each weapon was used to inflict the trauma was alternated, stabbing trauma was constrained to a single side of the body and hacking trauma to the other within each individual pig. Therefore, a chop mark identified, for example, on the right ulna would introduce some bias as the observer would know that, for that specific pig, trauma to the right side of the body in all other body regions was also the result of hacking. This could be overcome by inflicting stabbing and hacking trauma randomly to each pig, independent of the side of the body. However, specific characteristics associated with the defects were used to distinguish between stabbing and hacking trauma (Table 1), and this therefore reduced some bias.

Conclusion

Injuries as a result of SFT are common during incidences of violent crime, and a thorough examination of these injuries is critical for the proper clinical and forensic investigation of these cases. This study found CT scans to be most sensitive in both the detection and macroscopic interpretation of skeletal defects as a result of SFT. Therefore, when a radiological analysis of SFT is needed, the authors suggest that this be conducted using CT scans. When such scanners are not available, virtual SFT examinations should be performed using Lodox scans, while conventional X-rays should only be used as a last resort. However, best results are still achieved when performing an osteological analysis of the remains and should therefore be the method of choice whenever possible, feasible or practical. A macroscopic interpretation of the trauma in order to determine the type of SFT, and as a result, the class of weapon used, is possible using all imaging modalities, but caution should be used when interpreting stabbing trauma using Lodox scans. However, as Lodox may be used to detect trauma with moderate sensitivity, a CT scan or osteological analysis of the affected body region only can be performed for a more thorough interpretation of the trauma.

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Chapter 5: Discussion

One of the most critical steps during post-mortem medico-legal examinations is the detection and interpretation of skeletal trauma, which contributes to the proper investigation of cases of abuse, torture, and violent crime (Bilo *et al.*, 2010; İşcan & Steyn, 2013; Franklin *et al.,* 2016; Garvin & Stock, 2016). It is well documented that skeletal trauma is frequently undetected during conventional forensic autopsy (Cattaneo *et al.*, 2006; Thomsen *et al.*, 2009; Chevallier *et al.*, 2013; Mazzarelli *et al.*, 2021), and therefore radiology is often used to aid in the investigation. Forensic anthropologists and pathologists are thus often required to perform virtual skeletal assessments. The sensitivity with which these practitioners are able to radiologically identify skeletal trauma needs to be established to ensure that these examinations are performed as accurately as possible.

In this study, the diagnostic accuracies of the various imaging methods for detecting specifically blunt force trauma (BFT) and sharp force trauma (SFT) were assessed. Although this has been performed in several studies (Tables 2.1 – 2.3), only two have used the dry bone as the gold standard (Cattaneo *et al.*, 2006; Mulroy *et al.*, 2012), and neither of these included the Lodox scanner in the assessment. Low-dose full-body X-rays ("Lodox") are frequently used in medico-legal institutions particularly in South Africa (du Plessis *et al.,* 2020), and their abilities for detecting skeletal trauma need to be compared against other commonly used imaging methods such as computed tomography (CT) and conventional X-ray. As part of this study, the abilities of forensic anthropologists, relative to a trained radiologist, to detect skeletal trauma were investigated.

5.1. Comparison of trauma detection rates between forensic anthropologists and a radiologist

The ability of four observers – a novice forensic anthropologist (NFA), two experienced forensic anthropologists (EFAs), and a radiologist – to detect fractures were assessed using 5 piglet carcasses subjected to BFT. The level of agreement in fracture counts between each observer was assessed using Cohen's kappa, and the fracture detection rates, or sensitivity, of each observer was calculated.

Regardless of body region or radiological method employed, agreement levels between the radiologist and NFA were consistently the highest (k=0.77-1.00) and were substantial to almost perfect (Landis & Koch, 1977). Agreement between the EFAs and the radiologist, however, was significantly lower (k=0.21-1.00). The radiological training received by the NFA and her knowledge of pig anatomy are likely the causes of this disagreement, which resulted in the NFA being able to detect fractures radiologically at a rate comparable to that of the radiologist.

The importance of this radiological training, albeit brief, is further highlighted by the sensitivity with which each observer was able to detect fractures. Sensitivity was consistently the highest for the NFA regardless of body region or imaging method (0.0-89.3%), results which reflect the familiarity of the NFA with sub-adult pig osteology. The EFAs, however, consistently detected the least number of fractures (0.0-62.4%), despite these observers having many years of experience with dry bone forensic examination and trauma analysis. This once again demonstrates the benefit of radiological training and experience in performing virtual trauma assessments, which significantly increases the number of fractures detected. This conclusion was also reported by Loughran (1994), McLauchlan *et al.* (1997), Hong *et al.* (2011) and Schulze *et al.* (2013).

The body region with the greatest amount of disagreement between all observers, for all imaging methods, was the trunk, specifically the ribs. However, the ribs were assessed with the highest sensitivity, which was still considered low to moderate for the EFA, but moderate to high for the NFA and radiologist. This indicates that radiological training is specifically useful when identifying rib fractures, which are common in both instances of physical child abuse and violent crime (Kleinman, 1998; Kemp *et al.*, 2008; Bilo *et al.*, 2010; İşcan & Steyn, 2013; Clark *et al.*, 2017; Shelmerdine *et al.*, 2018), and are likely to be encountered during virtual forensic anthropological examinations.

In contrast, agreement levels were consistently highest for the vertebrae (k=0.70-1.00). This is likely because no observer detected vertebral fractures using X-rays or Lodox, and only a few fractures were detected using CT, resulting in strong agreement between observers. Sensitivity, however, was lowest for all observers for vertebral fractures, which were comparable between observers. This indicates that regardless of level of radiological training or experience, vertebral fractures are difficult to detect using virtual means, and forensic anthropologists may need to perform examinations on the dry bones in order to detect fractures of this region more accurately.

All observers, in general, displayed the highest levels of agreement and sensitivity when using CT scans. This suggests that forensic anthropological specialists, regardless of the degree of radiological experience, should ideally perform virtual examinations of skeletal trauma using CT scans rather than X-rays or Lodox. CT scans appear to be more user-friendly and easier to interpret for observers of all experience levels. This is a result of the availability of 3D renderings of each bone which eliminates structure superimposition. The fact that some post-processing training is required to read these scans, thus being time-consuming, is a drawback.

All observers displayed high specificity for detecting fractures (95.1-99.2%). This demonstrates that, while radiological experience and training does indeed affect the number of true-positive fractures detected by an observer, the likelihood of detecting false-positive fractures remains low. Forensic anthropologists of all levels of radiological experience may therefore be confident that fractures are not being incorrectly diagnosed as present when using any imaging modality. This contradicts the results of Hong *et al.* (2011), who reported decreased specificity for observers with more limited radiological training when using CT and X-ray scans.

The results of this part of the study indicate that, similar to findings for radiographers, radiologists and forensic pathologists (Loughran, 1994; McLauchlan *et al.*, 1997; Hong *et al.*, 2011; Schulze *et al.*, 2013), radiological training is essential for forensic anthropologists who wish to conduct virtual analyses of skeletal trauma, as it drastically improves fracture detection rates in all body regions and using all radiological methods. These results further demonstrate that specialists without this training or experience are insufficiently qualified to perform such assessments. While some forensic anthropologists may have more experience than others in conducting trauma analyses on dry bone cases, this experience does not translate to virtual trauma examinations. Radiological training, in the form of courses or workshops, should therefore be offered to all forensic anthropologists, regardless of their forensic experience, if they are required to detect fractures using radiographic material.

5.2. Detection and interpretation of BFT and SFT

BFT to the skeleton is the most common form of trauma in both children and adults as a result of violence (Kleinman, 1998; Kemp *et al.*, 2008; Bilo *et al.*, 2010; İşcan & Steyn, 2013). Compositional differences between the bones of children and adults mean that they react differently to BFT, resulting in differing fracture types (Zimmermann *et al.*, 2005; Alcalá-Galiano *et al.*, 2008; Bilo *et al.*, 2010; İşcan & Steyn, 2013; Ross & Juarez, 2016), and potentially in differing radiological detection rates (Zimmermann *et al.*, 2005; Alcalá-Galiano *et al.*, 2008). The radiological detection of skeletal BFT in both piglets used as proxies for human infants, as well as adult-sized pigs used as proxies for human adults, was therefore assessed.

The radiological detection of SFT, which is one of the most common types of trauma in cases of violent crime, including homicide, attempted murder, and assault (Cocks & Saayman, 2013; İşcan & Steyn, 2013; South African Police Services, 2020), was also assessed in adult-sized pigs. The sensitivity of the various imaging methods for detecting fractures/defects in each body region was calculated, and comparisons made between the two BFT samples, as well as the adult-sized BFT and SFT samples.

5.2.1. Sensitivity for detecting BFT fractures and SFT defects

Overall, CT was found to be substantially more sensitive than X-rays and Lodox in detecting BFT both in piglets and adult-sized pigs, as well as SFT in all body regions, including all skull and rib locations (CT: 0.0-95.0%; X-ray: 0.0-74.0%; Lodox: 0.0-80.0%). Therefore, when radiological imaging is needed to examine skeletal trauma as a result of BFT or SFT, CT scans should be performed in both children and adults as opposed to X-rays or Lodox, which appear to add no additional diagnostic value over CT. This was also a conclusion made by several other researchers who compared the diagnostic abilities of CT against X-ray and Lodox scans (Table 3.1). This is likely because the challenge of superimposition is overcome when using CT scans, as bones can be viewed 3-dimensionally (Franklin *et al.*, 2016; Obertová *et al.*, 2019). Superimposition of structures in X-rays and Lodox increases the difficulty of detecting trauma in these regions, resulting in low sensitivity.

Additional advantages of CT scans over both X-rays and Lodox are the visualization of intra-cranial and other soft tissue injuries and trauma (Costelloe *et al.*, 2013; Garvin & Stock, 2016; Culotta *et al.*, 2017; Martin *et al.*, 2020), and the possibility of printing 3D models of the skeleton for analysis as well as presentation as evidence in court (Errickson *et* *al.,* 2014; Baier *et al.,* 2018; Carew *et al.,* 2019). In addition, when compared to X-rays, the speed with which CT scans can be obtained, as well as the fact that only one scan needs to be taken rather than between 10 and 28 for X-rays (Chapter 3, Table 3.1) depending on the size of the imaging cassette available, are further benefits of using CT.

However, CT is not always a feasible option as they are rarely available in very resource-constricted institutions due to their high associated expenses and levels of training required (Bergeron *et al.,* 2017; Grabherr *et al.,* 2017; Willett, 2019). As a result, X-rays and Lodox are often the only radiological resources available, which is particularly the case in South African medico-legal institutions (du Plessis *et al.,* 2020). In these cases, X-rays and Lodox, despite their generally low sensitivity for detecting BFT and SFT to the skeleton, may have to be relied upon when conducting these virtual trauma examinations. For suspected cases of BFT in children, X-rays should be the preferred method when CT is not available since the sensitivity obtained using this radiological method are consistently higher than Lodox in the piglet sample. Although the Lodox scanner is much quicker and more cost-effective (Beningfield *et al.,* 2003; Chen *et al.,* 2010; Evangelopoulos *et al.,* 2011; Whiley *et al.,* 2013; du Plessis *et al.,* 2020), its very low sensitivity for detecting BFT in piglets does not support its use for examining cases of trauma in children. Since the sensitivity for BFT to the skull using Lodox scans was only slightly higher than that achieved using X-rays, assessments of this region in children may be performed either using X-ray or Lodox when a CT is not an option. In contrast, for examinations of both BFT and SFT in adults, greater diagnostic value is generally achieved when using Lodox scans as opposed to X-rays. Lodox should therefore be the method of choice when conducting radiological assessments of trauma in adult individuals when CT is not available or in very time-sensitive situations, as it only takes approximately 13 seconds to generate a Lodox scan (Beningfield *et al.,* 2003; Boffard *et al.,* 2006; Whiley *et al.,* 2013; du Plessis *et al.,* 2020). However, the detection of BFT of the lower limbs in adults should be performed using X-rays when CT is not an option, as sensitivity obtained for this region was higher for X-rays than for Lodox in adult-sized pigs.

CT sensitivity, however, is in general still only considered to be moderate, while X-ray and Lodox sensitivity is low to moderate. As a result, many BFT fractures and SFT defects remain undetected by all imaging methods, likely due to superimposition of structures, difficulty in detecting very subtle fractures or defects, or potentially mistaking fractures for sutures or epiphyseal fusion lines in subadults. This low to moderate sensitivity is significant since the skull, ribs, vertebrae and limbs are frequently affected by trauma during incidents of abuse, torture and violent crime (Kleinman *et al.*, 1992, 2011, 2013; Le *et al.*, 2001; Kimmerle & Baraybar, 2008; Bilo *et al.*, 2010; Berthold *et al.*, 2018; Adamsbaum *et al.*, 2019; Gentile *et al.*, 2019; Steyn *et al.*, 2021; Thomas *et al.*, 2021). In addition, specific types of fractures such as complex, depressed and diastatic skull fractures, as well as long bone metaphyseal fractures, are also highly indicative of abuse and violence (Hobbs, 1984; Worlock *et al.*, 1986; Meservy *et al.*, 1987; Lee *et al.*, 2003; Bilo *et al.*, 2010; Dwek, 2011; Kleinman *et al.*, 2011; Guyomarc'h *et al.*, 2010; Adamsbaum *et al.*, 2019). Moreover, specific trauma locations, such as BFT fractures to the posterior aspects of the ribs or SFT to the cervical vertebrae, often suggest abuse or violence (Kleinman & Schlesinger, 1997; Kimmerle & Baraybar, 2008; Bilo *et al.*, 2010; Symes *et al.*, 2012; İşcan & Steyn, 2013; Ross & Cunha, 2018).

Failure to detect these BFT fractures or SFT defects may therefore have detrimental effects during the forensic investigation of these cases, such as returning children to abusive environments due to misdiagnosis (Jenny *et al.*, 1999; Bilo *et al.*, 2010; Parisi *et al.*, 2015). Skull trauma detection rates, particularly for X-ray and Lodox scans, may potentially be improved by including additional skull views in the radiographic protocol, such as the Towne and Waters views. The Towne view is an angled antero-posterior radiograph which visualizes the occipital bone and the posterior cranial fossa, while the Waters view is an angled postero-anterior radiograph, beneficial for viewing the facial bones (Goh & Low, 2002). Including these views may therefore reveal fractures/defects typically obscured on the traditional antero-posterior and lateral skull views.

Healed fractures, which can indicate patterns of chronic abuse and torture (Kimmerle & Baraybar, 2008; Bilo *et al.*, 2010; İşcan & Steyn, 2013; Steyn *et al.*, 2021), were detected with moderate to high sensitivity in the piglet sample (60.0-100.0%). This is an important incidental finding as it shows that radiologists and forensic practitioners can be confident that the majority of healed rib fractures are detected using virtual means.

The best results are still achieved from dry bone analyses, and osteological assessments of the cleaned remains should therefore be considered the gold standard in post-mortem investigations of BFT and SFT whenever this is a feasible or practical option. If the entire body cannot be dissected or macerated, which is often the case due to time-constraints and ethical considerations (Kettner *et al.*, 2011; Brough *et al.*, 2012; King & Birch, 2015), it is suggested that only those regions with suspected BFT/SFT, based on soft tissue findings or identified during initial imaging, be cleaned to allow for a dry bone examination. This is especially true for the vertebrae where the radiological detection of trauma is particularly difficult, as indicated by the extremely low sensitivity for all imaging methods in this region. However, if a radiological examination is the only option available, such as in cases of the living or where maceration/dissection is prohibited, CT scans are considered the gold standard for assessments of all types of trauma in individuals of all age groups. An osteological assessment should also be the gold standard when performing research on this topic, rather than using autopsy or other radiological findings as the standard of reference. This will ensure that results obtained from such studies are as accurate as possible.

The sensitivity for each imaging method obtained in this study is generally lower than previously reported for both infant and adult samples, for both BFT and SFT (Tables 2.1 – 2.3), which ranged between 34.0% and 126.0% for CT, 13.5% and 100.0% for X-rays, and 9.0% and 100.0% for Lodox. These discrepancies are likely due to the fact that the vast majority of these studies did not use osteological analysis as the gold standard, but rather used autopsy results or various other imaging methods. It is expected that the sensitivity obtained in the present study would be much more comparable to previous research if a dry bone gold standard were used.

In general, diagnostic accuracies of all radiological modalities for detecting BFT were higher in adult-sized pigs compared to piglets, except for the ribs for which sensitivity was higher in the piglet sample. These results suggest that greater diagnostic value is achieved when imaging adults, except for fractures of the ribs. This is also confirmed by the vast majority of the literature, whereby studies examining the radiological detection of fractures in adults (Cabarrus *et al.*, 2008; Welling *et al.*, 2008; Deyle *et al.*, 2010, 2011; Huang *et al.*, 2012; Chawla *et al.*, 2015a, 2015b) have reported a higher sensitivity in most body regions as opposed to those assessing paediatric samples (Cattaneo *et al.*, 2006; Pitcher *et al.*, 2008; Mulroy *et al.*, 2012; Orman *et al.*, 2015), except for the ribs (Klotzbach *et al.*, 2003; Cattaneo *et al.*, 2006; Weber *et al.*, 2009; Hong *et al.*, 2011; Schulze *et al.*, 2013; Jöres *et al.*, 2015;

Chapman *et al.*, 2016; Shelmerdine *et al.*, 2018; Zhou *et al.*, 2020). One potential reason for this may be because the ribs of human infants and young children are more planar and horizontal in orientation compared to those of adults (Tsai *et al.*, 2012). As a result, the ribs of these younger individuals are oriented perpendicular to the scan axis, which would make visualization of these elements, particular the posterior aspects of the ribs, and fractures thereof easier.

Greater sensitivity for detecting skeletal lesions in adults compared to children may be due to the differences in the structure and composition of their bones. In children, the skeleton has unfused sutures and growth plates, an abundance of trabecular bone, stronger periosteum, and low bone mineralization (Zimmermann *et al.*, 2005; Alcalá-Galiano *et al.*, 2008; Bilo *et al.*, 2010; İşcan & Steyn, 2013; Ross & Juarez, 2016). As a result, children's bones have greater elasticity and flexibility compared to adult bones, resulting in bowing, greenstick, incomplete and non-displaced fractures being more frequent in children, and complete, comminuted and displaced fractures more common in adults (Zimmermann *et al.*, 2005; Alcalá-Galiano *et al.*, 2008; Bilo *et al.*, 2010; İşcan & Steyn, 2013; Ross & Juarez, 2016). These types of fractures typical of adult bones may be easier to detect radiologically, as the associated bone trauma may be more obvious and evident (Zimmermann *et al.*, 2005; Alcalá-Galiano *et al.*, 2008).

Sensitivity for detecting SFT, particularly hacking trauma, was generally higher than that for detecting BFT in adult-sized pigs, for which there are a few potential reasons. Hacking trauma often results in complete bone discontinuities or bisections with significant bone damage (Humphrey & Hutchinson, 2001; Lynn & Fairgrieve, 2009; Symes *et al.*, 2012; İşcan & Steyn, 2013) which may be much easier to detect in comparison to some of the small, subtle fractures which occur commonly as a result of BFT (Mulroy *et al.*, 2012; Kleinman *et al.*, 2013). In addition, soft tissue lesions as a result of the SFT, which are visible radiologically, may help to locate sites of bone trauma, although not specifically used as a guide, which is not necessarily the case in analyses of BFT. Sensitivity for detecting SFT may therefore decrease when remains are partially fleshed, decomposed or charred. Sensitivity for detecting stabbing trauma, however, was generally lower than for detecting BFT. This may be because the defects associated with stabbing trauma are often even smaller and more subtle than those associated with BFT.

