



The utility of computed tomography in evaluating rib fractures in live children investigated for suspected physical abuse

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Declaration

I, Nasser Alzahrani, confirm that the Thesis is my own work. I am aware of the University's Guidance on the Use of Unfair Means (www.sheffield.ac.uk/ssid/unfair-means). This work has not been previously been presented for an award at this, or any other, university.

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Abstract

Rib fractures are strongly associated with physical abuse in infants and young children. Computed tomography (CT) may be an accurate diagnostic tool when compared to chest radiography, the current imaging standard, for detecting rib fractures in children with suspected physical abuse (SPA). A systematic review showed that CT has better diagnostic accuracy than initial chest radiographs (CXR) for detecting rib fractures in children with SPA.

A multicentre retrospective observational study was conducted to assess the diagnostic accuracy of chest CT for detecting rib fractures in children under 2 years investigated for SPA, using initial and follow-up CXRs as the reference standard. An analysis of 64 of these cases showed overall accuracy of CT as 83.72%, 93.46% and 96.47%, per-patient, rib and location, respectively. A sub-study of the multicentre study, conducted to assess the feasibility of dating rib fractures using CT, showed substantial agreement between chest radiography and CT in estimating broad timeframes for rib fracture dating (acute vs. healing) (κ (k)=0.76). Callus formation features on CT scans showed a discriminative pattern for estimating the specific age range of rib fractures.

Concerns regarding higher radiation exposure of CT compared to chest radiography have made CT less desirable in routine clinical practice when evaluating children with SPA. A study using post-mortem animal models at two paediatric centres to optimise chest CT scanning parameters gave these sets with the lowest radiation dose and acceptable diagnostic image quality (≥ 3 out of 5): Centre 1: 80 kV/30 mA, effective dose 0.32 millisieverts (mSv), 93.5% sensitivity; Centre 2: 80 kV/40 mA, effective dose 0.2 mSv, 84.3% sensitivity.

Compared to the current clinical standard (initial and follow-up CXRs), chest CT shows high diagnostic accuracy. Furthermore, dating rib fractures from chest CT and optimising its radiation dose seems to be possible.

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Background

I earned a BSc in Diagnostic Radiology from King Abdulaziz University, Kingdom of Saudi Arabia and an MSc in Medical Imaging from Leeds University, United Kingdom.

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List of abbreviations

3D	Three-dimensional
3DVR	Three-dimensional volume rendering
ACR	American College of Radiology
ADMIRE	Advanced Modelled Iterative Reconstruction
AI	Artificial intelligence
ALARA	As low as reasonably achievable
AP	Anteroposterior
ASIR	Adaptive Statistical Iterative Reconstruction
AUC	Area under the curve
CCJ	Costochondral junction
CI	Confidence interval
CPR	Cardiopulmonary resuscitation
CT	Computed tomography
CXR	Chest radiograph
DICOM	Digital Imaging and Communications in Medicine
DLP	Dose length product
ED	Effective dose
ESPR	European Society of Paediatric Radiology
F18-NaF	Fluorine-18 sodium fluoride
FN	False negative
FP	False positive
HRA	Health Research Authority
IQR	Interquartile range
K	Kappa
KV	Kilovolts
LDCT	Low-dose computed tomography
m	millisecond
mA	milliampere
MDCT	Multidetector computed tomography
mGy	milligray
mm	millimeter
MPR	Multiplanar reconstructions

MRI	Magnetic resonance imaging
MDP	Methylene diphosphonate
mSv	millisievert
NFSP	National Family Safety Program
NPV	Negative predictive value
PA	Posteroanterior
PACS	Picture archiving and communication system
PET	Positron emission tomography
PM	Post-mortem
PMCT	Post-mortem computed tomography
PPV	Positive predictive value
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
QUADAS-2	Quality Assessment of Diagnostic Accuracy Studies 2
RCoR	Society and College of Radiographers
RCPCH	Royal College of Paediatrics and Child Health
RCR	Royal College of Radiologists
RECEPTOR	Rib fracturE diagnosis in suspeCted abusE: comPUted Tomography Or Radiographs
ROC	Receiver operator characteristic
RSSA	Radiological Society of Saudi Arabia
s	second
SCFHS	Saudi Commission for Health Specialties
SD	Standard deviation
SkS	Skeletal survey
SPA	Suspected physical abuse
SPNBF	Subperiosteal new bone formation
SPR	Society for Pediatric Radiology
SSDE	Size specific dose estimate
SSMRT	Saudi Society of Medical Radiological Technology
TN	True negative
TP	True positive
UK	United Kingdom
WB-MRI	Whole-body magnetic resonance imaging
WHO	World Health Organization

