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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 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. 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 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.

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 type of 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

Location of fracture	Sensitivity (%)/Specificity (%) 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 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.

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	44.3/98.4	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

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%),

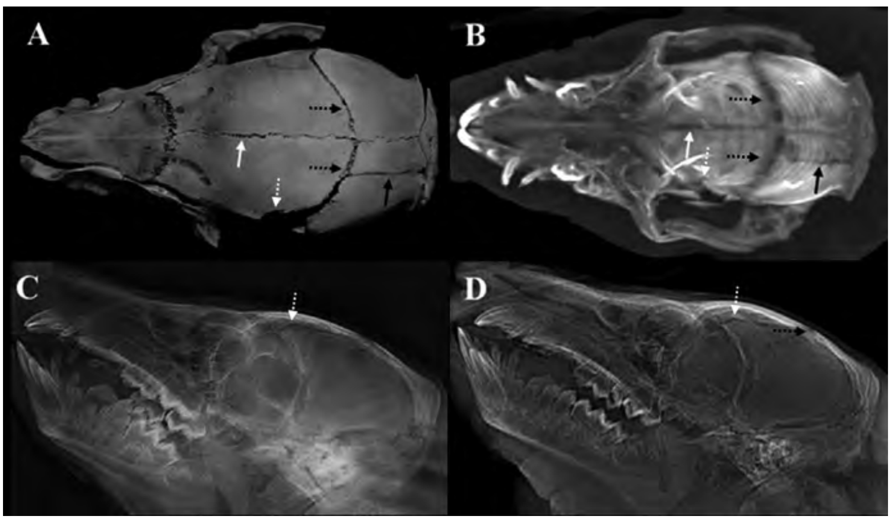

FIGURE 1 Parietal simple linear (solid black arrow) and sagittal diastatic fracture (solid white arrow) as seen on dry bone (A) and CT (B), but not visible on X-ray (C) or Lodox® (D) on any radiographic views. Frontal simple linear fracture (white dashed arrow) seen on dry bone (A) and all three imaging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

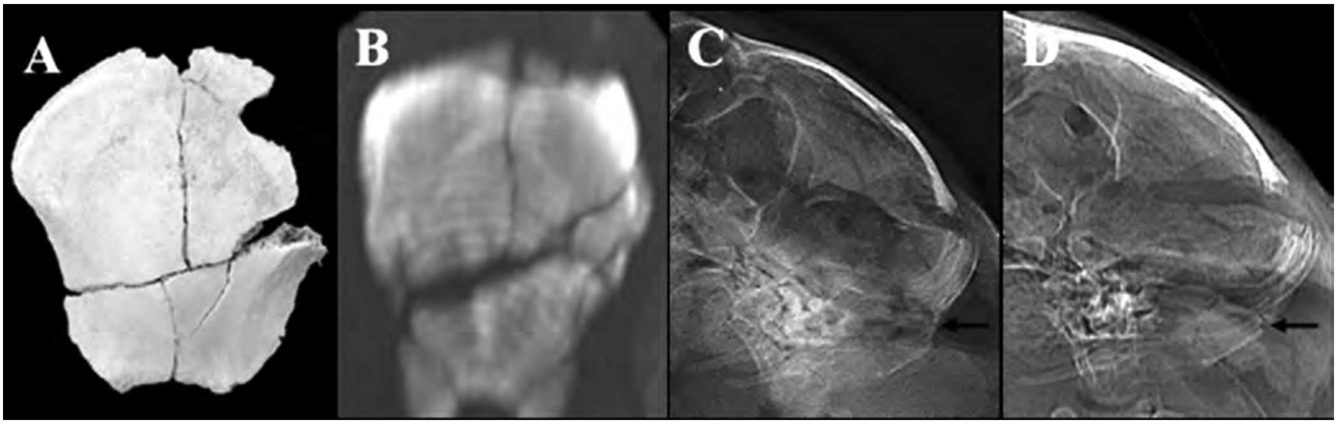

FIGURE 2 Complex occipital fracture as seen on dry bone (A) and CT (B) but classified as simple linear (solid black arrow) on X-ray (C) and Lodox® (D) on all radiographic views

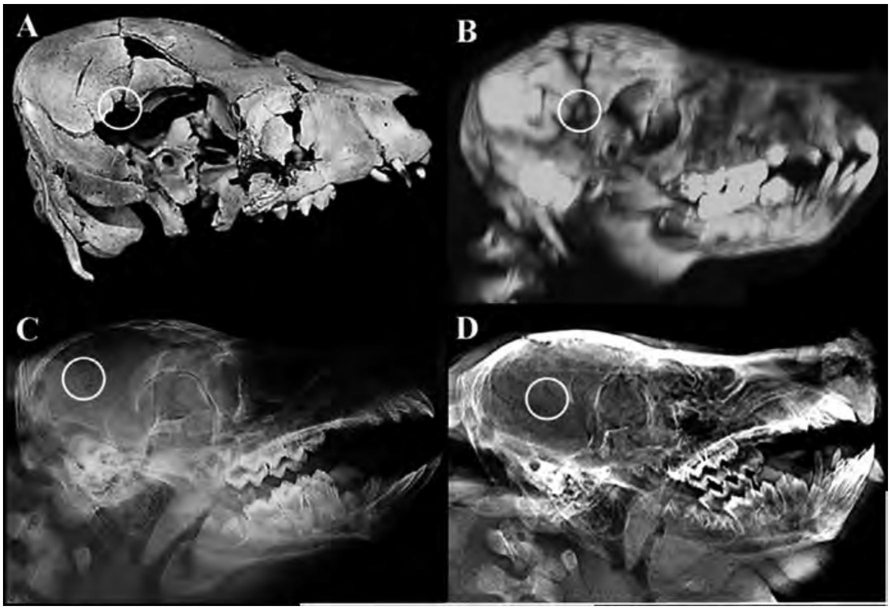

FIGURE 3 Depressed fracture of the parietal bone as seen on dry bone (A), CT (B), X-ray (C), and Lodox® (D), with central depressed part (white circle), and radiating and concentric fracture lines. Individual radiating and concentric fracture lines were not counted, and this was only scored as one depressed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