5.2.2. Specificity, positive predictive values (PPVs) and negative predictive values (NPVs)

Specificity for detecting BFT fractures in piglets and adult-sized pigs was extremely high using all radiological methods (piglets: 92.5-100.0%; adult-sized pigs: 80.0-100.0%), and is similar to those reported in previous BFT studies using CT and X-ray scans (87.0-100.0%) (Mulroy *et al.,* 2012; Schulze *et al.,* 2013; Chawla *et al.,* 2015a, 2015b; Culotta *et al.,* 2017; Shelmerdine *et al.,* 2018; Martin *et al.,* 2020), as well as Lodox (93.0-100.0%) (Huang *et al.,* 2012; Jöres *et al.,* 2016). Specificity for detecting SFT was also calculated and was high (79.0-100.0%) and comparable to that for BFT trauma in adult-sized pigs. This specificity, however, could not be compared to other studies as there is a considerable lack of research regarding the radiological detection of SFT to the skeleton, and the few studies that have been conducted (Schnider *et al.,* 2009; Thomsen *et al.,* 2009) did not report specificity.

This high specificity is significant and show that all imaging modalities are extremely accurate at identifying true-negative BFT fractures and SFT defects, and that false-positive detections are uncommon. This demonstrates that forensic maceration of a region without trauma is unlikely, as are the chances of incorrectly identifying an individual as a victim of violence based on skeletal trauma.

Positive predictive values (PPVs) and negative predictive values (NPVs) were also calculated in adult-sized pigs for both BFT and SFT. PPVs in the BFT sample were all above 80.0%, which indicates that a fracture detected by any modality is highly likely to indeed be a true-positive identification. BFT PPVs were slightly higher than those previously reported for CT and X-ray scans (7.2-100.0%) (Chawla *et al.,* 2015a; Culotta *et al.,* 2017; Shelmerdine *et al.,* 2018; Martin *et al.,* 2020), and comparable to those for Lodox scans (90.0-100.0%) (Jöres *et al.,* 2016). However, PPVs were much more variable in the SFT sample, ranging between 50.0% and 94.9% for CT, 0.0% and 100.0% for X-rays, and 25.0% and 92.9% for Lodox. This suggests that when assessing cases of SFT, the probability of a radiologically identified defect truly being a defect is variable. This may be because the number of true- and false-positive identifications can be affected by the presence of soft tissue lesions as a result of SFT, which in turn affects the PPV. This, however, is less of a challenge when considering BFT as soft tissue lesions, as was the case in the present study, are infrequently present.

NPVs in both samples were also highly variable (26.7-99.0%), even more so than previously reported for the various imaging modalities (52.6-100.0%) (Chawla *et al.,* 2015a; Jöres *et al.*, 2016; Culotta *et al.*, 2017; Shelmerdine *et al.*, 2018; Martin *et al.*, 2020). These results demonstrate variable probabilities that a bone not considered to have trauma radiologically is indeed trauma-free. This is due to the number of false-negative identifications varying across body regions, which differ in the degree of fracture visibility and superimposition. Caution should therefore be used when a fracture or sharp force defect is not detected by an imaging modality. This particularly concerns the skull, which has the lowest NPVs for both BFT and SFT, likely because trauma is often mistaken for sutures.

5.2.3. Minimum number of impacts

Estimating the minimum number of impacts incurred during a traumatic incident is an important step during forensic examinations, as it can aid in determining whether the incident was abusive or accidental and can help to establish patterns of long-term abuse (Grassberger *et al.,* 2011; İşcan & Steyn, 2013; Love & Wiersema, 2016). In both piglets and adult-sized pigs, including both BFT and SFT, CT was able to estimate the minimum number of impacts with high sensitivity (71.5-82.8%). This was also reported by Grassberger *et al.* (2011) and Johnson *et al.* (2014) in case studies of survived BFT and SFT to the skull, respectively, where CT could identify a minimum of six and four impacts, respectively. However, sensitivity for determining the minimum number of impacts was much lower for X-rays (43.5-59.0%) and Lodox (41.1-58.4%).

These results indicate that CT should be the preferred method for estimating the minimum number of impacts inflicted during a traumatic event involving BFT in both children and adults, as well as SFT. X-rays and Lodox should not be relied upon for this purpose as the resulting estimates may be misleading. However, all methods were still able to determine whether multiple impacts were incurred, regardless of the actual number of these impacts, information which may still contribute to evidence that an incident of trauma was abusive in nature.

5.2.4. Directionality of BFT

An attempt was made in the piglet sample to assess whether the various imaging modalities could determine the directionality of BFT to the skeleton. Results showed that for the ribs and limbs, sites of compression and tension were easily identifiable when using CT scans, and therefore information regarding the direction of the impact could be derived. This was also found by Grassberger *et al.* (2011) who reported that CT was able to determine the directionality of blows in two surviving victims of BFT. However, this was not the case when using X-rays and Lodox in the present study, which provided no indication of directionality.

Assessing the direction of a BFT impact is common practice during forensic anthropological examinations as it provides information regarding the events surrounding the traumatic injury (Love & Symes, 2004; Grassberger *et al.*, 2011; İşcan & Steyn, 2013; Love & Wiersema, 2016). For example, trauma directionality can aid in ascertaining whether an individual was impacted head on or from behind, giving an indication of the position of the perpetrator relative to the victim (Grassberger *et al.*, 2011). This information can help to reconstruct the event, and either corroborate or contradict witness testimony.

5.2.5. Classification of type of SFT/class of weapon

Two different types of SFT were analysed in this study; stab wounds and chop marks. All imaging modalities were substantially more sensitive for detecting chop marks as a result of hacking trauma compared to defects as a result of stabbing trauma. This is likely because the significant bone damage caused as a result of hacking trauma is much more obvious and easier to detect as opposed to the small, subtle defects often caused by stabbing trauma which can be considerably more difficult to identify (Kooi & Fairgrieve, 2013; Mazzarelli *et al.*, 2021). This has specific implications for decomposed remains where the soft tissues may be too decomposed for stab wounds to be visible on the surface and would obscure the defects on the underlying bone. In such cases, where only radiological imaging is used, these wounds may be easily overlooked. Garvin & Stock (2016) report that the detection of very narrow, shallow defects depends on the resolution and settings of the imaging method used, and it is therefore possible that using thinner CT slices may increase detection rates. However, difficulties in identifying subtle SFT defects has also been found to be the case during osteological examinations, where up to 15.0% of defects are only visible microscopically (Kooi & Fairgrieve, 2013).

By interpreting the macroscopic features of the bone as a result of each type of SFT, such as the width of the defect and the extent of bone damage, it may be possible to determine a class of weapon used, as stab defects are the result of trauma inflicted with an instrument such as a kitchen knife, and chop defects are caused by larger weapons such as pangas (Humphrey & Hutchinson, 2001; Lynn & Fairgrieve, 2009; Ferllini, 2012; İşcan & Steyn, 2013). Almost all sharp force defects were correctly classified by all radiological methods, with only Lodox having a sensitivity lower than 70.0% for classifying stab wounds. Results therefore indicate that distinguishing the type of SFT and, consequently, the broad class of sharp instrument used, is possible using radiological means. This was also confirmed by several researchers who found that hacking trauma was easy to distinguish using CT scans, and could therefore be used to confirm the class of weapon involved (i.e. an axe or hatchet) (Ampanozi *et al.,* 2010; Johnson *et al.,* 2014; Wittschieber *et al.,* 2016). While Lodox may have a limited ability to correctly establish trauma inflicted with smaller weapons such as kitchen knives, it is still able to detect these defects. Therefore, following the initial detection of SFT using Lodox scans, a CT or dry bone examination of the regions affected may then be performed in order to interpret this trauma if required.

5.3. Potential limitations and recommendations for future research

Several potential limitations and, as a result, avenues for future research, were identified in this study:

1. Piglets and adult-sized pigs were used in this study as proxies for human infants/children and adults, respectively. Differences in the anatomy and osteology between pigs and humans may have resulted in lower sensitivity for detecting fractures than what would have been achieved if human individuals were used. As a result, including human samples in such assessments should be considered in future research studies, as both forensic anthropologists and radiologists are more familiar with human subjects and are likely to have improved trauma detection rates.
2. The novice forensic anthropologist (NFA) / primary investigator of this study had a much greater familiarity with sub-adult pig osteology and anatomy in comparison to

both the radiologist and the two experienced forensic anthropologists, who all had no experience with this species. The use of a pig sample may have therefore introduced slight bias and shifted the study in favour of the NFA, resulting in higher fracture detection rates for this observer. This potential bias may be overcome by including additional observers who also have detailed knowledge of and specific training in pig osteology. Additional observers with differing levels of experience in forensic anthropology, comparative anatomy and radiology, as well as a human sample, should also be included in future research endeavours.

3. For the assessment of BFT in piglets, the thoracic cage was struck with a mallet in order to produce fractures of the ribs and vertebrae. However, these types of fractures in infants are most commonly the result of antero-posterior chest compression (Kleinman & Schlesinger, 1997; Bilo *et al.*, 2010), which was attempted in two piglets in this study but did not result in any rib fractures. Therefore, in future studies, compression of the rib cage and the resulting fractures should be further explored, preferably in humans who have very different chest shapes from that of pigs.
4. For the assessment of SFT, although the side of the body on which each weapon was used to inflict the trauma was alternated, within each individual pig, stabbing trauma was constrained to a single side of the body and hacking trauma to the other. Therefore, a chop mark due to hacking trauma identified, for example, on the right ulna would introduce some bias as the observer would know that, for that specific pig, trauma to the right side of the body in all other regions was also the result of hacking trauma. This could be overcome in future research studies by inflicting stabbing and hacking trauma randomly to each individual pig, independent of the side of the body. However, specific characteristics associated with the sharp force defects were used to distinguish between these two types of trauma (Table 3.2), which contributed to the reduction of this bias.
5. Only a kitchen knife and a panga were used in this study in order to establish the radiological sensitivity for detecting stabbing and hacking SFT, respectively. Saws are sharp instruments which are also commonly used in incidences of violent crime (Symes *et al.*, 2012), and the radiological detection and macroscopic interpretation of

the skeletal trauma caused by these and other sharp instruments should also be assessed in future studies.

6. The individuals who assisted in taking the X-ray and Lodox scans were not qualified radiographers, but were trained volunteers at the respective institutions. As a result, it is possible that in some cases when X-rays and Lodox scans were taken, the trunk or limbs of the pigs were oriented or positioned in a way that may have obscured the skeletal trauma. This may have resulted in decreased sensitivity for these imaging modalities in these regions. However, this is likely to be less of a limitation when imaging humans, as radiographers would perform standard radiographic views on more familiar subjects.
7. For CT scans, the slice thickness used for both piglets and adult-sized pigs was 3.0 mm. This is a relatively large slice thickness and may have compromised the visualization of very fine, hairline fractures or very small punctures or cut marks in the bone, which may have reduced detection sensitivity. It has been suggested that a maximum slice thickness of 1.25 mm be used when 3D CT bone reconstructions are being evaluated (Ford & Decker, 2016), and a maximum of 0.75 mm when imaging paediatric skeletal trauma (Shelmerdine *et al.*, 2019). Using thinner CT slices in future research studies is therefore recommended to improve trauma detection rates.
8. The technology, including the makes and models of the imaging modalities, as well as the scanning parameters used were specific to this study, and some of these parameters may have impacted the results by either increasing or decreasing trauma detection rates.
9. While the skeletal remains were macerated and reconstructed with extreme care, there is the possibility that additional trauma to the bones which was not present at the time of scanning, specifically in the case of SFT, was introduced during these phases of data collection. If this is the case, it may have resulted in decreased trauma detection sensitivity as this trauma would not have been present radiologically but would have been present on the dry bone. However, this is a potential situation during all forensic anthropological analyses but occurs relatively infrequently.
10. While soft tissue lesions as a result of SFT may have assisted in locating and detecting true-positive skeletal defects, they may also have resulted in a higher

incidence of false-negative and false-positive identifications. This is because soft tissue injury may obscure underlying bone trauma or may be mistaken for skeletal trauma when in fact only the soft tissue is injured. It is possible that a lack of soft tissue may therefore in fact improve SFT detection rates. Future research including partially fleshed, decomposed, or charred remains is therefore recommended.

11. While sensitivity and specificity were calculated in both piglets and adult-sized pigs, positive and negative predictive values (PPVs and NPVs, respectively) were only calculated for adult-sized pigs. Future research should aim to calculate PPVs and NPVs in samples of piglets or human infants/children.

Chapter 6: Conclusion

The results obtained in the present study support the following main conclusions:

1. The level of radiological training and experience does affect the number of BFT fractures that are detected by an observer, with even brief radiological training resulting in drastically increased detection rates.
2. Experience in conducting skeletal trauma analyses on dry bone does not translate to radiological trauma examinations. All forensic anthropologists, regardless of the level of forensic experience, should therefore receive some training in interpreting radiographic material if they wish to conduct virtual examinations of skeletal trauma.
3. Vertebral fractures are difficult to detect radiologically irrespective of the observer's level of radiological training or experience, and forensic anthropological trauma analyses of this region may need to be performed using the cleaned skeletal remains.
4. CT scans result in the highest fracture detection rates regardless of the extent of radiological experience, and forensic anthropologists and pathologists should conduct virtual skeletal trauma examinations using this imaging modality whenever possible.
5. Similarly, CT has the highest sensitivity for detecting both BFT and SFT in all body regions in children and adults. Therefore, whenever a CT scanner is available, it should always be the preferred method for performing post-mortem trauma analyses in individuals of all ages.
6. Only when a CT scan is not a viable option should X-ray or Lodox scans be used, and the radiological method employed will differ depending on the age of the individual being assessed. For examinations of BFT in infants and children, X-rays should be favoured over Lodox scans for most body regions, while the skull can be assessed using either X-ray or Lodox. For assessments of BFT in adults, Lodox scans are recommended for all body regions except the lower limbs, which should be imaged using X-rays. For SFT analyses, radiological examination of all body regions should be performed using Lodox.
7. Regardless of the imaging modality employed, increased diagnostic value is generally achieved when imaging BFT in adults compared to children for all body regions except for the ribs, as well as when imaging SFT compared to BFT in adults.

8. A macroscopic interpretation of skeletal defects in order to determine the type of SFT (stabbing vs hacking), and as a result, the broad class of weapon used (kitchen knife vs panga), is possible using all imaging modalities, but caution should be used when interpreting stabbing trauma using Lodox scans. However, a CT scan or osteological analysis only of the body region with evidence of SFT, as identified during initial imaging using Lodox, can be performed for a more thorough interpretation of the trauma.
9. All imaging modalities are highly specific for detecting BFT and SFT. This demonstrates that false-positive fracture/defect detections are uncommon, and specialists conducting radiological trauma analyses can be confident that trauma is not being incorrectly diagnosed regardless of the radiological method used.
10. Osteological analyses of the cleaned skeletal remains still produce the most accurate results and should therefore be the method of choice for detecting and interpreting skeletal BFT and SFT during post-mortem investigations whenever possible, feasible or practical.
11. No radiological method is infallible and there always exists the possibility that skeletal trauma can remain undetected regardless of the imaging modality used. A high index of suspicion is therefore recommended for both clinical radiologists and forensic practitioners, and the overall clinical picture as well as patient history should always be taken into consideration.

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8. Appendices

8.1. Turn-It-In Plagiarism Report

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1	Amy Joy Spies, Maryna Steyn, Elrentia Bussy, Desiré Brits. "Forensic imaging: The sensitivities of various imaging modalities in detecting skeletal trauma in simulated cases of child abuse using a pig model", Journal of Forensic and Legal Medicine, 2020 Publication	2%
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3	Amy Joy Spies, Maryna Steyn, Daniel Nicholas Prince, Desiré Brits. "Can forensic anthropologists accurately detect skeletal trauma using radiological imaging?", Forensic Imaging, 2021 Publication	1%
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8.2. Declaration: Student's contribution to article(s) and agreement of co-author(s)

I, **Amy Joy Spies**, student number **746773**, declare that this Thesis is my own work and that I contributed adequately towards research findings published in the article(s) stated below which are included in my Thesis.

Signature of Student ……………………………………………………………… **Date**…31/03/2021………………………….

Name of Primary Supervisor……Desiré Brits…………………………………………………………………………………….

Signature of Primary Supervisor ……………………………………………………**Date**……26/04/2021…………………………..

Agreement by co-authors: By signing this declaration, the co-authors listed below agree to the use of the article(s) by the student as part of his/her Thesis/Dissertation/Research Report. In cases where the student is not the 1st author of a published article, the primary supervisor must explain (under comments) why the student is entitled to use the paper for his/her degree purposes.

Article 1: Title: Can forensic anthropologists accurately detect skeletal trauma using radiological imaging?

Journal name, year, volume and page numbers: Forensic Imaging, 2021, 24, article number 200424

Authors	**Name**	**Signature**	**Date**
1st author	Amy Joy Spies	[signature]	31/03/2021
2nd author	Maryna Steyn	[signature]	28/04/2021
3rd author	Daniel Nicholas Prince	[signature]	31/03/2021
4th author	Desiré Brits	[signature]	26/04/2021

Comments by primary supervisor:

Ms Spies was involved in conceptualizing the research topic and was also contributed to the majority of the data collection. She also completed all the data analyses and interpretations of the results and also prepared the manuscript.

<u>Article 2:</u> Title: Forensic imaging: The sensitivities of various imaging modalities in detecting skeletal trauma in simulated cases of child abuse using a pig model

Journal name, year, volume and page numbers: Journal of Forensic and Legal Medicine, 2020, 76, article number 102034

Authors	**Name**	**Signature**	**Date**
1st author	Amy Joy Spies		31/03/2021
2nd author	Maryna Steyn		28/03/2021
3rd author	Elrentia Bussy		09/04/21
4th author	Desiré Brits		26/04/2021

<u>Comments by primary supervisor</u>:

<u>Ms Spies played a pivotal role in the study design and was also responsible for the data collection and analyses of the data. She also interpretated the results and prepared the manuscript.</u>

<u>Article 3</u>: Title: **A comparison of computed tomography, X-ray and Lodox® scans in assessing pediatric skull fractures using piglets**

Journal name, year, volume and page numbers: Journal of Forensic Sciences, 2021, 66, 470-478

Authors	**Name**	**Signature**	**Date**
1st author	Amy Joy Spies		31/03/2021
2nd author	Maryna Steyn		28/02/2021
3rd author	Desiré Brits		26/04/2021

<u>Comments by primary supervisor</u>:

<u>Ms Spies was instrumental in conceptualizing the research topic. She was also responsible for the data collection, analyses and interpretation of the results as well as preparing the manuscript.</u>

Article 4: Title: Diagnostic accuracies of CTs, X-rays and Lodox to detect blunt force trauma in adults, using a pig model

Journal name, year, volume and page numbers: Under review

Authors	**Name**	**Signature**	**Date**
1st author	Amy Joy Spies		31/03/2021
2nd author	Maryna Steyn		28/04/2021
3rd author	Desiré Brits		26/04/2021

Comments by primary supervisor:

Ms Spies was instrumental in conceptualizing the research topic along with the study design. She also collected, analyzed, and interpreted the data. Ms Spies also prepared the manuscript.

Article 5: Title: Radiological detection of sharp force skeletal trauma: implications for the accurate investigation of victims of violent crime

Journal name, year, volume and page numbers: Not yet submitted

Authors	**Name**	**Signature**	**Date**
1st author	Amy Joy Spies		31/03/2021
2nd author	Maryna Steyn		28/04/2021
3rd author	Daniel Nicholas Prince		31/03/2021
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The data for this research was collected by Ms Spies. She also analyzed and interpreted the findings and also prepared the manuscript.