List of conferences and publications arising from this thesis:

- **Alzahrani NM**, Jeanes A, Paddock M, Shuweihdi F, Offiah AC. The diagnostic performance of chest computed tomography for detecting rib fractures in children with suspected physical abuse: a systematic review and meta-analysis. The British Society of Paediatric Radiology (BSPR) Annual Conference, November 2020, Birmingham, United Kingdom, Oral presentation (On-line)
- **Alzahrani NM**, Jeanes A, Paddock M, Shuweihdi F, Offiah AC. The diagnostic performance of chest computed tomography in the detection of rib fractures in children investigated for suspected physical abuse: a systematic review and meta-analysis. *Eur Radiol* 31, 7088–7097 (2021). <https://doi.org/10.1007/s00330-021-07775-3>
- **Alzahrani NM**, Jeanes A, Paddock M, Shuweihdi F, Offiah AC. The diagnostic performance of chest computed tomography for detecting rib fractures in children with suspected physical abuse: a systematic review and meta-analysis. The International Pediatric Radiology (IPR) Congress, October 2021, Rome, Italy, Poster presentation (On-line). *Pediatr Radiol* 51 (Suppl 1). <https://doi.org/10.1007/s00247-021-05192-8>
- **Alzahrani NM**, Paddock M, Jeanes A, Shuweihdi F, Offiah AC. Professional practice and awareness of child abuse among radiologists and radiologic technologists: results from Saudi Arabia. The European Society of Paediatric Radiology (ESPR) Annual Meeting, June 2022, Marseille, France, Poster presentation. *Pediatr Radiol* 52 (Suppl 2). <https://doi.org/10.1007/s00247-022-05370-2>
- **Alzahrani NM**, Paddock M, Jeanes A, Shuweihdi F, Offiah AC. Professional practice and awareness of child abuse among radiologists and radiologic technologists: results from Saudi Arabia. *Pediatr Radiol* 53, 832–843 (2023). <https://doi.org/10.1007/s00247-022-05561-x>
- **Alzahrani NM**, Paddock M, Jeanes A, Rigby AS, Offiah AC, On behalf of the RECEPTOR Study Research Group. Rib fracture diagnosis in suspected abuse: computed tomography or radiographs (RECEPTOR): a multicentre diagnostic accuracy observational study. The European Society of Paediatric Radiology (ESPR) Annual Meeting, June 2023, Belgrade, Serbia, Oral presentation. *Pediatr Radiol* 53 (Suppl 2). <https://doi.org/10.1007/s00247-023-05678-7>
- **Alzahrani NM**, Paddock M, Jeanes A, Rigby AS, Offiah AC. Computed tomography-based rib fracture dating in children investigated for suspected physical abuse: a feasibility study. The

British Society of Paediatric Radiology (BSPR) Annual Conference, November 2023, Manchester,
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(Appendix 10, page 243)**

Chapter One

Introduction

Contribution Statement:

- Writing: **N.M.A.**
- Supervision and review: A.C.O. and A.J.

1.Introduction

1.1 Rationale for PhD project

Child abuse is a serious universal problem that is often unrecognised until a severe injury occurs [1]. Physical abuse of a child is associated with morbidity and mortality [1]. Rib fractures are highly specific injuries observed among abused infants and young children less than two years old [2]. Although chest radiography is the primary radiological investigation method used in clinical practice to detect rib fractures in children investigated for suspected physical abuse (SPA) [3, 4], undisplaced acute rib fractures are often missed [5, 6]. Therefore, chest radiographs (CXR) are repeated 11 to 14 days after initial CXR to detect acute rib fractures that are not visible via initial imaging [3, 4].