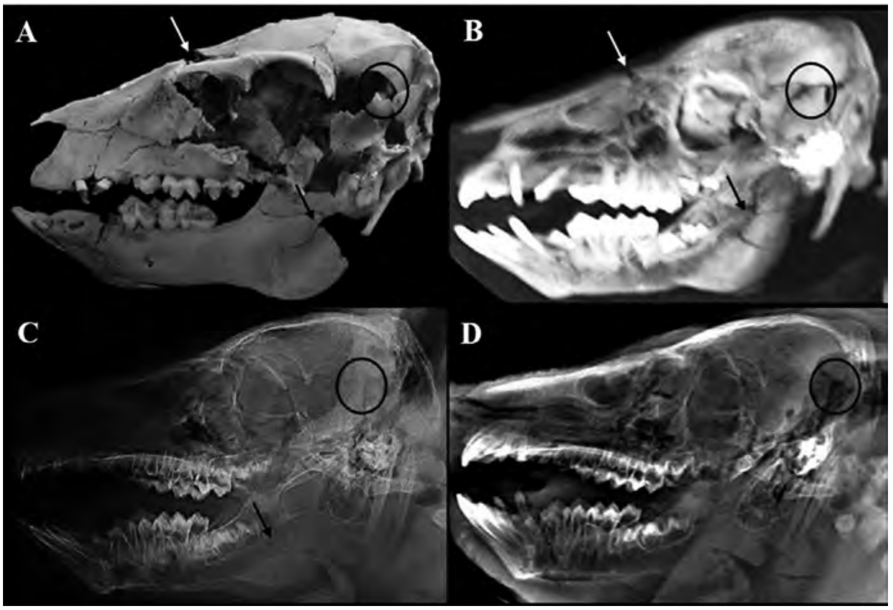

FIGURE 4 Parietal complex fracture (black circle) as seen on dry bone (A), CT (B), X-ray (C), and Lodox® (D). A fronto-nasal diastatic fracture (white arrow) is seen on dry bone (A) and CT (B), but not on X-ray (C) and Lodox® (D). A complex mandibular ramus fracture (black arrow) is also seen on dry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

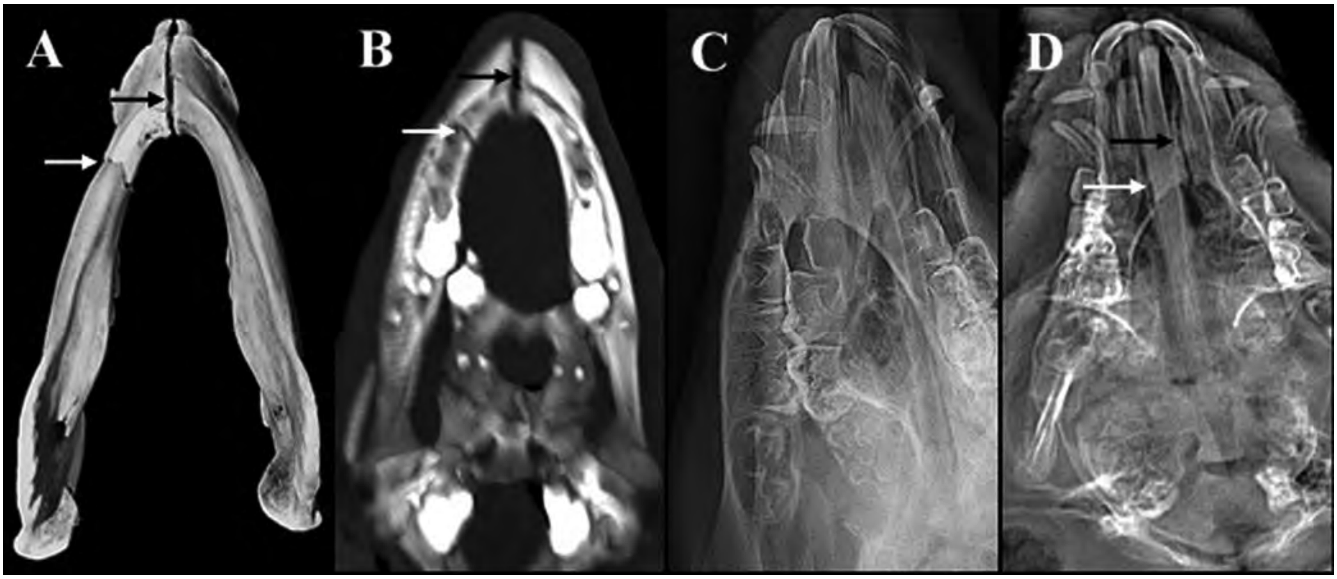

FIGURE 5 Simple linear fracture of the mandibular body (white arrow) and diastatic fracture of the mandibular symphysis (black arrow) as seen on dry bone (A), CT (B), and Lodox® (D), but not visible on X-ray (C)

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 incomplete 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 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 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 type of 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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