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8.4. Ethics certificates

8.4.1. Wits Animal Research Ethics Committee Clearance Certificate

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

STRICTLY CONFIDENTIAL

ANIMAL RESEARCH ETHICS COMMITTEE (AREC)

CLEARANCE CERTIFICATE NO. 2019/04/27/O

APPLICANT: Ms A Spies

SCHOOL: Anatomical Sciences
DEPARTMENT:
LOCATION:

PROJECT TITLE: A comparison of the sensitivities of X-ray, CT and Lodox scans in the detection of skeletal trauma in simulated cases of violent crime and physical child abuse using adult pigs and piglets

Number and Species

12 piglets 8-15kgs and 23 adult pigs 50-100kgs domestic pigs Sus scrofa domesticus

Approval was given for the use of animals for the project described above at an AREC meeting held on 2019/04/30. This approval remains valid until 2021/06/13.
Unreported changes to the application may invalidate the clearance given by the AREC
An annual progress report must be provided

The use of these animals is subject to AREC guidelines for the use and care of animals, is limited to the procedures described in the application form and is subject to any additional conditions listed below:

Signed: ______________ (Chairperson, AREC) Date: 20/6/2019

I am satisfied that the persons listed in this application are competent to perform the procedures therein, in terms of Section 23 (1) (c) of the Veterinary and Para-Veterinary Professions Act (19 of 1982)

Signed: ______________ (Registered Veterinarian) Date: 20 June 2019

cc: Supervisor: Prof D Brits and Prof M Steyn
Director: CAS

Works 2000/lain0015/AESCCert.wps

8.4.2. Wits Animal Research Ethics Committee Modification Approval

AREC 2017 M&E

Please note that <u>only typewritten applications</u> will be accepted.

UNIVERSITY OF THE WITWATERSRAND

ANIMAL RESEARCH ETHICS COMMITTEE
MODIFICATIONS AND EXTENSIONS TO EXPERIMENTS

a. Name: Amy Joy Spies

b. School and email address: School of Anatomical Sciences; amy.spies@students.wits.ac.za

c. Experiment to be modified / extended **AREC/AESC NO**

Original AESC number	**2019/04/27/O**		
Other M&Es:			None

d. Project Title: A comparison of the sensitivities of X-ray, CT and Lodox scans in the detection of skeletal trauma in simulated cases of violent crime and physical child abuse using adult pigs and piglets

		No.	**Species**
e.	Number and species of animals originally approved:	35	*Sus scrofa*
f.	Number of additional animals previously allocated on M&Es:	N/A	
g.	Total number of animals allocated to the experiment to date:	35	*Sus scrofa*
h.	Number of animals used to date:	35	*Sus scrofa*

i. Specific modification / extension requested:

Two additional pigs are required

j. Motivation for modification / extension:

Two pigs previously used in the study did not have any evidence of fractures following the infliction of trauma and can therefore not be included in the study sample. Two additional pigs are therefore required.

Date: 17/02/2021

Signature:

RECOMMENDATIONS

Approval for additional two pigs to the study as requested

Date: 19 Feberyary 2020 Signature:

Deputy Chair, AREC

8.5. Letters of approval

8.5.1. Department of Agriculture, Forestry and Fisheries Permission Letter

agriculture,
forestry & fisheries

Department:
Agriculture, Forestry and Fisheries
REPUBLIC OF SOUTH AFRICA

Directorate Animal Health, Department of Agriculture, Forestry and Fisheries
Private Bag X138, Pretoria 0001

Enquiries: Mr Herry Gololo • Tel: +27 12 319 7532 • Fax: +27 12 319 7470 • E-mail: HerryG@daff.gov.za
Reference:

Ms Amy Joy Spies
Faculty of Health Sciences
University of the Witwatersrand
7 York Road
Parktown, Johannesburg 2193

Email: Amy.Spies@students.wits.ac.za

Dear Ms Spies,

RE: PERMISSION TO DO RESEARCH IN TERMS OF SECTION 20 OF THE ANIMAL DISEASES ACT, 1984 (ACT NO. 35 of 1984)

Your application, submitted on 20 June 2019, requesting permission under Section 20 of the Animal Disease Act, 1984 (Act No. 35 of 1984) to perform a research project or study, refers.

I am pleased to inform you that permission is hereby granted to perform the following research/study, "The sensitivities of various imaging modalities in detecting skeletal trauma in stimulated violent crime and physical child abuse: a pig model" with the following conditions:

Conditions:

1. This study is approved as per the application form dated 18 June 2019 and the correspondence thereafter. Written permission from the Director: Animal Health must be obtained prior to any deviation from the conditions approved for this study under this Section 20 permit. Please apply in writing to HerryG@daff.gov.za
2. If required, an application for an extension must be made by the responsible researcher at least one month prior to the expiry of this Section 20 approval.

3. This permission does not relieve the researcher of any responsibility which may be placed on him by any other act of the Republic of South Africa;
4. All potentially infectious material utilised or collected during the study is to be destroyed at the completion of the study. Records must be kept for five years for audit purposes. A dispensation application may be made to the Director Animal Health in the event that any of the above is to be stored or distributed;
5. Samples to be transported must be packaged in compliance with the Regulations of the National Road Traffic Act, 1996 (Act No 93 of 1996) or IATA requirements;
6. The study may only start after Ethics approval was obtained;
7. Only a registered Waste Disposal Company may be used;
8. No carcasses to be used in the study may be originate from a farm under any State Veterinary restriction;
9. No carcasses of animals suspected to have died of a controlled or notifiable disease, may be used;
10. The responsible State Vet has to be informed when a carcass is collected from the farm;
11. All research procedures have to be completed in the School of Anatomical Sciences at the University of Witwatersrand;
12. Skeletal remains may be stored at the School of Anatomical Sciences at the University of Witwatersrand;
13. This section 20 expires on 31 December 2021.

Title of research/study: "The sensitivities of various imaging modalities in detecting skeletal trauma in stimulated violent crime and physical child abuse: a pig model."

Researcher (s): Ms Amy Joy Spies

Institution: Faculty of Health Sciences, University of the Witwatersrand, Parktown, Johannesburg

Your Ref./ Project Number:

Our ref Number:

Kind regards,

MMaja.

DR. MPHO MAJA

DIRECTOR OF ANIMAL HEALTH

Date: 2019 -07- 10

8.5.2. Chief State Veterinarian Permission Letter

agriculture and
rural development
Department: Agriculture and Rural Development
GAUTENG PROVINCE

Diamond Corner Building, 68 Eloff & Market
Street, Johannesburg
P O Box 8769, Johannesburg, 2000

Telephone: (011) 355-1900
Fax: (011) 337-2292
Email: dace@gpg.gov.za

Reference: Ms. Amy Joy Spies
Date: 20 June 2019
Enquiries: Dr AMM Grobler
Telephone: (012) 316 1702

Dear Ms. A Spies

Subject: APPROVAL LETTER FOR THE STUDY TO COMPARE THE SENSITIVITIES OF X-RAY, CT AND LODOX SCANS IN THE DETECTION OF BLUNT TRAUMA IN SIMULATED CASES OF VIOLENT CRIME AND PHUSICAL CHILD ABUSE USING ADULT PIGS AND PIGLETS WITH RESPECT TO THE ACTUAL NUMBER OF FRACTURES PRESENT ON THE CLEAN SCELETAL REMAINS, AND TO COMPARE THE SENSITIVITIES OF THESE SAME IMAGING MODALITIES IN THE DETECTION OF SHARP FORCE SKELETAL TRAUMA IN SIMULATED CASES OF VIOLENT CRIME, AND TO ASSIST IN THE ESTABLISHMENT OF STANDARD GUIDELINES AND PROCEDURES FOR ASSESSING SUSPECTED CASES OF VIOLENT CRIME AND PHYSICAL CHILD ABUSE

The above matter has reference in the application for the following research study titled: "The sensitivities of various imaging modalities in detecting skeletal trauma in simulated violent crime and physical child abuse: a pig model".

The researcher intent to move pig carcasses from GHB Farms in Bronkhorstspruit to the University of the Witwatersrand Medical School for this research.

GHB Farms should inform the State Veterinarian in cases of abnormal increases in mortalities. Carcasses should be packaged and transported according to International Standards for the transportation of biological samples and waste should be handled and disposed of according to your protocol.

Yours sincerely

Dr AMM GROBLER
Chief State Veterinarian
Pretoria

Dr. A. Grobler
BVSc Reg No: D94/3497
Chief State Veterinarian
Themba Animal Clinic
FC15/13424

Page 1 of 1

8.5.3. GHB Farms Permission Letter

EST 1955 GHB FARMS

26 March 2019

To whom it may concern,

I hereby grant Amy Spies, a student at the University of the Witwatersrand with student number 746773, permission to make use of adult pigs and piglets that have died of natural causes from GHB Farms in order to fulfil the aims of her PhD project entitled "A comparison of the sensitivities of X-ray, CT and Lodox scans in the detection of skeletal trauma in simulated cases of violent crime and physical child abuse using adult pigs and piglets". There is a veterinarian associated with GHB Farms that will declare cause of death for all pig mortalities, and will confirm that all pigs used in this PhD project have died of natural causes.

Please do not hesitate to contact me should you require further information or have any queries.

Sincerely,

Dries Du Plessis

0833680474

Director: GHB Farms(Pty)Ltd

8.5.4. Wits Donald Gordon Permission Letter

DR T. J. NEL Inc.

RADIOLOGY PRACTICE

PRACTICE NO: 3802841 **REG NO. 2002/021907/21**

The Donald Gordon Medical Centre
21 Eton Road, Parktown, 2193
P.O. Box 2072, Houghton, 2041

TEL: (011) 356 6004
(011) 726 4340
FAX: (011) 726 5938

DR THEO NEL
DR CHARLES SANYIKA
DR LUNGILE GABUZA
DR MARK HAAGENSEN
DR JOHN CANTRELL
DR ERNST BOSHOFF
DR STEVE BRACHMAYER
DR MOHAMMED OMAR
DR OWEN TERREBLANCHE

---

26 March 2019

LETTER OF PERMISSION FOR USE OF FACILITES

To whom it may concern

This is to confirm that the radiology department at Wits-Donald Gordon Medical Centre, Johannesburg, are prepared to assist Ms Amy Spies in her PhD studies, entitled:

1. A comparison of the sensitivities of X-ray, CT and Lodox scans in the detection of skeletal trauma in simulated cases of violent crime and physical child abuse. Supervisor: Dr Desiré Brits (PhD).

The CT imaging arm of the study will take place at our department after hours of specimens packed in vacuum sealed double body bags.
The scanning will be organised by Mrs E Bussy and under my supervision in accordance with the following conditions:

1. The research studies will be scheduled after hours, mainly on Sundays at the convenience of the radiographers.
2. The researchers must provide storage medium in the form of an external drive for data transport.
3. The radiology practice of DR TJ NEL Inc. at Wits-Donald Gordon Medical Centre will be acknowledged when results are published.

After the pilot study an appropriate mutual agreed upon fee will be determined for services rendered.

Yours sincerely,

Dr. Mark Haagensen
MB.BCH.,FFRAD
markhaagensen@mac.com

8.5.5. Central Animal Services Permission Letter

Central Animal Service, Research Office
Health Science Building, 7 York Rd, Parktown, 2193, South Africa Tel. +27 11 717 7300

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

1 April 2019

LETTER OF PERMISSION FOR USE OF FACILITIES

To whom it may concern

This is to confirm that the Central Animal Services (CAS) at the University of the Witwatersrand are prepared to assist Ms Amy Spies in her PhD studies, entitled: "A comparison of the sensitivities of X-ray, CT and Lodox scans in the detection of skeletal trauma in simulated cases of violent crime and physical child abuse using adult pigs and piglets".

The infliction of trauma and X-ray scanning will take place at CAS under the following conditions:

1. Approval from Wits AREC will be obtained prior to using animal tissue to simulate the required injury.
2. Trauma will be inflicted in a secluded room separate from other researchers and staff so as not to impact on their sensitivity.
3. Specimens will be vacuum sealed and placed in double body bags prior to scanning.
4. The researchers must provide storage medium in the form of an external drive for data transport.
5. CAS will be acknowledged when results are published.

Yours sincerely,

Sr M Costello

Director CAS

8.5.6. Johannesburg Forensic Pathology Services Permission Letter

GAUTENG PROVINCE
HEALTH
REPUBLIC OF SOUTH AFRICA

Forensic Pathology Service: Johannesburg

Ms PC Mdluli
Tel: 011 489 1618
Cell: 082 306 3016
E-mail: Phumzile.Mdluli@gauteng.gov.za

Date: 08 April 2019

Re: LETTER OF PERMISSION FOR USE OF FACILITIES

To whom it may concern

This is to confirm that the Johannesburg Forensic Pathology Services (JHB-FPS) are prepared to assist Ms Amy Spies in her PhD studies, entitled: *"A comparison of the sensitivities of X-ray, CT and Lodox scans in the detection of skeletal trauma in simulated cases of violent crime and physical child abuse using adult pigs and piglets"*.

Lodox scanning will take place at the JHB-FPS under the following conditions:

1. Specimens will be vacuum sealed and placed in double body bags prior to scanning.
2. The researchers must provide storage medium in the form of an external drive for data transport.
3. The JHB-FPS will be acknowledged when results are published.

Yours sincerely,

P Mdluli
Acting Assistant Director

8.6. Published Paper 1

Forensic Imaging 24 (2021) 200424

Contents lists available at ScienceDirect

Forensic Imaging

journal homepage: www.sciencedirect.com/journal/forensic-imaging

Can forensic anthropologists accurately detect skeletal trauma using radiological imaging?

Amy Joy Spies [a,*], Maryna Steyn [a], Daniel Nicholas Prince [b], Desiré Brits [a]

[a] Human Variation and Identification Research Unit (HVIRU), School of Anatomical Sciences, Faculty of Health Sciences, University of the Witwatersrand, 7 York Road,
Parktown, Johannesburg 2193, South Africa
[b] Department of Diagnostic Radiology, Faculty of Health Sciences, University of the Witwatersrand, 7 York Road, Parktown, Johannesburg 2193, South Africa

ARTICLE INFO

Keywords:
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forensic anthropology
skeletal trauma
fracture detection ability
Computed Tomography (CT)
X-ray
Lodox®

ABSTRACT

Radiological imaging is often used to aid in forensic anthropological examinations. While forensic anthropologists may need to detect skeletal trauma virtually, they generally have very little to no radiological training. The aim of this study was to assess the ability of forensic anthropologists to accurately detect fractures using radiology. Five piglets were struck with a mallet, post-mortem, and then scanned using CT, X-ray and Lodox®. The number of fractures detected on each modality was recorded by a senior radiology resident (SRR), a novice forensic anthropologist (NFA) with brief radiological training, and more experienced forensic anthropologists (EFA) with limited to no radiological training. The piglets were macerated and the number of fractures present on the dry bone were counted. The percentage of fractures detected by each observer using each method in comparison to the dry bone was calculated. Cohen's kappa revealed that agreement between the NFA and SRR was considered substantial to almost perfect (k=0.77-1.00), while agreement between the EFA and SRR was fair to almost perfect (k=0.21-1.00). However, while the SRR and NFA had comparable sensitivities (0.0-83.7% and 0.0-89.3% respectively), the EFA detected on average 22.0% less fractures than the NFA (0.0-62.4%). This indicates that even brief radiological training increases the sensitivity of fracture detection, and that the ability of forensic anthropologists to detect fractures virtually without training is not sufficient when evaluating cases with suspected trauma. It is therefore suggested that all forensic anthropologists, both novice and more experienced, should receive radiological training in order to accurately detect fractures.

Introduction

Both forensic pathologists and forensic anthropologists are involved in the examination and identification of deceased individuals. Forensic pathologists conduct autopsies in order to determine cause and manner of death and are also commonly relied upon to determine the identification of unknown decedents [1]. Forensic anthropology is concerned with the analysis and identification of decomposed or skeletal remains, which includes the construction of a biological profile and the evaluation of bone pathologies and trauma [2, 3]. In recent times, these disciplines have started to shift toward a more virtual approach, with examinations being conducted less invasively, using various radiographic tools [3].

Forensic odontologists, pathologists and anthropologists also rely on radiological methods to assist in the identification of unknown decedents by comparing ante- and post-mortem records of dentition [4-6], paranasal sinuses [1, 7-9] and unique skeletal variations, pathology or trauma [1, 3, 10, 11]. These methods of identification are particularly useful when dealing with decomposed [12], skeletonized [3] or burnt remains [13, 14], as well as during disaster victim identification [3, 5,

Author contributions: A.J Spies, M. Steyn and D. Brits contributed to the study conception and design; all authors contributed to the acquisition of data, and the revision and final approval of the article; A.J. Spies conducted the analysis and interpretation of data, and drafted the article.
Declarations of interest: none.
Roles of funding sources: funding for this research was provided by the National Research Foundation (NRF) (grant number: 118149) and the NRF/Deutscher Akademischer Austausch Dienst (DAAD) (grant number: 117943). These funding sources however did not have any involvement in study design, collection, analysis and interpretation of data, writing of the report, or in the decision to submit the article for publication.
* **Corresponding author:** Amy Joy Spies; Human Variation and Identification Research Unit (HVIRU), School of Anatomical Sciences, Faculty of Health Sciences, University of the Witwatersrand, 7 York Road, Parktown, Johannesburg 2193, South Africa
E-mail addresses: amy.spies@students.wits.ac.za (A.J. Spies), maryna.steyn@wits.ac.za (M. Steyn), desire.brits@wits.ac.za (D. Brits).

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Available online 29 November 2020
2666-2256/

8], when DNA or fingerprint analysis is not possible or feasible.

Forensic imaging is being used more frequently in the construction of biological profiles during forensic anthropological analyses. Methods for the estimation of sex, age-at-death and living stature have been conducted using magnetic resonance imaging (MRI) scans [15-17], computed tomography (CT) scans [18-20], conventional X-rays [21-23] and low-dose full-body X-ray (Lodox®) scans [24, 25]. Skull radiographs have also been used to aid in the construction of craniofacial approximations [26].

Forensic pathologists increasingly rely on the use of imaging modalities as a complementary tool during traditional autopsy procedures and in some institutions, these modalities are even used to conduct virtual autopsies, or "VIRTOPSIES®" [27, 28]. Conventional autopsies are extremely time-consuming, labour-intensive, invasive, and have many cultural, religious and emotional implications, and the use of radiological imaging to conduct virtual autopsies have therefore garnered much interest [3, 27, 28]. The assessment of both soft tissue and the skeleton can be conducted using radiological methods such as CT and MRI scans, and is particularly important for the detection of skeletal trauma which is regularly assessed during autopsies and forensic anthropological examinations in order to establish the circumstances surrounding death, and to identify victims of abuse [3]. Fractures, which are common in victims of physical abuse and violent crime [29], and the detection of which is critical in these cases, are regularly missed during traditional autopsies, with between 9% and 69% of fractures going unnoticed [30, 31]. Fractures sustained perimortem and which have not yet begun to heal and form calluses are frequently undetected during autopsy procedures [30]. In addition, fractures in regions particularly difficult to assess during autopsy are also regularly undetected [31, 32]. While remains may be macerated so that forensic anthropologists can conduct skeletal analyses to detect trauma, this process is time-consuming, expensive and not always feasible [33]. Furthermore, in living individuals, skeletal trauma can only be visualized radiologically. The use of imaging tools aids in the rapid and accurate detection of bone fractures [3], which could assist in identifying both victims and perpetrators of abuse and violent crime.