As a result, the presence or absence of undisplaced rib fractures in children investigated for SPA cannot always be confirmed until at least 11 days after initial CXR. The time interval between initial and follow-up imaging is vital because children must stay in a safe place. Furthermore, a return of children for follow-up imaging is not guaranteed [7].

Computed tomography (CT) is a rapid and valuable imaging technology that has been used for decades to diagnose a broad spectrum of pathologies. CT generally offers high sensitivity in detecting bone trauma such as fractures, which are the most common manifestations in children with SPA [8]. However, the associated risks of radiation dose of CT should be considered. In the context of SPA, whilst implementing CT imaging as the primary diagnostic imaging tool may allow improved accuracy for the detection of rib fractures, the benefits and risks must be considered. The risk of exposure to ionizing radiation from CT imaging should be carefully evaluated against the risk of a missed diagnosis of abuse.

Few current studies have shown that CT improves the detection of rib fractures when compared to CXR in live children with SPA [5, 6, 9, 10]. However, these studies have several limitations, including use of inappropriate reference standards (initial CXR only), small sample sizes and few reporters. Therefore, the diagnostic accuracy of CT in the detection of rib fractures in children investigated for SPA must be evaluated using a large sample size as well as the currently utilised imaging method (initial and follow-up CXR) as the reference standard. Employing CT imaging for the detection of rib fractures in children investigated for SPA could provide immediate evidence of abusive injury. Thus, CT may potentially protect children from additional injuries due to being returned to abusive environments.

In cases of SPA, the clinical history offered by caregivers is often incomplete or absent and the injuries are usually unwitnessed [11]. Radiologists are often asked to date injuries to assess discrepancies between the provided history and the timing of the injury [11]. This information is also crucial in decision-making regarding the potential pool of perpetrators and the optimum placement of the child

[11]. Chest radiography as part of the skeletal survey is the current imaging standard for evaluating rib fractures (detection and dating) in children with SPA. Given that chest CT has shown promising results in improving the detection of rib fractures in children with SPA [5, 6, 9, 10], it may become the clinical standard imaging for this purpose. Therefore, there is a need to assess the feasibility of dating rib fractures from CT.

The potential risk of high radiation dose compared to chest radiography could make chest CT a less desirable option in assessing children with SPA. However, the advancements in CT technology over the last decades have led to improvements in its clinical use with lower radiation doses [12, 13]. A low-dose CT (LDCT) protocol has been developed and is used for various CT imaging applications in adults and children [14, 15]. Because children are more radiosensitive [16], it is important to optimise CT protocols to achieve the lowest possible radiation dose while maintaining acceptable diagnostic image quality. If chest CT is to replace the chest radiography in imaging children investigated for SPA, efforts need to be made to develop a LDCT chest protocol in this scenario.

Child abuse is a worldwide problem, estimated to affect up to 1 billion children aged 2–17 years globally per year [17]. Knowledge, awareness and training of healthcare professionals about child abuse are essential for the identification, reporting and managing of suspected child abuse cases. In recent decades, the Saudi Government has worked to improve child welfare by establishing the National Family Safety Program (NFSP), which is particularly focused on preventing child abuse [18, 19]. The NFSP seeks to increase awareness of child abuse, offer a supportive environment for victims of abuse and their families and improve the capabilities of professionals handling these cases [18, 19]. Radiologic technologists and radiologists play an integral role in the diagnosis of children investigated for SPA. To the best of my knowledge, current clinical practice, knowledge and awareness of radiologists and radiologic technologists about child abuse in Saudi Arabia has not been assessed yet.

1.2 Aims and objectives

The overall aim of this thesis is to assess the role of chest CT in evaluation of rib fractures in children investigated for SPA. This thesis also aims to optimise scanning parameters and radiation dose of chest CT for the assessment of rib fractures in infants with SPA. Additionally, the thesis intends to assess current practice, knowledge and awareness of child abuse among radiologic technologists and radiologists in Saudi Arabia.

To achieve these aims, the objectives of this PhD thesis are as follows:

- 1- To systematically review and summarise the findings of the published literature regarding the diagnostic accuracy of CT in children investigated for SPA
- 2- To assess the diagnostic performance of chest CT for detecting rib fractures in children investigated for SPA using initial and follow-up CXRs as a reference standard
- 3- To assess the feasibility of chest CT in dating rib fractures in children with SPA
- 4- To optimise scanning parameters and radiation dose of chest CT imaging for assessing of rib fractures in infants with SPA.
- 5- To assess current practice, knowledge and awareness of child abuse among radiologic technologists and radiologists in Saudi Arabia.

1.3 Thesis organisation

This thesis has been written and presented in a format suitable for publication in a peer-reviewed journal. This thesis format is supported by the University of Sheffield to reduce the time of rewriting publications into thesis chapters and to improve the academic skills of PhD students required for publications.

This PhD thesis has the following chapters:

Chapter One (current chapter) explains the rationale for this PhD project and outlines the aim, objectives and organisation of the thesis.

Chapter Two, the introductory chapter, includes a definition of physical child abuse, the explanation of proposed mechanisms of rib fractures inflicted on children and their related locations, evaluation of methods used to diagnose/exclude rib fractures in children with SPA and a description of the differential diagnoses that may mimic rib fracture in radiological images.

Chapter Three includes the systematic review and meta-analysis of the literature regarding the diagnostic accuracy of chest CT in detecting rib fractures in children investigated for SPA. This chapter has been published as an original article in *European Radiology* (IF:5.9, Q1) (doi.org/10.1007/s00330-021-07775-3)

Chapter Four is a multicentre diagnostic accuracy observational study to assess the diagnostic performance of chest CT for detecting rib fractures in children investigated for SPA using initial and follow-up CXRs as a reference standard. This chapter will be submitted for publication in *Lancet Child and Adolescent Health*.

Chapter Five extends the results of Chapter Four and assesses the feasibility of chest CT in dating rib fractures in children with SPA. This chapter will be submitted for publication in *Pediatric Radiology*.

Chapter Six is an experimental study to optimise radiation dose of chest CT for the diagnosis of rib fractures in infants investigated for SPA. This chapter will be submitted for publication in *Child Abuse & Neglect*.

Chapter Seven includes a survey study to assess professional practice and awareness of child abuse among radiologists and radiologic technologists in Saudi Arabia. This chapter has been published as an original article in *Pediatric Radiology* (IF:2.3, Q2) (doi.org/10.1007/s00247-022-05561-x)

Finally, **Chapter Eight** includes an overall summary and discussion of the studies presented in this thesis as well as directions for future work.

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Chapter Two

Literature review

Contribution Statement:

- Writing: **N.M.A.**
- Supervision and review: A.C.O. and A.J.

2.Literature review

2.1 Child abuse

Child abuse is a serious global problem resulting in severe consequences for affected children, their families and society [1-3]. Child abuse takes different forms and includes neglect and sexual, emotional and physical abuse [1]. There is no universal consensus on the definition of child abuse and its forms, because the definitions vary from concise to comprehensive, depending on the contextual circumstances in which the definition is used (e.g. medical, legislative and cultural) [4]. Child abuse is defined by the World Health Organization (WHO) as follows: 'Child abuse includes all types of physical and/or emotional ill-treatment, sexual abuse, neglect, negligence and commercial or other exploitation, which results in actual or potential harm to the child's health, survival, development or dignity in the context of a relationship of responsibility, trust or power' [5]. It has been estimated that 1 billion children worldwide experience abuse over a period of one year [6], with about half a million children in the United Kingdom (UK) suffering from abuse annually [7].

2.2 Physical child abuse

Physical abuse is the most well-known form of child abuse and is defined by WHO as 'acts that cause actual physical harm or have the potential for harm' [8]. In the UK, physical abuse is defined as 'a form of abuse which may involve hitting, shaking, throwing, poisoning, burning or scalding, drowning, suffocating or otherwise causing physical harm to a child. Physical harm may also be caused when a parent or carer fabricates the symptoms of, or deliberately induces, illness in a child' [9]. Children under two years old, who are nonverbal and nonambulatory, are most at risk for physical abuse [10-13].