Ali et al. [1] suggest that forensic pathologists with limited radiological experience can accurately compare ante- and post-mortem records of skull features in order to identify unknown decedents. However, the detection of trauma in the rest of the skeleton may be more challenging and may require the expertise of a radiologist, which is not always practical during forensic analyses where forensic anthropologists who typically have no to limited radiological training and experience, may be required to interpret radiological scans themselves [3]. Although many authors agree that the use of virtual methods to detect skeletal trauma is a critical part of modern forensic anthropology [3, 10, 11, 34], the ability of forensic anthropologists to accurately identify this trauma radiologically is not currently known. The aim of this study was therefore to determine the ability of both novice and experienced forensic anthropologists, in comparison to a radiologist, to accurately detect the number of skeletal fractures on CT, X-ray and Lodox® scans. For this purpose, a pig model was used.

Materials and methods

The Animal Research Ethics Committee at the University of the Witwatersrand (Clearance Certificate No 2019/04/27/O) and the South African Department of Agriculture, Forestry and Fisheries granted ethical permission for the completion of this study.

This paper forms part of a larger study by Spies et al. [35, 36] which investigated the sensitivities of various imaging modalities in detecting skeletal trauma. In order to assess whether forensic anthropologists can accurately detect skeletal trauma, the trunk (including the ribs and vertebrae), the anterior limbs and the posterior limbs of five piglets (5-15 kg each) were each hit between 1 and 10 times with a mallet post-mortem. Piglets were then radiographed. Helical computed tomography (CT) scans were taken at the Wits Donald Gordon Medical Centre in Johannesburg using a 64 Slice Philips Brilliance CT scanner, with parameters of 120 kV, 150 mA, 3.0 mm slice thickness with a 1.5 mm slice increment, 0.391 pitch, and a reconstruction kernel C: 500 W: 1500 on a D filter (bone kernel). Conventional X-rays (58kV, 2.2-2.5mA) were taken at the Central Animal Services at the University of the Witwatersrand, and included ventrodorsal and left and right lateral views of each body region, as well as oblique views of both the left and right ribs. Lodox® scans (80 kV, 160 mA) were taken at the Johannesburg Forensic Pathology Services and included ventrodorsal and right and left lateral views. Lodox® scanners are frequently used both in South Africa and worldwide, producing full-body X-ray images with very low doses of radiation and at very high speeds, and are therefore invaluable for performing initial trauma screening procedures [37]. For a more detailed description of the Lodox® scanner, the reader is referred to work by du Plessis et al. [37].

Four observers, including a fairly novice forensic anthropologist, more experienced forensic anthropologists, and a senior radiology resident read each scan. For the more experienced forensic anthropologists, one read the X-rays and another the CT and Lodox® scans. Two experienced forensic anthropologist observers, both with very limited radiological experience, were used due to the availability of each observer. While all forensic anthropologist observers had limited radiological experience, the novice received brief training in the basics of interpreting radiological images prior to the start of this study. This training amounted to approximately 10 hours, and included two workshops on detecting skeletal fractures and anomalies, as well as training by a radiologist on how to differentiate between anatomical and non-anatomical disruptions in bone cortex, and how to interpret CT scans using multiplanar reconstruction (MPR), maximum intensity projection (MIP) and volume rendering (3-dimensional reconstructions). The novice also had prior experience with sub-adult pig anatomy and osteology, which both the radiologist and experienced forensic anthropologists lacked.

Each observer recorded the exact number and location of fractures present in each body region as detectable on CT, X-ray and Lodox® scans. Fractures were detected based on non-anatomical linear radiolucencies and disruptions of the bone cortex. The skulls were not assessed as some were highly fragmented, and exact fracture numbers could not be determined as with the other body regions. All observers read the scans of each imaging modality using RadiAnt DICOM Viewer, and for CT scans, both 2-dimensional and 3-dimensional images were assessed.

The inter-observer repeatability between each of the observers for detecting the number and location of fractures was assessed using Cohen's kappa, where the level of agreement was considered slight with a kappa score of 0.00 - 0.20, fair with a score of 0.21 - 0.40, moderate with a score of 0.41 - 0.60, substantial with a score of 0.61 - 0.80, and almost perfect with a score >0.81 [38]. Intra-observer repeatability for the primary investigator, who was the novice forensic anthropologist, was also assessed using Cohen's kappa. As the aim of this study was specifically to assess inter-observer repeatability, the intra-observer repeatability for each other observer was not assessed.

The cleaned skeletons, which were considered as the standard of comparison in this study, were also assessed following maceration and skeletal reconstruction of each piglet, and the number of fractures present in the trunk, anterior and posterior limbs was determined. The sensitivity and specificity of each observer for detecting these fractures using each type of scanning method was calculated. Sensitivity is the correct radiological detection of a fracture which is also present on the dry bone, while specificity refers to detecting no fracture radiologically which is also not present osteologically [39]. Sensitivity is represented by the number of true-positive fractures divided by the total number of true-positives and false-negatives, whereas specificity is represented by dividing the number of true-negatives by the combined total of the number of true-negative and false-positive fractures [39]. IBM® SPSS®

version 25.0 was used to perform all statistical analyses.

Results

A total of 279 post-cranial fractures were present on the dry bones, which included 178 rib fractures, 29 vertebral fractures, 31 anterior limb fractures and 41 posterior limb fractures. The overall sensitivities for the senior radiology resident (SRR) were 73.1% for CTs, 51.3% for X-rays, and 45.9% for Lodox® scans. The novice forensic anthropologist (NFA) had sensitivities of 77.4%, 54.5% and 47.7% for CTs, X-rays and Lodox® scans respectively, while the sensitivities for the more experienced forensic anthropologists (EFA) were 53.4%, 28.3% and 31.5% respectively. Overall specificities ranged between 95.1% and 99.2% for all observers. Examples of frequently undetected fractures are presented in Figures 1-3.

The overall detection of fractures was highly repeatable between the SRR and NFA, with kappa values indicating almost perfect agreement between the two observers (CT 0.91; X-ray 0.86; Lodox® 0.89). Agreement between the SRR and the EFA (CT 0.64; X-ray 0.45; Lodox® 0.62) was similar to that between the NFA and EFA (CT 0.62; X-ray 0.48; Lodox® 0.62), and both were considered moderate to substantial agreement. Intra-observer repeatability for the NFA was considered substantial to almost perfect (CT 0.92; X-ray 0.78; Lodox® 0.86).

The kappa values indicating agreement levels between observers for each body region using each imaging modality are presented in Table 1. Repeatability between the SRR and NFA was consistently the highest, with substantial to almost perfect agreement for all regions and all radiological methods (kappa values between 0.77 and 1.00). Agreement between the SRR and EFA, and between the NFA and EFA, were comparable across all body regions and imaging modalities, with kappa values ranging between 0.21 for rib fractures detected using X-rays and 1.00 for vertebral fractures detected using both X-ray and Lodox® scans. In general, CT scans had the highest agreement between observers for all body regions, except the vertebrae, where X-rays and Lodox® had higher repeatabilities, and the anterior limbs for which repeatability was highest using X-rays. Repeatability using Lodox® scans was higher than X-rays for the ribs and posterior limbs, but repeatability using X-rays was higher than Lodox® scans for the anterior limbs. In general, regardless of imaging modality used, the highest agreement between all observers was for fractures of the vertebrae (k= 0.70-1.00), while the lowest agreement between all observers was for the ribs (k=0.21-0.87).

The sensitivities for each observer in detecting fractures in each body region using each radiological method is presented in Table 2. The NFA had the highest sensitivities for all body regions using all diagnostic tools, with a range of 0.0% to 89.3%, and were comparable to the sensitivities of the SRR (0.0% to 83.7%). The EFA had the lowest sensitivities for detecting fractures across all regions and using all modalities, ranging between 0.0% and 62.4%. Sensitivities were highest for CT scans for all observers and all body regions (31.0-89.3%), and in general Lodox® scans had the lowest sensitivities (0.0-56.2%). In general, the ribs were the region with the highest sensitivity for all observers using all modalities (25.8-89.3%), while the spine had the lowest sensitivities (0.0-37.9%). For the SRR, NFA and EFA respectively, specificities ranged between 92.2-100.0%, 94.5-100.0% and 92.7-97.9% for CT scans; 83.0-100.0%, 93.8-100.0% and 89.8-98.3% for X-rays; and 97.9-100.0%, 94.0-100.0% and 91.5-100.0% for Lodox® scans.

Discussion

Radiological imaging is often used during forensic anthropological analyses, which includes the assessment of skeletal trauma. Two papers from the same larger study compared the sensitivities of CT, X-ray and Lodox® scans in detecting fractures of the skull, trunk, forelimbs and hindlimbs of piglets subjected to blunt force trauma [35, 36]. The results of these papers showed that many fractures were missed using all imaging modalities, but that CTs consistently had the highest sensitivities

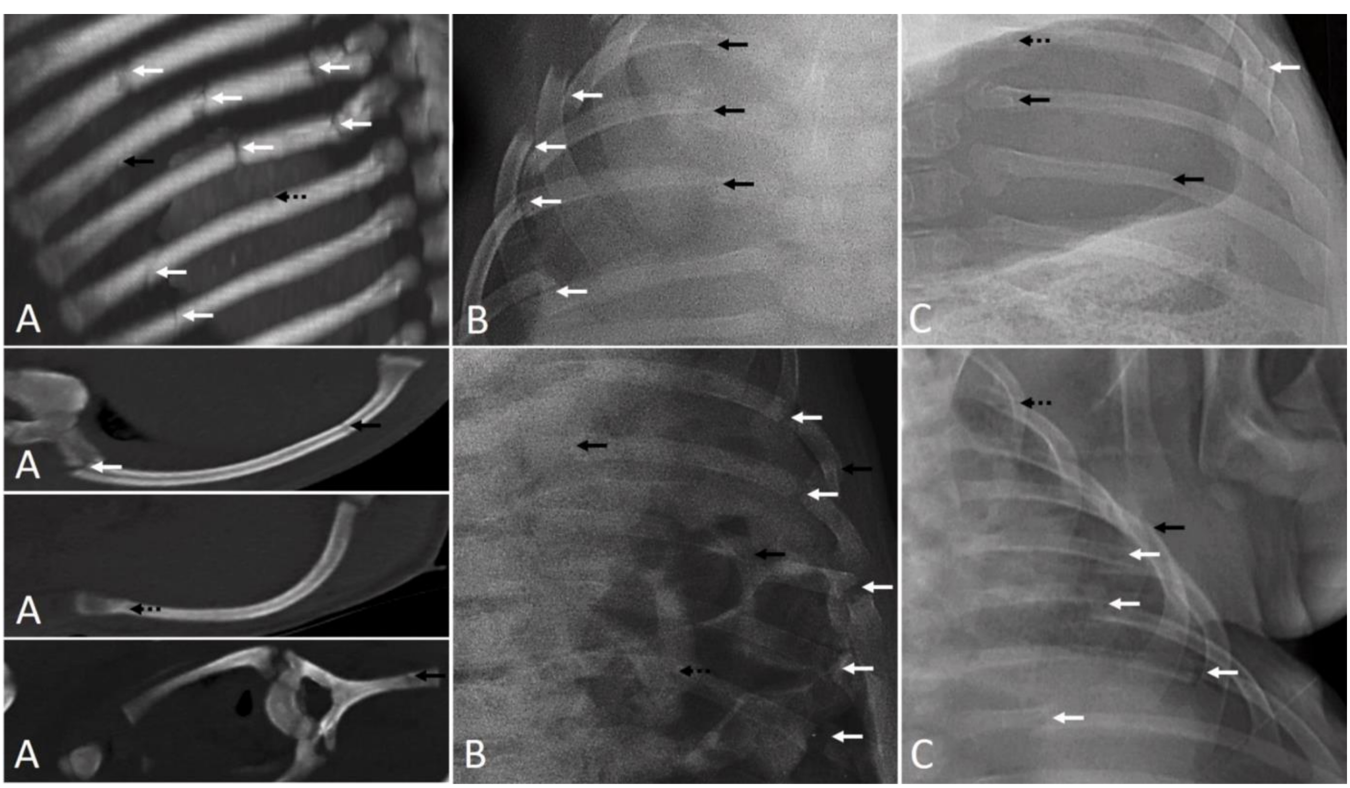

Fig. 1. Frequently unidentified fractures of the ribs and vertebrae as shown with CT (A), X-ray (B) and Lodox® (C) scans. Solid white arrows indicate fractures identified by all observers; solid black arrows indicate fractures identified only by the SRR and NFA; dashed black arrows indicate fractures identified only by the NFA.

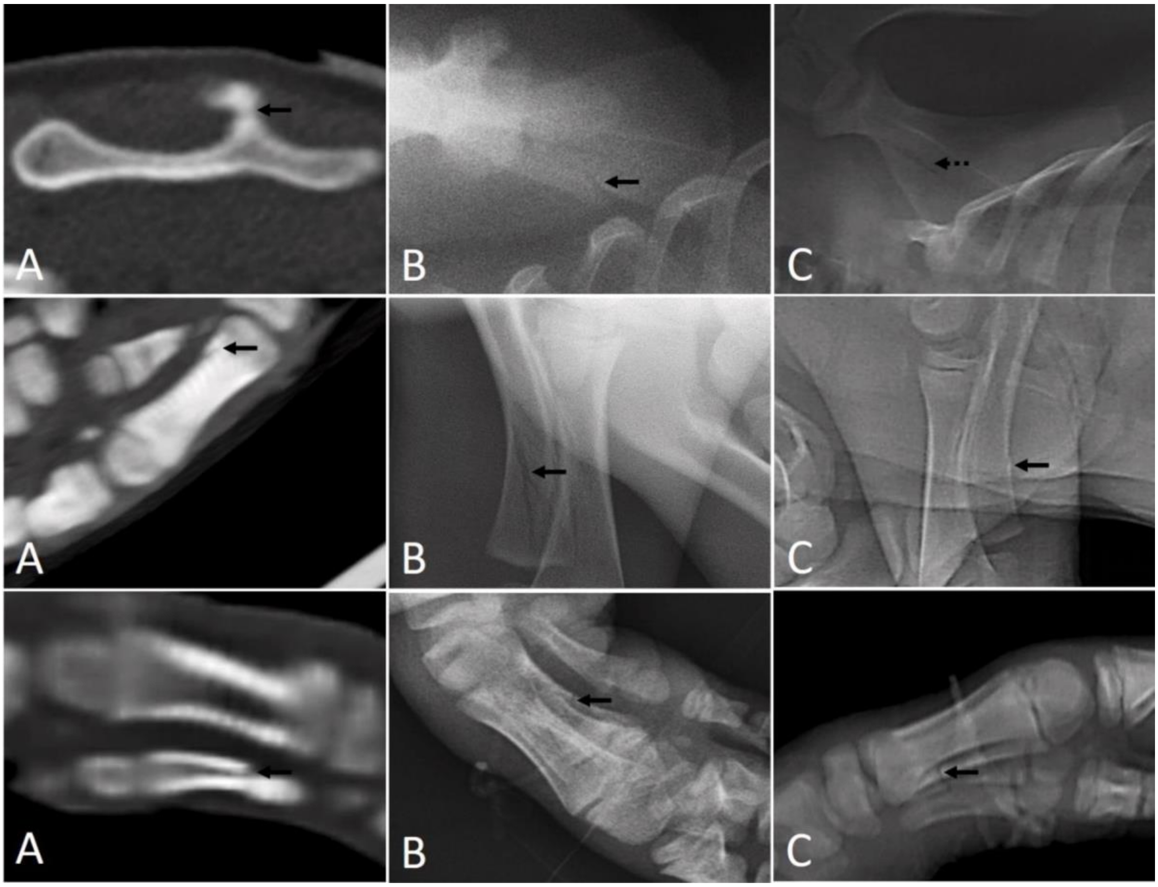

Fig. 2. Frequently unidentified fractures of the anterior limb as shown by CT (A) (top: scapula; middle: metacarpal; bottom: metacarp al), X-ray (B) (top: scapula; middle: ulna; bottom: metacarpal) and Lodox® (C) (top: scapula; middle: ulna; bottom: metacarpal). Solid black arrows indicate fractures identified only by the SRR and NFA; dashed black arrows indicate fractures identified only by the NFA. A lack of white arrows indicates that none of the fractures were identified by all thee observers.

while plain radiographs were insufficient in detecting fractures in these cases. The aim of the present study was therefore not to compare the sensitivities of the imaging modalities themselves or to assess how efficient they are, but to compare the ability of different observers, including forensic anthropologists, to detect fractures using these methods. While the use of a pig model is challenging in terms of the anatomy and osteology, and may have reduced the overall detection of fractures, the senior radiology resident used in the present study was as unfamiliar with pig anatomy as most forensic anthropologists, and therefore the results can still be considered accurate.

The number of fractures detected by the NFA was highly comparable to those detected by the SRR for all body regions using all radiological methods (k=0.77-1.00). The level of agreement between these two observers was substantial to almost perfect [38], indicating that the NFA was able to identify fractures visible radiologically at the same level as the SRR. The number of fractures detected by the more experienced forensic anthropologists (EFA) was less comparable with those identified by both the SRR (k= 0.21-1.00) and the NFA (k= 0.28-1.00). However, agreement between the EFA and SRR was still considered fair to almost perfect. The much higher repeatability of the NFA may be because this observer received brief radiological training prior to the start of this study, and therefore had slightly more experience with reading scans in comparison to the EFA. The NFA also had the highest sensitivities for detecting fractures in all body regions using all imaging modalities (0.0-89.3%). Sensitivities of the NFA were on average 3.0% higher than that of the SRR (0.0-83.7%) and 22.0% higher than that of the EFA (0.0-62.4%). The higher sensitivities of the NFA are, when compared with the EFA, likely due to the fact that the NFA had a slightly higher level of radiological experience. In addition, the NFA had a much more detailed knowledge of piglet osteology and anatomy, which explains why the NFA had higher sensitivities than both the SRR and EFA who are less familiar with pig anatomy. It is therefore likely that the sensitivities for detecting fractures by both the SRR and the EFA may increase when reading scans of human infants and children, with which all observers are much more familiar.

These results, which indicate that observer experience does indeed affect the number of fractures detected using radiological scans, are similar to those of Hong et al. [40] who reported an increase in sensitivity of pediatric rib fracture detection from 29% to 46% for X-rays and 52% to 85% for CT scans when a more senior radiologist read the scans in comparison to a less experienced observer. However, Shelmerdine et al. [41] found that observer experience was not a significant predictor of sensitivity when detecting rib fractures in children.