Physical abuse is a significant problem that exists worldwide. In the UK, it is estimated that 1 in 11 children are affected by physical abuse annually [14]. However, the prevalence of physical child abuse is likely to be an underestimate. The published literature is based on self-reported and substantiated child abuse cases (i.e., cases that come to the attention of child protection agencies) [3, 15], with several studies demonstrating that self-reported incidents of physical child abuse are higher than those reported by agencies [3, 15-17]. In addition, physical abuse is often hidden from healthcare professionals [15], and the incidence and prevalence of childhood physical abuse vary according to the definition used, with the incidence and prevalence of abuse being higher if the definition used is broader [6].

Physical abuse is a significant cause of childhood morbidity and mortality [1, 2] and has long-term consequences on children's mental and physical health that can continue throughout adulthood [1, 10]. Abused children are at risk of behavioural problems, including depression, drug abuse, physically

aggressive behaviour and poor educational performance [1, 18], with victims of abusive head trauma having a high risk of neurologic disability and cognitive and developmental delay [19, 20].

Various terms in the literature refer to physical child abuse including nonaccidental trauma, nonaccidental injury, abusive trauma and inflicted injury. The term *inflicted injury* may be the most appropriate because it describes an injury occurring due to a person's action without describing the perpetrator's intention [4, 21]. In other words, *inflicted injury* does not necessarily exclude accidental trauma but describes the causal mechanism of injury as being due to the direct action of another individual. For example, an angry caregiver forcefully raises the infant's legs to change a nappy without intending to cause a fracture to the femur. In this case, the injury is inflicted, but it is not reasonable to describe it as a *nonaccidental injury* because the caregiver did not intentionally cause the fractures. Abusive trauma refers to injuries inflicted on a child intentionally. The term 'suspected physical abuse' (SPA) is increasingly being used to describe physical child abuse. In this thesis, the term 'SPA' is used.

2.3 Rib fractures

After cutaneous lesions (e.g. bruises and contusions), fractures are the most common injury in childhood physical abuse [22-24]. Certain fractures are highly specific for physical abuse in the absence of plausible explanation; these include rib fractures, classic metaphyseal lesions (also known as bucket-handle fractures or metaphyseal corner), sternal, scapular or spinous process fractures [13, 25].

Rib fractures are unusual injuries; when seen in adults, they most commonly occur following accidental circumstances such as falls from a height or traffic collisions [4, 26]. Due to the plasticity of the young child's rib cage, which allows their ribs to bend and deform with trauma rather than break [11, 13, 27, 28], rib fractures are uncommon following accidental trauma [28-32]. Thus, when rib fractures are seen in infants and young children, physical abuse has a high probability [13, 22, 31, 33, 34]. Barsness *et al.* [32] reported that 51 out of 62 (82%) children under 3 years of age with rib fractures were physically abused, with a 95% positive predictive value for rib fractures as an indicator of physical abuse. A systematic review conducted by Paine *et al.* [35] found that the prevalence of rib fractures in physically abused children younger than 1 year ranged from 67% to 84%.

2.3.1 Mechanisms and locations of rib fractures

Depending on the mechanism, rib fractures may occur to any of the 12 ribs, and anywhere along the rib arc (Figure 2.1). The published literature lacks consistency in reporting the location of rib fractures [27], resulting in variation in the reported prevalence of rib fracture locations. Some authors report the

anatomical location of fractures, such as rib head fractures and costovertebral fractures [36, 37], whereas others describe the fractures according to the site along the rib arc [32], and some further subdivide the ribs into anterior, anterolateral, lateral, posterolateral and posterior [38].

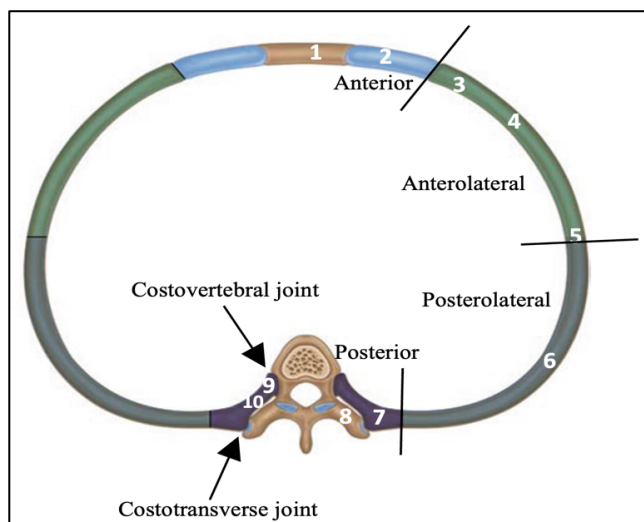


Figure 2.1 Anatomy and regions of a typical rib.