Both inter-observer repeatability as well as fracture detection sensitivity was generally highest for CT scans, for all observers and all body regions. This indicates that CTs are not only more sensitive than both X-ray and Lodox® scans in detecting fractures, but that CT scans are also much easier to read and interpret regardless of observer experience or level of training, as was seen by Spies et al. [35, 36]. While the superimposition of bones in X-ray and Lodox® scans may cause the detection of fractures to be much more challenging, the three-dimensional renderings of each bone available with CT scans contributes to fractures being detected much more easily by observers of all levels of experience. Hong et al. [40] suggest that the use of CT scansin addition to X-rays may only be of benefit for observers with less radiological experience, as more senior observers may have a high

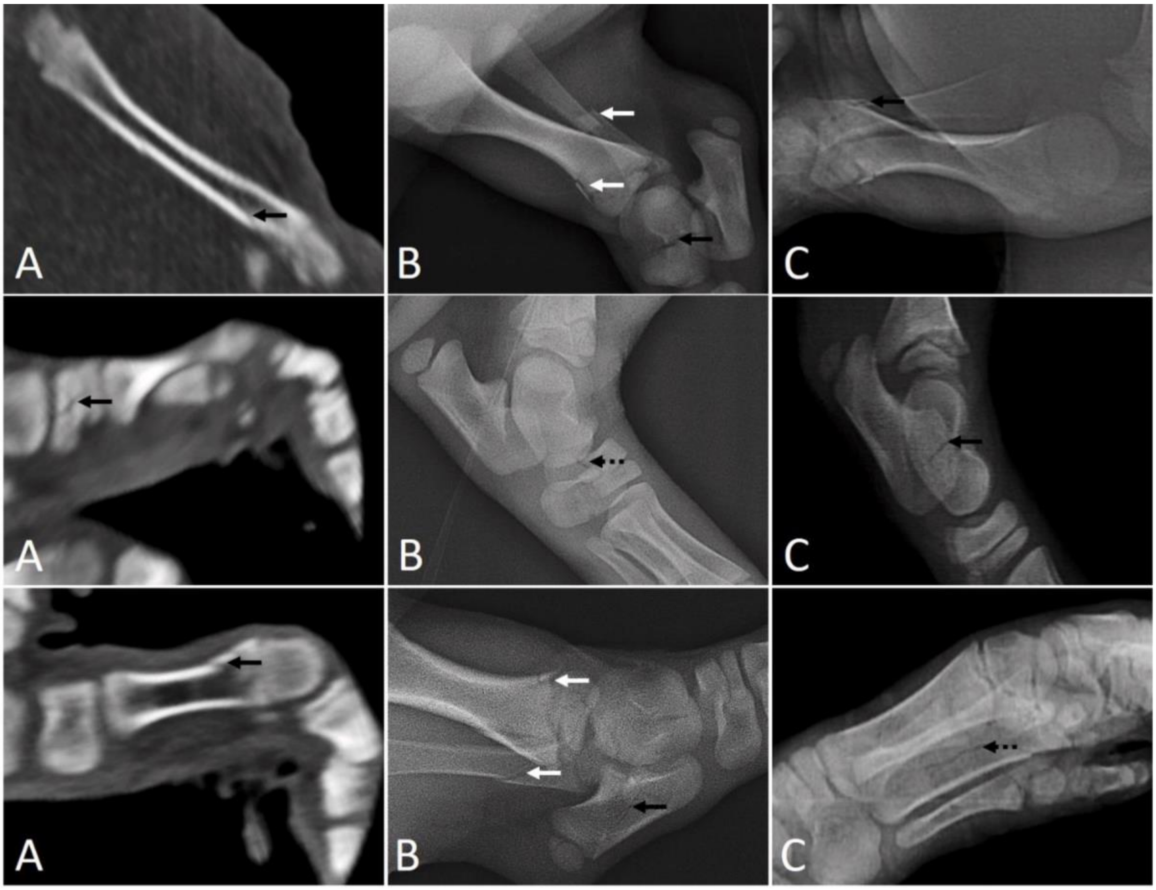

Fig. 3. Frequently unidentified fractures of the posterior limb as shown by CT (A) (top: fibula; middle: tarsal; bottom: metatarsal), X-ray (B) (top: tibia, fibula and talus; middle: tarsal; bottom: tibia, fibula and calcaneus) and Lodox® (C) (top: fibula; middle: talus; bottom: metatarsal). Solid white arrows indicate fractures identified by all observers; solid black arrows indicate fractures identified only by the SRR and NFA; dashed black arrows indicate fractures identified only by the NFA.

Table 1
Kappa values indicating level of agreement between the number of fractures detected by the senior radiology resident (SRR), novice forensic anthropologist (NFA) and experienced forensic anthropologist (EFA) in each body region using each imaging modality.

	Ribs			**Vertebra**			**Anterior limbs**			**Posterior limbs**		
	CT	X-ray	Lodox	CT	X-ray	Lodox	CT	X-ray	Lodox	CT	X-ray	Lodox
SRR-NFA	0.87	0.77	0.83	0.97	1.00	1.00	0.86	1.00	0.95	0.97	0.90	0.88
SRR-EFA	0.54	0.21	0.53	0.70	1.00	1.00	0.59	0.69	0.53	0.67	0.56	0.66
NFA-EFA	0.52	0.28	0.54	0.72	1.00	1.00	0.60	0.69	0.49	0.64	0.57	0.63

Table 2
Sensitivities (%) of the senior radiology resident (SRR), novice forensic anthropologist (NFA) and experienced forensic anthropologist (EFA) in detecting fractures in each body region using each imaging modality.

	Ribs			**Vertebra**			**Anterior limbs**			**Posterior limbs**		
	CT	X-ray	Lodox	CT	X-ray	Lodox	CT	X-ray	Lodox	CT	X-ray	Lodox
SRR	83.7	60.7	55.6	37.9	0.0	0.0	64.5	48.4	45.2	58.5	48.8	36.6
NFA	89.3	64.6	56.2	37.9	0.0	0.0	67.8	48.4	48.4	61.0	53.7	43.9
EFA	62.4	25.8	36.5	31.0	0.0	0.0	41.9	38.7	29.0	39.0	26.8	34.1

enough diagnostic accuracy using X-rays alone. However, the results of this study, as well as the study by Shelmerdine et al. [41], show that all observers have a higher diagnostic accuracy using CT scans than when using plain radiographs. In addition to higher sensitivities with CTs, scanning times are also much quicker than conventional X-rays, and only one scan needs to be taken in comparison to three scans for Lodox®, and between 10 and 15 images for X-rays, depending on the size of the image cassettes. Furthermore, there is the added benefit of using 3-dimensional reconstructions, and even 3-dimensional printed models of the CT scans, which may be used as evidence in court during criminal trials [42]. Therefore, CTs are preferred over X-ray or Lodox® scans regardless of observer experience.

Repeatability between all observers was lowest for the ribs using all imaging modalities. This is likely due to difficulties in counting the ribs, which range between 14 and 16 in pigs, as well as superimposition of the ribs in X-ray and Lodox® scans. In addition, abdominal gas often obscured the lower ribs, making fracture detection challenging. Sensitivities, however, were lowest for the spine, likely due to superimposition of the vertebrae in X-ray and Lodox® scans which makes it challenging to identify fractures of the transverse and spinous processes. Sensitivities were also relatively low for the limbs, which may be due to difficulty in detecting long bone metaphyseal fractures, as well as superimposition of some bones. While long bones such as the humerus and femur were easily visualised, smaller bones like the metacarpals and metatarsals were highly superimposed, making fractures difficult to detect. This is evident as 19.0-56.3% and 26.1-63.6% of all limb fractures undetected by observers using X-rays and Lodox® respectively, were those of the metacarpals/metatarsals. Again, increased radiological experience and training, as well as an increase in knowledge of piglet osteology may result in both improved inter-observer repeatability and sensitivity for these body regions. Furthermore, in human infants and children, where the bones of the hands and feet are not superimposed, sensitivities for detecting fractures in these regions are expected to be higher for all observers.

Specificities were extremely high for all observers (95.1-99.2%), indicating very few false-positive fracture identifications. This is significant since it suggests that all observers, irrespective of level of training, are not likely to incorrectly identify victims of abuse. For all observers, specificities were comparable between CT, X-ray and Lodox® scans, indicating that the level of observer experience does not affect the likelihood of making false-positive identifications using any imaging method. Hong et al. [40], however, suggest that limited radiological experience may result in lower specificities for CTs in comparison to X-rays, and that with increased experience and training, the risk of false-positive identifications can be reduced. The results of the present study, however, contradict this.

The results of both inter-observer repeatability and fracture detection sensitivity in the present study show that an increase in observer experience results in an increase in the number of fractures detected using all imaging methods, as expected. The NFA received brief training in the basics of radiological imaging interpretation prior to the start of this study, while the EFA had little to no radiological experience. This training resulted in the NFA having a sensitivity for fracture detection comparable to that of the SRR, and which was on average 22.0% higher than the EFA. This indicates that even very brief radiological training and experience can result in a drastic increase in sensitivity, and that the ability of forensic anthropologists without this training to detect fractures is limited and not sufficient when evaluating cases with skeletal trauma such as in cases of physical child abuse.

A potential limitation of this study is the fact that a CT slice thickness of 3.0 mm with a slice increment of 1.5 mm is relatively thick and may have made the detection of very fine fractures more difficult, thus resulting in lower sensitivities. In addition, the fact that the NFA had a much more detailed knowledge of piglet anatomy and osteology may have resulted in higher fracture detection sensitivities and skewed the results in favour of the NFA. Therefore, including more observers familiar with piglet anatomy may improve results. Furthermore, including more observers of all levels of experience, including specialist pediatric radiologists, as well as increasing the sample size, may increase the validity of the results.

Conclusion

The field of forensic anthropology is becoming much more virtual in its approach and is making use of radiological tools to conduct forensic anthropological analyses, including the interpretation of trauma [3]. However, it was previously unknown whether forensic anthropologists, who generally have very limited to no radiological experience and training, are able to accurately identify skeletal trauma using various imaging modalities. Results of this study show that observer experience does indeed affect the number of fractures detected using CT, X-ray and Lodox® scans, with sensitivity increasing as level of experience increases. This indicates that even very brief radiological training, as was received by the NFA in this study, can drastically improve the ability of the observer to detect skeletal trauma. While forensic anthropologists do have fair to almost perfect agreement with the number of fractures detected by the SRR, fracture detection sensitivities of forensic anthropologists without radiological training are low and not sufficient for assessing cases of suspected trauma, such as physical child abuse or violent crime. The authors therefore suggest that all forensic anthropologists, both novice and experienced, should receive radiological training, either included in undergraduate courses or offered as professional courses for more advanced anthropologists before they comment on fractures observed on radiographic material.

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Forensic imaging: The sensitivities of various imaging modalities in detecting skeletal trauma in simulated cases of child abuse using a pig model

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A B S T R A C T

Physical child abuse is a major problem in South Africa and throughout the world, and the detection of skeletal trauma in victims of abuse may be critical in the accurate investigation of these cases. Since many of these fractures are not detected during traditional autopsy, the use of various diagnostic imaging tools is implemented in order to aid in the detection of trauma. In South Africa, Lodox (low-dose full-body X-ray) is commonly used in forensic mortuaries and the aim of this study was to assess the sensitivities of CT, X-ray and Lodox, in comparison to dry bone as the gold standard, in detecting both the number of fractures and minimum number of impacts in piglets subjected to blunt force trauma. Ten piglets were beaten with a mallet post-mortem in every region of the body. CT, X-ray and Lodox scans were taken of each piglet, after which the piglets were macerated in order to conduct an osteological analysis of the remains. The number of fractures and impacts present in each scan and on the dry bone were recorded. CT scans were the most sensitive in identifying trauma in all regions of the body, detecting 73% of fractures and 79% of impacts. X-ray and Lodox scans were less sensitive in detecting both fractures (50% and 42% respectively) and impacts (59% and 54% respectively). An assessment of the directionality of trauma was possible using dry bone and CT scans, but not when using X-rays or Lodox scans. CT scans can be used to assess skeletal trauma in suspected victims of child abuse, but the use of X-ray and Lodox scans is not recommended other than for initial screening procedures. Osteological analysis, however, is still considered the gold standard and should be performed whenever possible.

1. Introduction

Crimes against children are extremely prevalent in South Africa, and indeed throughout the world, and include sexual, psychological and physical abuse.[1,2] In the 2017/2018 period in South Africa, a total of 43 540 crimes against children were reported.[3] Of these, 23 488 were victims of sexual assault, 10 211 of common assault, 7562 of assault with the intent to inflict grievous bodily harm, 1059 of attempted murder and 985 of murder. South Africa has a child homicide rate more than double the global average at 8 per 100 000,[4] and of these homicides, approximately 44.5% are the result of physical abuse.[2]

One of the most common indicators of physical child abuse is the presence of fractures, which occur in approximately 30–55% of abused children.[5–8] In infants under the age of one year, between 50% and 69% of fractures are due to abuse.[9,10] According to various authors,[11–14] the probability of abuse given a skull fracture is 27–30%, while it ranges between 71 and 95% for rib fractures, 54 and 79% for humeral fractures, and 43 and 60% for femoral fractures. While accidents may also result in similar patterns of trauma, multiple skeletal injuries are more common in cases of abuse than in accidents. The minimum number of impact sites may also be informative and are regularly assessed during forensic anthropological analyses. An impact site is the location where a blow was inflicted, and knowledge of the number of impact sites can give insight into the minimum number of blows a victim was subjected to.[15] A single impact can cause more than one fracture, while multiple impacts may not cause any fractures. Multiple impacts are more likely to be

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the result of abuse than a single impact, and therefore it is important to be able to identify both the minimum number of impacts and the number of fractures when investigating cases of child abuse.

During an autopsy, which must be conducted in all cases of non-natural death according to the Inquest Act of South Africa (No. 58 of 1959), it can be difficult to locate and detect fractures. Calluses, which forensic pathologists often use to locate fracture sites, are not present in cases of peri-mortem trauma, and soft tissue damage, also often used to locate sites of trauma, may be extremely subtle or not even visible at all.[16] Furthermore, decomposition, which is much quicker in children, and other taphonomic processes may conceal both soft tissue and skeletal trauma.[17,18] Fractures in locations difficult to assess such as the skull, particularly the base and facial skeleton, scapula, spine, posterior ribs, pelvis and long bones, as well as hairline fractures, are frequently undetected during autopsy.[19–22] Radiological methods are usually used to aid in the identification of trauma. These include computed tomography (CT) scans, conventional X-rays and, in South Africa, full body low-dose X-ray (Lodox®) scans. The Lodox scanner was developed in South Africa in order to perform full body low-dose scans of miners to prevent the theft of diamonds. These scanners are now often used in medicine and forensic pathology in order to detect both soft tissue and skeletal trauma,[23] and has more recently been used in forensic anthropology in order to detect skeletal trauma and conduct forensic anthropological analyses.[24] The Lodox scanner emits far less radiation than conventional X-rays and CTs, and is thus much safer for both the living victim and the operator.[23,25] It produces a full-body image in only 13 seconds which does not need to be "stitched", does not require the expertise of professional radiographers, and has very low running costs.[23,25]

The use of imaging modalities in both forensic pathology and anthropology may improve the detection of skeletal trauma or be used to perform virtual autopsies or "virtopsies".[26,27] This is particularly significant in countries like South Africa where conventional autopsies, especially of children, violate many cultural and religious beliefs,[28] and may eliminate the need for bodies or specific body parts to be macerated and skeletonized in order to conduct forensic anthropological analyses. The importance of these imaging modalities goes without saying in the living, where the detection of trauma is based solely on these methods. These imaging tools are therefore vital, and the sensitivity of each method in detecting skeletal trauma needs to be explored.

Several researchers investigated the sensitivities of various modalities, including autopsy, to detect fractures. For example, both Williamson and Perrott[29] and McGraw et al.[30] found that radiological methods detected many fractures that were missed during autopsy, and Antúnez et al.[27] found that CTs detected more fractures than X-rays in 39% of paediatric cases. Studies have found both autopsy and CT scans to be more sensitive than X-rays in detecting paediatric rib[31–34] and skull fractures.[35] Douglas et al.[36] reported that in children, fractures were detected by Lodox that would have been missed if only computed radiography were employed. Pitcher et al.[37] found that, when using computed radiography as the gold standard, Lodox detected 96% of fractures.

Most previous studies assessing the sensitivity of various diagnostic tools in paediatric trauma have either used autopsy results, CTs or computed radiography as the reference standard against which to compare results. To the best of our knowledge, only one study[16] has compared the sensitivities of various imaging modalities in detecting fractures on control cases, using dry bone as the reference standard. In simulated cases of child abuse using a pig model, they found autopsy to be the most sensitive in detecting fractures of the ribs (65%) and forelimbs (91%), while CTs, X-rays and autopsy all detected 100% of hindlimb fractures. For the skull, autopsy and X-rays detected only approximately a third of fractures, while CT scans incorrectly identified more fractures than were present osteologically.

To the best of our knowledge, the sensitivity of the Lodox scanner in detecting trauma in simulated cases of child abuse has not been assessed before. Furthermore, the minimum number of impacts identified by various imaging modalities has yet to be evaluated. The aim of the current study was therefore to compare the sensitivities of CT, X-ray and Lodox scans, which are commonly employed by forensic pathologists in South Africa, in detecting the number of fractures and minimum number of impacts in simulated cases of physical child abuse, using a pig model. The dry bone (macerated remains) were used as the gold standard.

2. Materials and methods

Ethical clearance for this study was obtained from the Animal Research Ethics Committee at the University of the Witwatersrand (Clearance Certificate No 2019/04/27/O), as well as from the Department of Agriculture, Forestry and Fisheries in South Africa.

2.1. Materials

Ten piglets which had died of natural causes were sourced from GHB Farms (Pty) Ltd in Bronkhorstspruit, South Africa. Piglets ranged between 5 and 15 kg, a weight range that was chosen since it is comparable to that of human infants and young children. Piglets with peri- or post-mortem trauma were excluded from the study. One additional piglet was used as a negative control in order to ensure that fractures detected radiologically were only the result of trauma and not confounding variables associated with the imaging methods.

2.2. Methods

2.2.1. Trauma

Piglets were subjected to blunt force trauma in order to simulate physical child abuse. Piglets were, post-mortem, subjected to blunt force trauma with a 55 mm $\times$ 55 mm, 500 g mallet in four major regions of the body: the skull, thorax, forelimbs and hindlimbs. This weapon was used in order to simulate a fist, which is one of the most common weapons of choice in cases of child abuse.[38] Between one and five blows were inflicted to the skull, and between one and 10 blows to each other body region. Trauma was inflicted by an independent observer so as to keep the principal investigator blind to the exact number of blows inflicted to each body region. The skull was struck on the cranial and left and right lateral surfaces; the thorax was struck on the dorsal and left and right lateral surfaces; and the limbs were struck on the left and right lateral surfaces. Piglets were then vacuum sealed and placed in body bags prior to scanning to prevent any leakage of fluid.

2.2.2. Radiological assessment

Full body helical CT scans (64 Slice CT Brilliance) were taken of each piglet at the Department of Radiology, Wits Donald Gordon Medical Centre in Johannesburg, South Africa. Scans were taken at 120 kV, 150 mA and a slice thickness of 1.5 mm. X-rays were taken at the Central Animal Services in the Faculty of Health Sciences at the University of the Witwatersrand, South Africa. Ventro-dorsal and lateral X-rays were taken of the skull, thorax, fore- and hindlimbs. Two additional views were taken of the thoracic region, including left 45° dorsal-right ventral oblique and right 45° dorsal-left ventral oblique images. Full body ventro-dorsal, lateral, and 7° and 15° oblique Lodox scans were taken at the Forensic Pathology Services Medicolegal Laboratory in Johannesburg, South Africa.

For each CT, X-ray and Lodox scan, the number and location of fractures visible in the thorax, forelimbs and hindlimbs was recorded. The minimum number of impacts visible on the skeleton was also assessed by determining which fractures were likely the result of the same blow. The minimum number of impacts takes into consideration that some impacts may not result in any fractures, and some fractures may be the result of more than one blow. For the skull, it was only documented whether the skull was fractured/impacted or not. This was done due to the heavily fragmented state of some of the skulls. Fractures were identified based on the presence of radiolucencies in the bone and cortical bone discontinuities. Where possible, the direction of the impact was also assessed by determining sites of compression and tension, with the impact located at the site of compression.