(1) sternum, (2) rib cartilage, (3) sternal end of the rib, (4) anterior costal arch, (5) lateral costal arch, (6) posterolateral costal arch, (7) posterior costal arch (costal tubercle), (8) transverse process of the vertebra, (9) rib head, (10) rib neck (Adapted with permission from Bilo et al. [4])

Generally, rib fractures in abused children are thought to result from the application of compressive squeezing forces [4, 27, 31, 39-42] or direct impact to the chest wall [4, 27, 31]. The most common mechanism of inflicting rib fractures on children is considered to be anteroposterior (AP) compression of the chest [24, 27, 40, 43], whereby the hands of the perpetrator encircle the child's chest, with the thumbs at the front and fingers at the back, forcefully squeezing the chest (Figures 2.2 and 2.3) [27, 40, 43]. Fractures resulting from compression of the chest may occur along the posterior, lateral or anterior arc (Figure 2.4) [27, 39]. Posterior rib fractures are widely considered to be a strong indicator of physical child abuse [25, 31, 32, 34, 37, 41, 44]. The presumed causative mechanism for posterior rib fractures is forceful AP compression of the chest, resulting in leverage of the necks of the posterior ribs over the transverse processes of the thoracic vertebra, which acts as a pivot [24, 27, 40, 45]. Lateral rib fractures are common in physical abuse and are proposed to result from AP compression of the chest, resulting in stress on the outer aspect of the ribs and compression of the inner aspect of the rib. Once the tensile strength of the rib is reached, a fracture results [4, 27, 31, 36, 41, 44, 46]. Anterior rib fractures may also result from AP compression of the chest [30, 32, 37]; it is postulated that the squeezing forces applied

by the adult thumbs, to the front of the chest over the costochondral junctions (CCJ) or sternum, result in inward bending of the CCJ, with subsequent fractures [4, 27, 36, 42].

Lateral compression of the chest (compression from side to side) has also been described as a mechanism for inflicting rib fractures [4, 27, 42, 45], although this is less well documented [27]. Fractures occurring as a result of compressive forces are often bilateral, multiple and sited on adjacent ribs on the same rib arc [4, 39, 42]. Fingertip bruising is the most common sign of injury in AP compression of the chest and is typically seen over the posterior chest next to the spine or anterior chest [4, 45]. However, rib fractures in children with SPA resulting from chest compression are typically occult, and external evidence of injury, such as bruising, is unusual [30, 47].

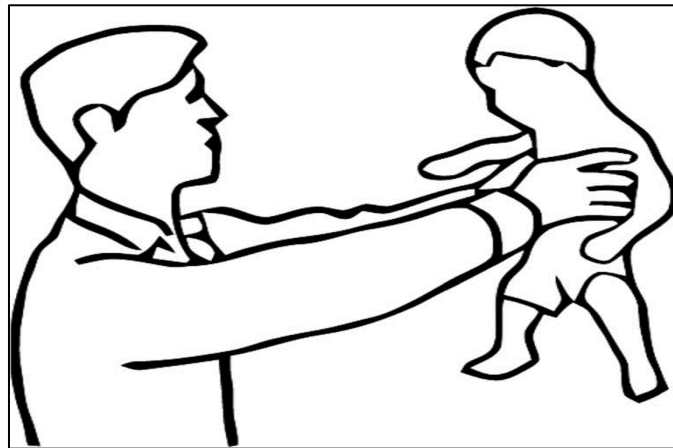


Figure 2.2. The position of a child during an abusive chest compression by a perpetrator (Reproduced with permission from Kriss et al. [41])