2.2.3. Osteological assessment

Piglets were macerated and skeletonized in the School of Anatomical Sciences at the University of the Witwatersrand, South Africa. Piglets were gently boiled in hot water for between one and two days, after which the soft tissue was carefully removed from the bone so as not to introduce any additional trauma. The cleaned skeletons were then rearticulated and the number and location of fractures, as well as the minimum number of impacts visible on the skeleton in each body region were recorded. The direction of impacts was also assessed where possible.

2.2.4. Repeatability

All assessments were done by the primary investigator, and intra-observer repeatability was assessed by this investigator on 5 pigs, by reading and then re-reading the same scans about two months later, in a different order to reduce recollection bias. Inter-observer repeatability was conducted by a professional radiologist on the same pigs. Both the number of fractures and minimum number of impacts detected in each body region, using each type of imaging modality, as well as on the cleaned skeletons, were counted.

2.2.5. Data analysis

The intra- and interobserver repeatability of detecting fractures on CT, X-ray and Lodox scans was tested using Cohen's kappa on 5 piglets. The percentage of both fractures and impacts detected by each method with respect to the number of fractures and minimum number of impacts detected on the bones was then calculated. In line with suggestions by Cattaneo et al.,[16] differences between means were assessed using a two-way ANOVA, with body region (skull, thorax, forelimb, hindlimb) and imaging modality being the main factors. Logarithmic transformations were used when variances were not equal.

3. Results

Cohen's kappa tests revealed no significant differences for both intra- and inter-observer fracture counts ($k = 0.61–1.00$) for any imaging modality or any body region. For the minimum number of impacts, only the intra-observer thorax count using X-rays had a kappa value less than 0.61 ($k = 0.50$), indicating some difficulty in repeatably scoring this region.

A total of 586 fractures were present on the skeletons, of which CT correctly detected 427 (73%), X-ray 294 (50%) and Lodox 245 (42%). All 10 piglets had fractured/impacted skulls, which were also detected by CT scans. X-rays and Lodox scans both only detected 9 fractured/impacted skulls (90%) (Fig. 1). There were therefore no significant differences in fracture/impact counts between dry bone and any of the imaging techniques for the skull ($p > 0.05$).

Of 453 thoracic fractures (88 vertebral and 365 rib) identified osteologically, 346 (76%) were identified using CT, 220 (49%) using X-rays and 182 (40%) using Lodox (Fig. 1). X-ray and Lodox scans did not identify any vertebral fractures, while CT detected 38 (43%). When considering the ribs, there were 106 posterior fractures (CT 83%; X-ray 56%; Lodox 43%), 209 shaft fractures (CT 89%; X-ray 70%; Lodox 61%) and 50 sternal end fractures (CT 44%; X-ray 22%; Lodox 18%) (Fig. 2). A large portion of the rib fractures that were missed were those of the lower ribs. Surprisingly, 10 healed rib fractures were also present. All 10 of these were seen on CT, 8 on X-ray and 6 on Lodox (Fig. 2). Statistically, there were significant differences ($p < 0.001$) in the number of fractures detected between dry bone and all imaging modalities for the thorax.

Osteological analysis showed 60 forelimb and 63 hindlimb fractures. Of these, CT scans detected 58% and 57% respectively, X-rays 52% and 54% respectively, and Lodox 45% and 43% respectively (Fig. 1). For all imaging modalities, the majority of fore- and hindlimb fractures missed were those of the metacarpals/metatarsals, hairline fractures and fractures of the proximal and distal metaphyses of long bones (Fig. 3). Significant differences ($p < 0.05$) existed between the number of fractures detected by dry bone and all imaging modalities for the forelimbs, while only CTs did not differ from the osteological control ($p > 0.05$) when considering the hindlimbs.

A minimum of 219 impacts were identified on the dry bone (10 skull, 126 thoracic, 42 forelimb and 41 hindlimb). CT detected 174 of these impacts (79%), X-rays 129 (59%) and Lodox 118 (54%). Minimum impact counts from all scanning methods were significantly different from dry bone for both limbs ($p < 0.05$), while for the thorax, only counts from CTs did not differ ($p > 0.05$).

Fracture and minimum impact counts between CT, X-ray and Lodox

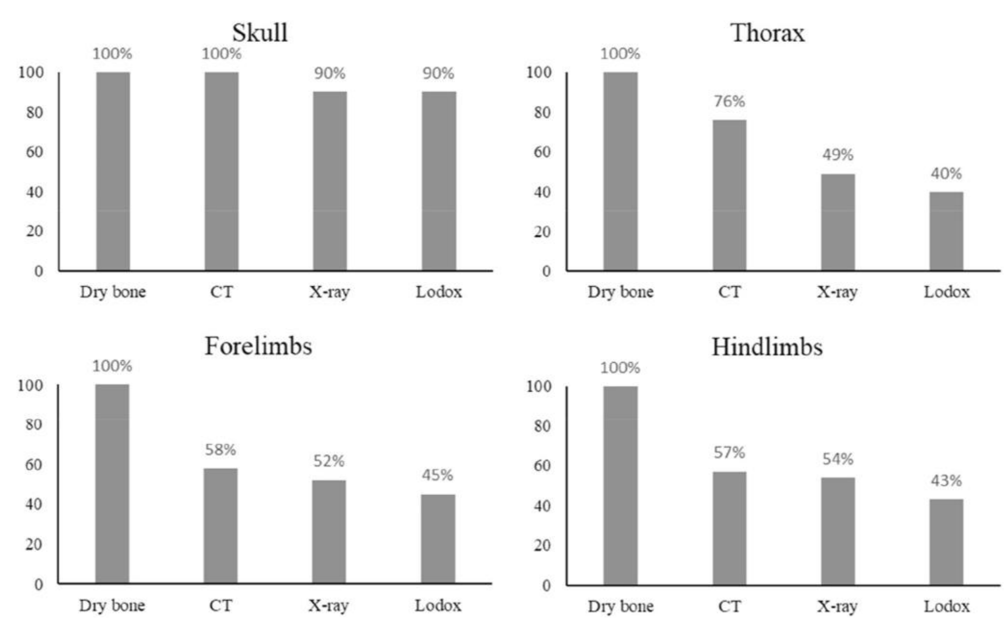

Fig. 1. Comparison of percentage of fractures detected by dry bone, CTs, X-rays and Lodox scans in each body region.

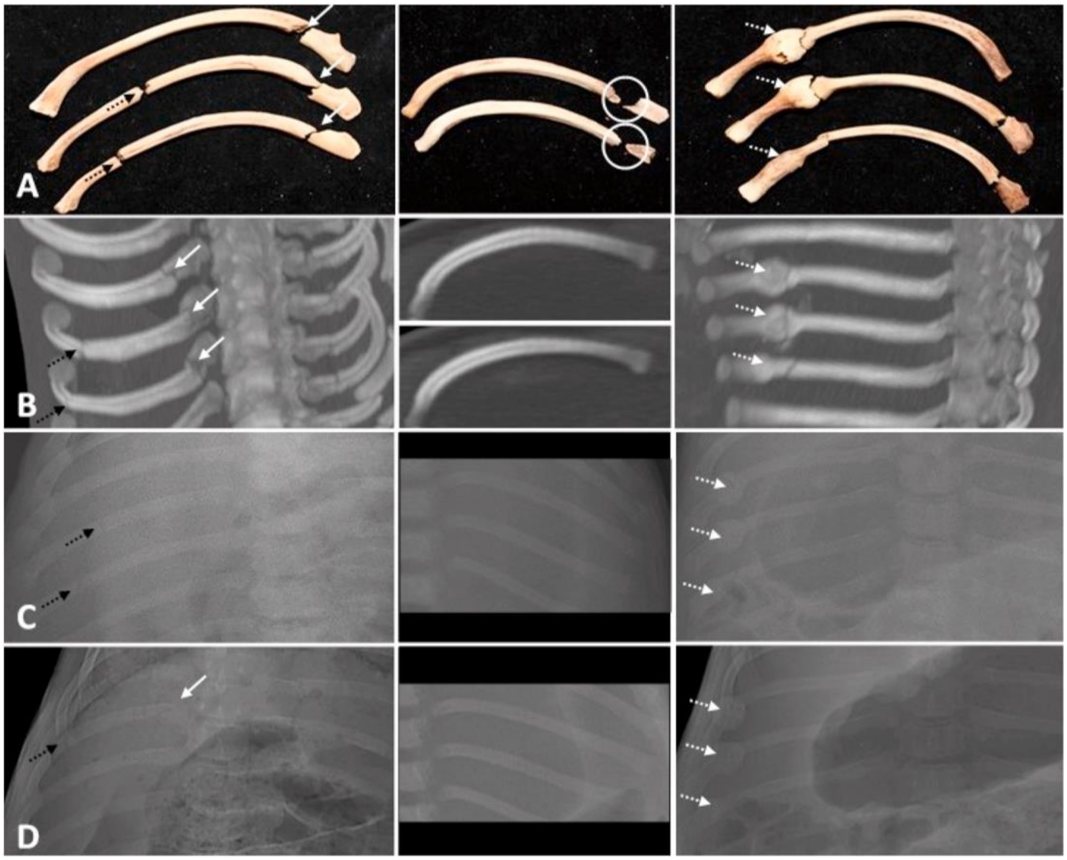

Fig. 2. Posterior, sternal end and healed rib fractures (columns 1–3) of the same piglets as seen on dry bone (A), CT (B), X-ray (C) and Lodox (D). White arrows indicate posterior rib fractures, most of which were not observed on X-ray and Lodox scans. Note how gas obscures the lower ribs in X-ray and Lodox scans as seen in the first and third columns. Fractures of the shaft (dashed black arrows) are detected but fractures of the sternal end (white circle) are often missed by CTs, X-rays and Lodox. Almost all healed fractures (dashed white arrows) are identified by all modalities. The absence of any arrows or circles indicates no fracture detected.

scans did not differ significantly for the skull, fore- and hindlimbs ($p > 0.05$) but X-ray and Lodox scans differed significantly from CTs for the thorax ($p < 0.05$).

For fractures of the ribs and limbs, it was possible to determine the direction of impact using dry bone and CT analysis, but not possible using X-ray and Lodox scans (Fig. 4).

4. Discussion

This study compared the sensitivities of CT, X-ray and Lodox scans in detecting bone fractures and impact sites in simulated cases of physical child abuse. Child abuse is a worldwide crisis, with child homicide rates (per 100 000) of 4 in the United States of America, 6 in Sudan, 8 in South Africa, 13 in Rwanda, 18 in Lesotho and 27 in El Salvador.[4] Of these child homicides, a large portion is the result of physical abuse.[2] One of the most common indicators of child abuse is skeletal fractures,[11,39] and the detection of these fractures both in the living and the dead are critical for the accurate investigation of these cases. Here, fractures present on the skeletons of 10 piglets exposed to blunt force trauma were compared to the number of fractures detected using various imaging modalities in order to assess their sensitivities.

Cohen's kappa tests revealed moderate to almost perfect agreement[40] for both intra- and inter-observer fracture and impact counts. This indicates that all counts are highly repeatable, and that, due to substantial agreement with observations made by the professional radiologist, the results of this study can be considered accurate.

In paediatric skulls, the bones are much more elastic and more resistant to fracturing, and the presence of skull fractures may therefore suggest incidences of severe trauma or abuse.[41] Results from the present study indicate that CT, X-ray and Lodox scans are all highly sensitive in detecting impacted/fractured skulls. However, due to the highly fragmented nature of the skulls, it was only ascertained whether the skulls were impacted and/or fractured, and not precisely how many fractures or impacts were present. The complex anatomy of piglet crania makes them susceptible to extensive fracturing once they are compromised, in a sense making it easier to detect fracturing. Furthermore, distinguishing fractures from suture lines was challenging and has implications for the identification of trauma, thus requiring more research.

For the thorax, the number of fractures detected by all imaging modalities was significantly different from dry bone. While CTs may have some sensitivity in detecting spinal fractures, X-rays and Lodox are particularly insensitive. This is significant since vertebral fractures have a high specificity for physical abuse.[42,43]

When considering the ribs, CT scans were the most sensitive (84%) and Lodox scans the least sensitive (50%) in detecting fractures in all locations. Sensitivities reported by Cattaneo et al.[16] were lower than those of the present study for both CTs (34%) and X-rays (47%). It is interesting to note that in their study, X-rays fared better than CT. In the current study, CT scans detected almost all fractures of the posterior rib and shaft, but were only moderately sensitive in identifying fractures of the sternal end. Both X-rays and Lodox scans detected most shaft fractures, but were only moderately sensitive in detecting posterior fractures and had a very low sensitivity for sternal end fractures. These results are quite alarming since rib fractures, particularly those of the posterior and sternal ends, are highly indicative of physical abuse and account for between 5% and 27% of all abuse-related fractures.[32,34,44,45] These low sensitivities mean that many cases of physical child abuse may go undetected, especially if rib fractures are the only indicator of abuse which

Fig. 3. Metaphyseal fractures (black arrows) of the distal ulna (top) and distal tibia (bottom) as seen on dry bone (A), but missed by CT (B), X-ray (C) and Lodox scans (D) of the same piglets. The absence of any arrows indicates no fracture detected.

is often the case.[14] Future research should include the use of antero-posterior and lateral chest compressions in order to better simulate rib fractures in children.

Between 60% (Lodox scans) and 100% (CTs) of healed rib fractures were detected. This is important since healed fractures can be indicative of cases of repeated abuse and their detection is essential.[16,34] However, callus formation only occurs within 11–14 days of injury, and therefore when these injuries occur peri-mortem, these fractures are difficult to detect,[34] which is shown by the results for X-ray and Lodox scans in the present study. Most rib fractures missed by X-ray and Lodox scans were those of the lower ribs, which is likely due to the presence of gas in the abdomen which obscures these ribs (Fig. 2).

For both the fore- and hindlimbs, CTs were most sensitive and Lodox scans were least sensitive in detecting fractures. However, sensitivities were comparable between CTs and X-rays, similar to results of Cattaneo et al.,[16] who reported equal sensitivities for both CT and X-rays in these regions. A large portion of limb fractures that were missed by all diagnostic tools were those of the proximal and distal metaphyses of long bones. These results are significant since metaphyseal fractures have a high specificity for abuse.[42,46–48] While metaphyseal fractures with evidence of bone remodelling and healing can be detected radiographically,[49] this is not the case when fractures are incurred peri-mortem and healing processes have not yet begun. Hairline fractures and fractures of the metacarpals and metatarsals were also often undetected, which again could result in cases of physical child abuse not being identified.[50] While the sensitivity of CT scans in detecting limb fractures may be adequate, especially for the hindlimbs where CT results did not differ significantly from dry bone, X-ray and Lodox scans have relatively low sensitivities and should not be relied upon solely for the detection of limb fractures.

This study also assessed the sensitivities of these diagnostic techniques in determining the minimum number of blows or impacts present in each body region. Knowledge of the minimum number of impacts may help to distinguish between abusive and accidental injury, and may also indicate repeated trauma over time.[15] Again, CT scans were most sensitive in detecting impacts in all body regions (79%), while Lodox scans were the least sensitive (54%). This indicates that none of the imaging techniques, apart from CT scans for the thorax which did not differ significantly from the dry bone, should be relied upon to determine the minimum number of impacts.

An assessment of the direction of trauma was possible using dry bone and CT scans, but not when using X-ray and Lodox scans. Directionality may be important as it can help to reconstruct the event of injury, as well as corroborate cause and manner of death.

Although skeletal surveys using X-rays are common practice in hospitals and morgues in order to detect fractures in suspected victims of

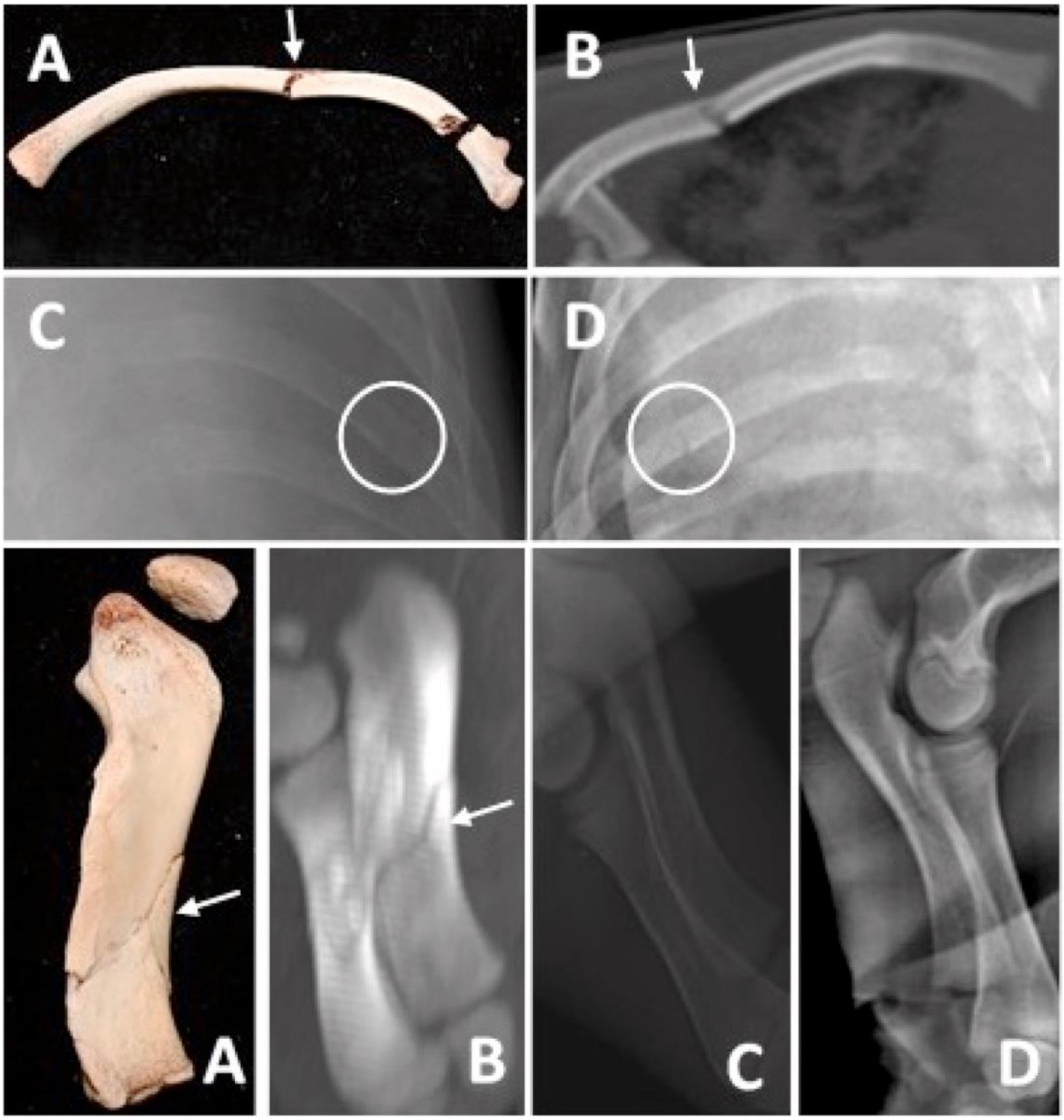

Fig. 4. Direction of impact (white arrows) to the ribs (above) and ulna (below) of the same piglets as identified by dry bone (A) and CT (B), but not possible with X-ray (C) and Lodox scans (D). White circles show presence of fracture but no directional information.

child abuse,[51] results of the present study have shown X-ray and Lodox scans to not be sufficiently sensitive in identifying fractures in any body region. Their sole use in evaluating suspected child abuse cases is therefore not recommended, alarming results considering that they may sometimes be the only diagnostic tools used to detect skeletal trauma.[52] Their low sensitivities, as suggested by Cattaneo et al.[16] in the case of X-rays, may be the result of superimposition of bones on the scans or the small size of the bones. It is interesting to note that Lodox was consistently less sensitive than even conventional X-rays. While some authors have suggested that Lodox scans are of similar or even better quality than X-rays,[25,53,54] the results of this study contradict that. Although Lodox scans are advantageous due to their low dose of radiation, as well as their speed and cost-effectiveness,[52] the low sensitivity in detecting skeletal trauma does not promote their use when assessing cases of suspected child abuse. While Cattaneo et al.[16] suggest a combination of autopsy, CT scans, X-rays and osteological survey be used in cases where abuse is suspected, this is not practical in a real-life forensic setting such as in South Africa as it would be extremely time-consuming and expensive. The authors therefore suggest that osteological analysis, when practical and feasible, remain the method of choice when assessing suspected cases of child abuse. However, maceration of the entire skeleton is often not practical, and therefore specific bones or regions suspected to have trauma, either based on soft tissue findings or initial radiological findings, should be macerated and the dry bone assessed.

When skeletal analysis is not possible, such as in cases of the living or in cases where full-body maceration is not practical, CTs should be used to detect skeletal trauma.

5. Conclusion

The detection of skeletal injuries may be critical in the accurate investigation of suspected cases of physical child abuse. Many of these fractures are undetected during autopsy procedures and therefore various imaging modalities are used to aid in the identification of this trauma. The present study found that X-ray and Lodox scans, which are commonly employed by both doctors and forensic pathologists in South Africa and around the world, are insensitive in identifying fractures and impacts in simulated cases of abuse. CT scans are the most sensitive in detecting trauma in all regions of the body and may therefore be used to diagnose victims of abuse when dry bone analysis is not a possibility, such as in living individuals. However, skeletal analysis is still considered the reference standard and the authors suggest conducting an osteological assessment whenever possible or practical in order to investigate cases of suspected physical child abuse.

Declaration of competing Interest

None to declare.

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PAPER

Anthropology

A comparison of computed tomography, X-ray and Lodox® scans in assessing pediatric skull fractures using piglets

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Abstract

Skull fractures are common in children both due to abuse and accidental incidences. The accurate detection of these fractures may therefore be critical. The aim of this study was to investigate the reliability of CT, X-ray, and Lodox® scans, the latter which has not previously been evaluated and is commonly employed in South Africa, in de-tecting the number, location and type of pediatric skull fractures. Blunt force trauma was inflicted with a mallet on ten piglet skulls, which were CT, X-ray, and Lodox® scanned and then macerated. The number, location, and type of skull fractures visible using each imaging modality, and on the cleaned skulls, were recorded. Sensitivities and specificities of each method were calculated. For fracture number and location, CTs had a sensitivity of 47.3%, X-rays 22.4% and Lodox® 23.3%. For fracture type, sensitivities were 46.1%, 16.6%, and 17.8% for CT, X-ray, and Lodox®, respectively. Specificities were high (92.5%–100%) which reduces the risk of incorrectly diagnosing fractures. However, low sensitivities increase the risk of failing to identify fractures and possible victims of abuse. Osteological analysis should preferably be the method of choice when evaluating pediatric skull trauma, and CTs should be used when os- teological analysis is not feasible. If CT scanners are not available, X-rays and Lodox® may have to be used. In these cases, additional radiographic views of the skull are imperative and may increase the sensitivity of these methods, although they are not recommended to detect exact pediatric skull fracture number, location, and type.

KEYWORDS
skeletal trauma, pediatric skull fractures, radiological tools, computed tomography, X-rays, low-dose full-body X-rays and Lodox®, forensic anthropology

1 | INTRODUCTION

Head injuries are extremely common in young children and infants, both as a result of accidents and abuse, and often result in skull fractures [1–3]. It is imperative that pediatric skull fractures be accurately detected in order to determine possible cause and manner of death [3–8]. In addition, it is important that all skull fractures are detected in order to identify potential victims of abuse, since failure to do so can put them at further risk of injury and allow perpetrators to go free [9]. One study found that 54 of 173 children with abusive head trauma were not identified as victims of abuse, resulting in re-injuries of 15 children, and 4 deaths which may have been prevented [10]. This demonstrates how difficult it can be to detect cranial fractures using radiological means.

Various imaging tools have been employed in order to accurately detect pediatric skull fractures, including computed tomography (CT) scans, X-rays and, particularly in South Africa, Lodox® scans. Lodox® scanners emit very low doses of radiation, produce full-body X-ray images in a matter of seconds, and are very cost-effective, making them advantageous over CTs and conventional X-rays

[11]. They are used widely in South African mortuaries; in fact, they are often the only radiological modality available in most Forensic Pathology Services.

Some studies have assessed the diagnostic accuracy of these imaging tools in detecting fractures in pediatric patients and have found that CT scans identified more fractures than X-rays, and that many fractures identified by X-rays were false-positives [3,12]. In a study of 85 pediatric patients with skull fractures, CT scans were found to be more sensitive than X-rays in identifying linear, depressed, and diastatic skull fractures [4]. Culotta et al. [5], however, reported no significant difference in the sensitivities for CTs and X-rays when identifying skull fractures of 177 children. The CT scans of 76 children with skull fractures showed that a combination of 2-dimensional (2D) and 3-dimensional (3D) CT scans had a sensitivity of 83.1% while 2D scans alone had a sensitivity of 74.5% [6]. In addition, the combination of 2D-3D scans yielded fewer false-negatives than 2D scans [6]. Douglas et al. [13] and Pitcher et al. [14] both found that Lodox® scans were highly sensitive in detecting long bone fractures in pediatric patients, but information on the diagnostic accuracy of Lodox® scans in detecting skull fractures is limited.

Almost all previous studies used either autopsy results or CT scans as the reference standard, and very few have tested the sensitivities of these diagnostic modalities under controlled circumstances and using dry bone as the gold standard. Mulroy et al. [7] subjected six human pediatric cadaver skulls to blunt force trauma and found that CT scans had a sensitivity of 71% for identifying single skull fractures, while X-rays had a sensitivity of 63%. Results also showed that linear fractures were more easily detected compared to diastatic fractures but had a higher rate of false-positive identification. Cattaneo et al. [8] used piglets to compare the sensitivities of autopsy, CTs, and X-rays against dry bone and found that autopsy detected 31% of skull fractures, while X-rays detected 35%. CT scans detected more fractures than were actually present (126%), indicating a high rate of false-positive identifications. In a previous study [15], the diagnostic accuracies of CTs, X-rays, and Lodox® scans in detecting blunt force trauma in piglet skeletons were compared. As far as the simple detection of cranial trauma was concerned, CT scans were found to be most sensitive (100%), while X-rays and Lodox® scans were somewhat less sensitive (90%). However, it was only recorded whether fractures were present, and the actual number of fractures, the types of fractures, and their exact locations were not assessed. This was due to the highly fragmented nature of the skulls, and the difficulty in distinguishing fractures from unfused pediatric sutures, which required further exploration. During forensic anthropological examinations, the aim of trauma analysis is to document the location and characteristics of each skull fracture, which could aid in determining the minimum number of blows inflicted and to decide whether the trauma inflicted was accidental or abusive. The potential of various imaging modalities in performing these skeletal trauma assessments therefore needs to be evaluated as these may be the only tools available, such as is the case in South Africa where the Lodox® scanner is often the only radiological method available in Forensic Pathology Services laboratories. Therefore, the aim of this study was to compare the sensitivities and specificities of CT, X-ray, and Lodox® scans in detecting the number, location, and typeof skull fractures in cases of piglets subjected to blunt force trauma, using the skeletonized remains as the reference standard.

Highlights

- Skull fracture number, location, and type detected using imaging methods have rarely been assessed.
- Lodox® has not yet been included in such an assessment and is commonly used in mortuaries.
- Cranial fractures, especially facial, were missed with all methods, especially X-ray and Lodox®.
- CT is the preferred method, but when used it should be noted that some fractures may be missed.
- If X-ray or Lodox® is used, multiple images from various angles should be taken.

2 | MATERIALS AND METHODS

Ten piglets, each weighing between 5 and 15 kg and who had died of natural causes, were used in this study. The skull of each piglet was subjected to blunt force trauma and was struck between one and five times with a 500 g, 55 × 55 mm rubber mallet, postmortem. Trauma was inflicted by an independent observer so that the principal investigator was blind to the number of blows inflicted to each skull. An additional piglet with no trauma was also included in this study as a negative control. Ethical clearance to conduct this study was obtained from the Animal Research Ethics Committee at the University of the Witwatersrand (Clearance Certificate No 2019/04/27/O), and permission was also obtained from the South African Department of Agriculture, Forestry and Fisheries.

Following the infliction of blunt force trauma, piglets underwent CT, X-ray, and Lodox® scanning. Helical CT scans (64 Slice CT Brilliance; 120 kV; 150 mA; 1.5 mm slice thickness) were taken at the Department of Radiology at the Wits Donald Gordon Medical Centre. Ventrodorsal and left and right lateral X-rays of the skull were taken at the Central Animal Services at the University of the Witwatersrand, and ventrodorsal and left and right lateral Lodox® scans were taken at the Johannesburg Forensic Pathology Services.

The number, location, and type of fractures visible on each skull using each imaging modality were recorded. The number of fractures was counted as the overall number of fractures present on the skull, while the presence of a fracture on a specific bone or skull region was considered the fracture location. Fracture locations were scored according to the locations listed in Table 1. The location of simple linear fractures traversing two or more bones was scored as the bone where the majority of the fracture occurred. The location of complex and depressed fractures was scored as the bone where the impact site likely was. Fracture types were classified as either simple linear, complex,

TABLE 1 Sensitivity and specificity of CT, X-ray, and Lodox® scans in detecting the location of skull fractures. All fractures involving sutures are diastatic fractures

	Sensitivity (%)/Specificity (%)		
Location of fracture	CT	X-ray	Lodox®
Neurocranium	**49.1/100.0**	**24.5/99.7**	**26.4/100.0**
Frontal	45.5/100.0	54.5/100.0	54.5/100.0
Parietal	66.7/100.0	66.7/100.0	58.3/100.0
Occipital	62.5/100.0	37.5/100.0	62.5/100.0
Temporal	61.5/100.0	15.4/100.0	15.4/100.0
Skull base	54.5/100.0	6.1/98.5	12.1/100.0
Coronal suture	60.0/100.0	40/100.0	60/100.0
Sagittal suture	16.7/100.0	0.0/100.0	0.0/100.0
Face	**37.5/100.0**	**15.4/100.0**	**12.5/100.0**
Nasals/maxilla	18.2/100.0	6.1/100.0	9.1/100.0
Orbit	50.0/100.0	37.5/100.0	12.5/100.0
Zygomatic arch	45.5/100.0	14.5/100.0	14.5/100.0
Fronto-nasal suture	44.4/100.0	33.3/100.0	11.1/100.0
Fronto-maxillary suture	0.0/100.0	0.0/100.0	0.0/100.0
Mandible	**74.2/99.2**	**38.7/100.0**	**48.4/100.0**
Mandibular ramus	68.4/96.8	26.3/100.0	31.6/100.0
Mandibular body	90.0/100.0	70.0/100.0	80.0/100.0
Mandibular symphysis	50.0/100.0	0.0/100.0	50.0/100.0
Total	**47.3/97.8**	**22.4/97.7**	**23.2/100.0**

depressed, or diastatic [1,2] (Table 2). Simple linear fractures were determined as single, isolated, generally straight fractures. Both complex and depressed fractures were classified as having two or more, often interconnected, fracture lines likely associated with a single point of impact, and depressed fractures were distinguished as having an area of depression at the point of impact. Individual fracture lines were not counted but were only scored as one complex/depressed fracture. Diastatic fractures were those involving the sutures (outlined inTable 1), causing a widening of the suture. Fractures were identified as non-anatomical radiotransparencies and compact bone discontinuities, and all scans and images were read by the principal investigator,who had received training in the basics of radiology and interpreting radiological images prior to the start of this study. All images were read

TABLE 2 Sensitivity and specificity of CT, X-ray, and Lodox® scans in detecting the type of skull fracture

	Sensitivity (%)/Specificity (%)		
Type of fracture	CT	X-ray	Lodox®
Simple linear	44.3/98.4	16.5/95.3	22.6/95.6
Complex	51.2/98.0	15.5/97.0	13.1/98.0
Depressed	54.5/100.0	27.3/100.0	9.1/100.0
Diastatic	29.0/100.0	16.1/100.0	16.1/100.0
Total	46.1/99.4	16.6/97.6	17.8/97.9

using RadiAnt DICOM Viewer, version 5.5.1, and when examining CT scans, both slice images and three-dimensional volume renderings of each bone were used to detect trauma.

The skulls of the piglets were then gently simmered and manually cleaned in the School of Anatomical Sciences, University of the Witwatersrand. The skeletonized skulls were carefully reconstructed by gluing them back together, being careful not to introduce additional trauma, and the sensitivity and specificity of each diagnostic method were then assessed by comparing the readings to the true locations and types of fractures present on the dry bone, which was the reference standard. Sensitivity refers to the imaging modality's ability to correctly identify fractures and was calculated by dividing the number of true-positives (fracture seen both on both dry bone and radiologically) by the sum of the numbers of true-positives and false-negatives (fracture seen on dry bone but not radiologically) [7,16]. Specificity refers to the imaging modality's ability to not incorrectly diagnose the presence of a fracture and was calculated by dividing the number of true-negatives (no fracture seen both on dry bone and radiologically) by the sum of the numbers of true-negatives and false-positives (no fracture seen on dry bone but seen radiologically) [7,16]. One-way ANOVA with number of fractures as the independent variable and two-way ANOVA with imaging modality and location/type of fracture as the independent factors were used to assess differences in the mean number of fractures detected. Differences were considered significant when $p < 0.05$.

Intra- and inter-observer repeatability for detecting the number, location, and type of fractures using CT, X-ray, and Lodox® scans was assessed using Cohen's kappa. The principal investigator reread the scans of 5 piglets to calculate the intra-observer repeatability, while a professional radiologist read the scans of the same 5 piglets to assess inter-observer repeatability. All statistical analyses were conducted using IBM® SPSS® version 25.0.

3 | RESULTS

3.1 | Repeatability

Intra-observer repeatability for detecting the number, location, and type of skull fracture was almost perfect for all imaging modalities, with kappa values ranging between 0.95 and 1.00. Kappa values were also high for inter-observer repeatability of fracture number, location, and type using CT (0.75 for all three), X-ray (0.78, 0.78, and 0.74, respectively), and Lodox® scans (0.83, 0.83, and 0.78, respectively).

3.2 | Number of fractures

A total of 241 fractures were present on the skulls of the piglets. There were 210 cranial fractures and 31 mandibular fractures. Cranial fractures included 106 fractures of the neurocranium and 104 facial fractures. Of the total 241 fractures, CT scans correctly identified 114 (sensitivity of 47.3%; specificity of 97.8%), while X-rays and Lodox® scans correctly detected 54 (sensitivity of 22.4%; specificity of 97.7%) and 56 (sensitivity of 23.2%; specificity of 100%), respectively. Results of the one-way ANOVA showed a significant difference in the overall number of fractures detected between dry bone and all imaging modalities ($p < 0.05$). CT also differed significantly from both X-ray and Lodox® ($p < 0.05$), but X-ray and Lodox® did not differ significantly ($p > 0.05$).

3.3 | Location of fractures

For identifying the correct location of a fracture, CTs had a sensitivity of 47.3% (97.8% specificity), X-rays 22.4% (97.7% specificity), and Lodox® 23.2% (100% specificity) (Table 1). Sensitivities and specificities, respectively, for identifying fractures of the cranium were 43.3% and 100% for CTs, 20.0% and 99.8% for X-rays, and 19.5% and 100% for Lodox®. The sensitivity of mandibular fracture detection was 74.2% (specificity: 99.2%) for CT scans, 38.7% (specificity: 100%) for X-rays, and 48.4% (specificity: 100%) for Lodox® scans. For CT scans, the sensitivities of detecting fractures of the neurocranium and face were 49.1% and 37.5%, respectively, with a specificity of 100% for both regions. When considering X-rays, fracture detection sensitivity for the neurocranium was 24.5% with a specificity of 99.7% and for the face 15.4% with a specificity of 100%. Lodox® scans had a sensitivity and specificity, respectively, of 26.4% and 100% for the neurocranium, and 12.5% and 100% for facial fractures.

The skull bone or region with the highest sensitivity was the mandibular body for all imaging modalities (90% for CTs, 70% for X-rays and 80% for Lodox®), while all diagnostic tools had a 0% sensitivity for detecting diastatic fractures of the fronto-maxillary suture (Table 1). X-rays and Lodox® scans also had a 0% sensitivity for detecting diastatic fractures of the sagittal suture, and X-rays had a 0% sensitivity for diastatic fractures of the mandibular symphysis (Table 1). CT scans had the highest sensitivity for almost all locations, and in general, Lodox® had higher sensitivities compared to X-rays (Table 1). In one case with 17 fractures, both X-ray and Lodox® did not detect any fractures, all of which were fractures of the face and skull base, as well as diastatic fractures.

Two-way ANOVA tests showed that only parietal fractures, coronal suture diastatic fractures, mandibular body fractures, and mandibular symphysis diastatic fractures did not differ significantly from dry bone for any radiological method ($p > 0.05$). In addition, CT did not differ significantly from the dry bone for occipital and mandibular ramus fractures, while Lodox® also did not differ significantly for occipital fractures ($p < 0.05$). CT only differed significantly from X-ray and Lodox® for nasal/maxillary, skull base, and zygomatic arch fractures ($p < 0.05$), while X-ray and Lodox® were not significantly different for any fracture location ($p > 0.05$).

3.4 | Type of fractures

A total of 115 simple linear, 84 complex, 11 depressed and 31 diastatic fractures were noted on the dry bones. For correctly detecting the type of fracture, CTs had a sensitivity of 46.1% (99.4% specificity), X-rays a sensitivity of 16.6% (97.6% specificity), and Lodox® a sensitivity of 17.8% (97.9% specificity) (Table 2; Figures 1–5). CT scans had the highest sensitivity for all fracture types, while X-rays had higher sensitivities than Lodox® for complex and depressed fractures (Table 2). For CT scans, depressed fractures had the highest sensitivity (54.5%, with a specificity of 100%),

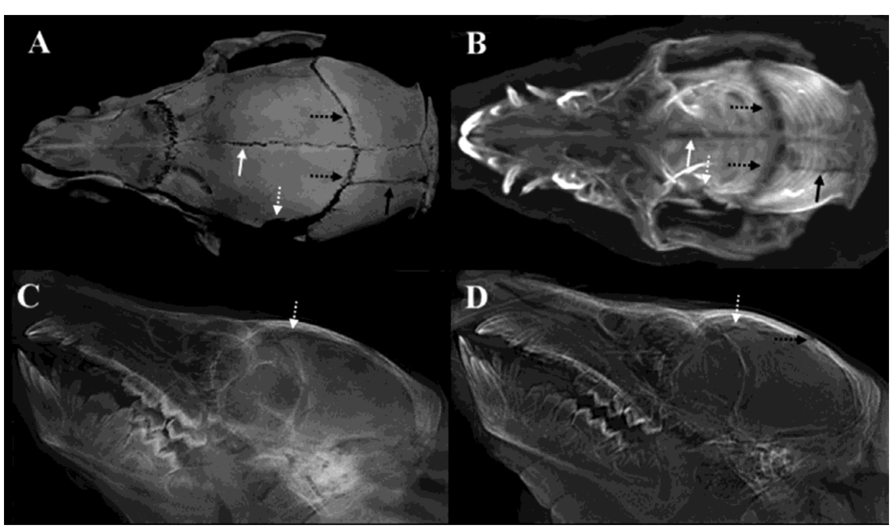

FIGURE 1 Parietal simple linear (solid black arrow) and sagittal diastatic fracture (solid white arrow) as seen on dry bone (A) and CT (B), but not visible on X-ray (C) or Lodox® (D) on any radiographic views. Frontal simple linear fracture (white dashed arrow) seen on dry bone (A) and all three imaging modalities (B–D), and coronal diastatic fracture (dashed black arrows) seen on dry bone (A), CT (B), and Lodox® (D), but not on X-ray (C)

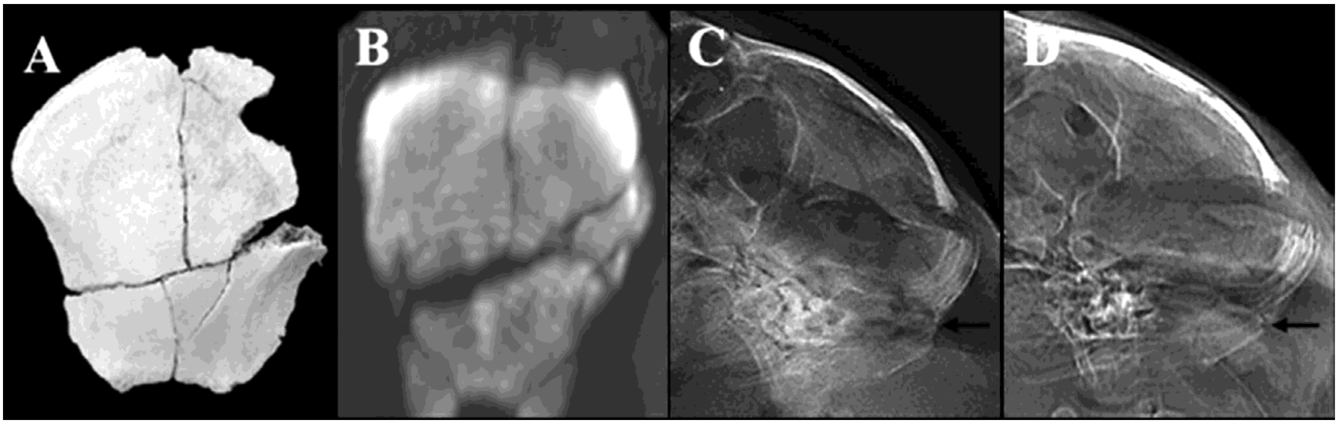

FIGURE 2 Complex occipital fracture as seen on dry bone (A) and CT (B) but classified as simple linear (solid black arrow) on X-ray (C) and Lodox® (D) on all radiographic views

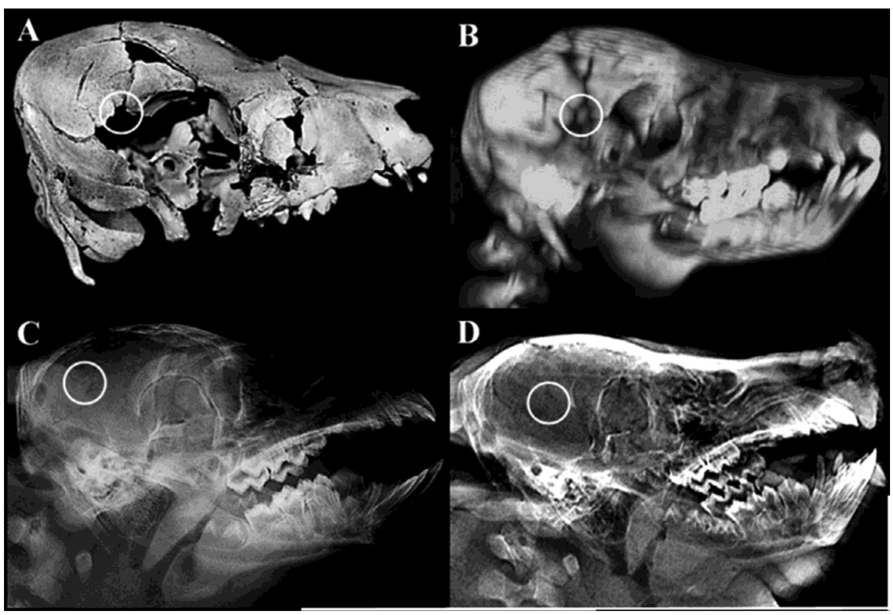

FIGURE 3 Depressed fracture of the parietal bone as seen on dry bone (A), CT (B), X-ray (C), and Lodox® (D), with central depressed part (white circle), and radiating and concentric fracture lines. Individual radiating and concentric fracture lines were not counted, and this was only scored as one depressed fracture

while the lowest sensitivity was for diastatic fractures (29%, with a specificity of 100%). For X-rays, depressed fractures also had the highest sensitivity (27.3% sensitivity; 100% specificity), and complex fractures had the lowest (15.5% sensitivity; 97% specificity). For Lodox® scans, simple linear fractures had the highest sensitivity (22.6% with a 95.6% specificity), and depressed fractures had the lowest sensitivity (9.1% with a 100% specificity). For both X-rays and Lodox® scans, complex and depressed fractures were more likely to be classified as simple linear fractures (Figures 2 and 5). Results of the two-way ANOVA revealed significant differences between the dry bone and all imaging methods for all fracture types ($p < 0.05$), except for depressed fractures detected by CT scans ($p > 0.05$). CT did not differ from X-ray and Lodox®for simple linear and depressed fractures ($p > 0.05$), and X-rays and Lodox® scans did not differ significantly for any fracture type ($p > 0.05$).

4 | DISCUSSION

Skull fractures are common in children, both as a result of accidental and abusive trauma [1–3]. The accurate detection of these fractures is critical in order to determine possible cause and manner of death [3–8]. Furthermore, as is common during forensic anthropological examinations, assessing the location and pattern of each skull fracture has implications for determining the minimum number of blows inflicted, as well as potentially distinguishing between accidental and abusive trauma. In this study,

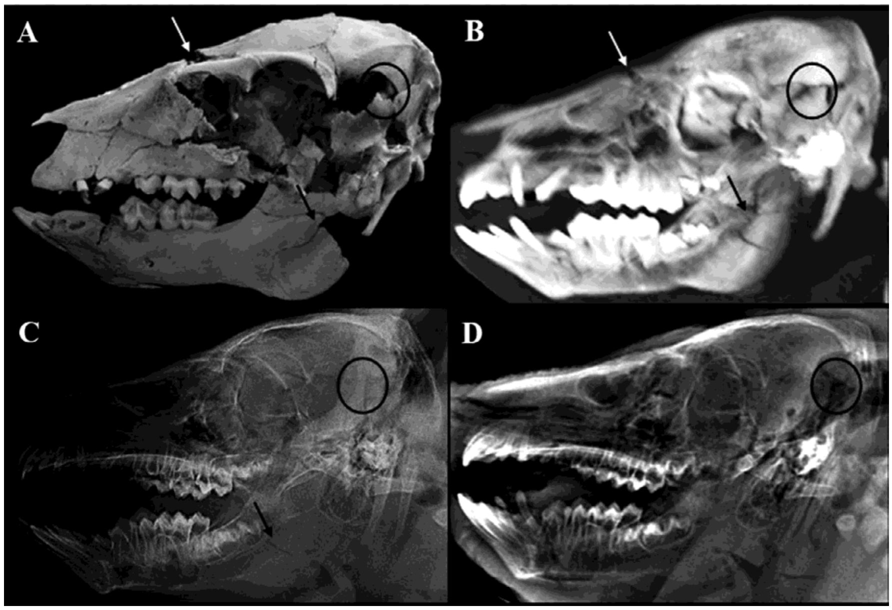

FIGURE 4 Parietal complex fracture (black circle) as seen on dry bone (A), CT (B), X-ray (C), and Lodox® (D). A fronto-nasal diastatic fracture (white arrow) is seen on dry bone (A) and CT (B), but not on X-ray (C) and Lodox® (D). A complex mandibular ramus fracture (black arrow) is also seen on dry bone (A) and CT (B), but is classified as simple linear on X-ray (C) and not visible on Lodox® (D)

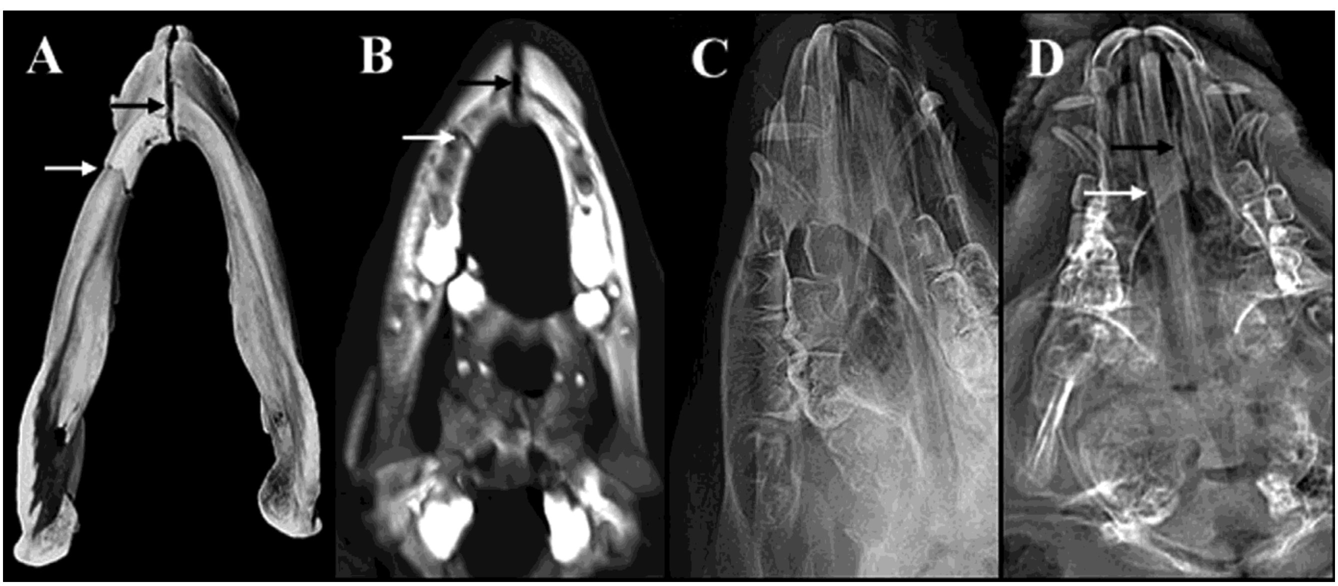

FIGURE 5 Simple linear fracture of the mandibular body (white arrow) and diastatic fracture of the mandibular symphysis (black arrow) as seen on dry bone (A), CT (B), and Lodox® (D), but not visible on X-ray (C)

the sensitivities of CT, X-ray, and Lodox® scans for detecting the number, location, and type of pediatric skull fractures were assessed using a piglet model.

Both intra- and inter-observer agreement for detecting skull fractures was substantial to almost perfect for all imaging modalities [17]. Agreement was slightly higher for detecting the location of fractures than for detecting the type of fractures for all imaging methods. While repeatability was similar for CTs and X-rays, repeatability was highest for Lodox® scans for both fracture location and type. The substantial to almost perfect inter-observer agreement between the principle investigator and the professional radiologist indicates that the fractures detected using each imaging modality can be considered accurate.

The sensitivity for detecting the correct number of fractures at the correct location was 47.3% for CT scans, 22.4% for X-rays, and 23.2% for Lodox® scans. While CTs had the highest sensitivity for detecting fracture location, more than half of all fractures were undetected. These results are different from those reported by Cattaneo et al. [8] who found that CT scans had a high rate of false-positives and detected more fractures than were actually present. Even more alarming were the results for X-rays and Lodox® scans, the modalities generally used when conducting skeletal surveys in hospitals and morgues [18,19], which only detected approximately 1/5th of all skull fractures. The sensitivity for X-rays was only slightly lower than that reported by Cattaneo et al. [8], where X-rays detected only a third of all pediatric skull fractures. Sensitivities for CTs and X-rays in the present study were also lower than those reported by Martin et al. [12] who found sensitivities of 81% for CTs and 77-81% for X-rays, and Culotta et al. [5] who cited a 97% sensitivity for CTs and 90% for X-rays. However, both authors used either the CT or X-ray scans as the gold standard, not osteological analysis. Sensitivities for the detection of adult skull fractures appear to be better than those found in the present study, with sensitivities of 85.4% reported for CT scans [20] and 71.4% for X-rays [21]. The lower sensitivities found in the present study for pediatric compared to adult skull fractures is likely due to the presence of unfused sutures and incomplete fractures in pediatric skulls, which may make fracture detection more difficult [22].

All imaging modalities were more sensitive for identifying fractures of the mandible than fractures of the cranium. For the mandible, all radiological techniques detected almost all body fractures, while sensitivity for fractures of the ramus was much lower. This is significant since the ramus is often fractured as a result of blows to the face or jaw, which commonly occur during both accidents and incidences of abuse [1,9,23]. Since most of these fractures are missed, many cases of abuse which involve blows to the face may go undiagnosed, especially when other facial fractures as a result of these blows are also not detected, as is the case in the present study. Only 37.5% of facial fractures were detected by CTs, while 15.4% and 12.5% were detected using X-rays and Lodox®, respectively. The anatomy of the piglet skull, which has a more elongated snout and face compared to the more orthognathic face of humans, may have contributed to the lower sensitivities for detecting facial fractures, particularly using X-rays and Lodox® scans. In addition, the presence of paranasal sinuses in facial structures may also pose a challenge for identifying fractures in these regions, as could the presence of unfused sutures in pediatric skulls.

All imaging methods also had low sensitivities for detecting fractures of the neurocranium, with CTs only detecting half of all fractures and X-rays and Lodox® detecting only a quarter of fractures. The majority of fractures missed were those of the skull base and diastatic fractures. In addition, most temporal fractures, and many parietal and frontal fractures close to the vertex of the skull, such as the parietal fracture seen in Figure 1, were undetected using X-rays and Lodox®. The low sensitivities for detecting skull fractures in the correct locations may, in the case of CTs, be the result of the orientation of the scan slice with respect to that of the fracture [8,12]. In the case of X-rays and Lodox® scans, superimposition of bones, very thin or incomplete fractures, and the limited three-views of the skull (anteroposterior and left and right lateral) may limit the detectability of fractures and cause the underestimation of the number of fractures present [4,7,8,24]. Since CT scans have the highest sensitivity for detecting fractures at the correct location, children with suspected cranial fractures should undergo CT scans where possible rather than X-rays and Lodox®, which are insensitive and add no diagnostic value over CTs, a recommendation also made by a number of other authors [3,4,12]. Moreover, CT scans have the additional advantage of visualizing intracranial injury and trauma [5,12]. However, the use of CT scans is not always feasible, especially in hospitals or morgues with limited resources and funding [25,26]. Although X-rays and Lodox® are not sufficiently sensitive for detecting skull fractures in piglets, results for human infants and children may be different and requires some investigation. Additional views of the skull, such as the angled "Towne" and "Waters" views, may be beneficial and improve visualization of fractures of the neurocranium and face which may not be detected on the anteroposterior and lateral views. Many pediatric radiographic guidelines recommend using only these twoviews of the skull, or only encourage additional views if fractures are already detected on the anteroposterior or lateral view [1,24,27–30].

The sensitivity for identifying the correct type of skull fracture was 46.1% for CTs, 16.6% for X-rays and 17.8% for Lodox®. CTs had the highest sensitivity for all fracture types, similar to results reported by Kim et al. [4], who found CTs to be more sensitive in identifying both depressed and diastatic fractures compared to X-rays. For all imaging modalities, sensitivity was higher for simple linear fractures than for diastatic fractures, results also observed by Mulroy et al. [7], likely because diastatic fractures may be more difficult to distinguish from normal sutures, particularly the unfused sutures of infants and children. However, sensitivities for detecting simple linear fractures using X-rays and Lodox® scans were still low (16.5% and 22.6%, respectively), which may be because very thin or incom- plete linear fractures are not easily identifiable on plain radiographs [7]. The very low sensitivities for detecting the type of skull fracture, particularly for X-rays and Lodox® scans, may prevent the accu- rate diagnosis of physical child abuse, since it is possible that some fracture types, such as complex, depressed and diastatic fractures, are more indicative of abuse than accidental trauma [1,2,31–33]. Moreover, certain fracture types such as diastatic and depressed fractures may be more associated with intracranial trauma [4,34], and thus, the low sensitivities for detecting depressed and diastatic fractures (Table 2), specifically with X-rays and Lodox®, may mean that intracranial injuries are not suspected or detected, especially when CT scans are not available.

Specificities for all fracture locations and types for all imaging modalities were extremely high, ranging between 92.5% and 100.0% (Tables 1 and 2), comparable to those of other studies [5,7,12]. This indicates that very few false-positive fracture identifications were made, which is significant since it reduces the risk of incorrectly diagnosingphysical child abuse, which could result in unwarranted and potentially traumatic investigations in non-abusive situations [1,35]. However, the very low sensitivities for all radiological methods in detecting pediatric skull fractures means that many cases of physical child abuse may be undetected and undiagnosed, which may increase the risk that a child is returned to an abusive situation and subsequently re-injured [1,10,35]. In postmortem cases, osteological analysis should always be the method of choice when evaluating pediatric skull trauma and can be used in conjunction with CT scans which have the highest sensitivity. However, when dry bone analysis or even autopsy is not possible, as with living children, CT scans should be the radiological method employed. However, while X-ray and Lodox® should not be used to replace autopsy, dry bone, or CT evaluations, they are often the only radiological resource available. Therefore, despite their low sensitivities, they may have to be relied upon to detect pediatric skull fracture locations and types.

A potential limitation of this study, as is with all forensic anthropological examinations, is that the maceration and manual reconstruction of the skulls may have introduced additional damage or trauma not present during the scanning process, despite how carefully the skulls were handled. Furthermore, the radiologist employed to perform the inter-observer repeatability was not specifically trained in pig anatomy, and therefore, the detection of fractures may have been more difficult and may have resulted in some fractures not being detected. Future research should consider the use of a radiologist trained in comparative anatomy and osteology.

In summary, the results of this study are a stark reminder that no radiological technique is infallible, and no matter what technique is used there is always the possibility that trauma can be missed. This reiterates the fact that clinicians and forensic experts should always have a high index of suspicion and realize that it is relatively easy to miss fractures on imaging modalities. Therefore, the clinical picture and associated information should always be kept in mind.

5 | CONCLUSION

The detection of pediatric skull fractures is critical in diagnosing victims of abuse and may also have implications for determining cause and manner of death. This study assessed the sensitivities of CT, X-ray, and Lodox® scans for detecting the number, location, and typeof pediatric skull fractures. While specificities for all imaging modalities were high, sensitivities were very low, which may increase the risk of fractures and potential victims of abuse being unidentified. Osteological analysis therefore remains the gold standard and is the best method of choice to assess skull trauma in children whenever possible or practical. However, when this is not possible, CT scans should be used to detect skull fractures. In cases when even CTs are not feasible or available, and X-rays and Lodox® have to be used, although not recommended, additional radiographic views of the skull may improve the detection of skull fractures.

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