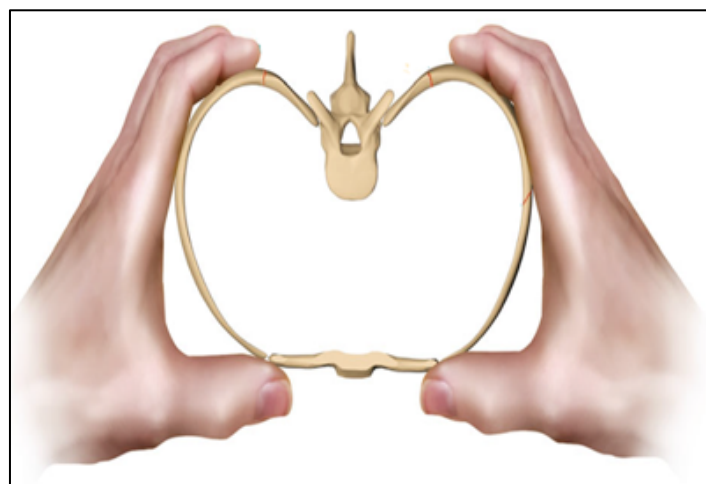


Figure 2.3. Depiction of anteroposterior compression applied to a child's thorax. Red lines indicate the most vulnerable fracture sites (Adapted with permission from Pfeifer et al. [48])

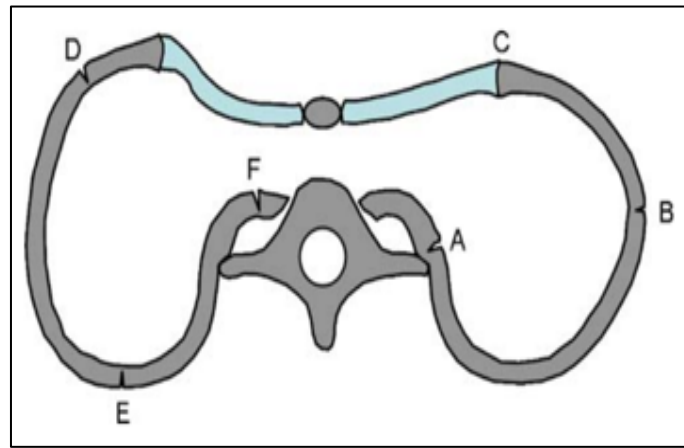


Figure 2.4. Anteroposterior compression to a child's chest can fracture ribs at the following locations: A) costovertebral process articulation, B) lateral arc, C) costochondral junction, D) anterior arc, E) posterior arc, F) rib head (Reproduced with permission from Offiah et al. [13])

Rib fractures may also occur as a result of dynamic impact forces, through the application of a rapid and excessive force to the chest wall (e.g. a direct blow such as punching or kicking) or by rapid deceleration and impact of the chest wall onto a hard or firm object [4, 27, 31]. Impact-type forces typically result in fractures at the site of impact [31]. Posterior rib fractures may result when a child is struck from behind [49], whereas a direct forceful blow to the anterior chest wall could cause anterior rib fractures [42, 45, 50], which often result in additional injury to intra-abdominal organs when the blow is centred upon the lower chest/epigastrium [51]. Rib fractures due to chest compression are more likely to occur in non-ambulant children under 2 years old, whereas rib fractures due to direct trauma are found primarily in children over 2 years old [4, 42].

Although the likely mechanisms involved in the causation of rib fractures in children with SPA are documented in the literature, there is no clear understanding of the degree of force required to cause rib fractures in children [27]. In clinical practice rib fractures are very rare; it is therefore likely that rib fractures do not occur as a result of reasonable, normal everyday handling of children but result from significant forces [4, 21]. Biomechanical studies based on in vitro animal models [40] or finite element modelling [52] could help improve the understanding of the biomechanical mechanisms involved in abusive rib fractures, and further research in this area is needed.

2.3.1.1 Fracture risk from cardiopulmonary resuscitation (CPR)

It has been argued that CPR can result in rib fractures in infants and young children [4]. The traditional method of CPR used in children is called 'two-fingers' in which two fingers are placed over the sternum,

and AP compression is applied with the infant lying on a flat solid surface (Figure 2.5.A) [4, 27]. Rib fractures from the two-finger CPR technique are rare [4, 27].

The current CPR guidelines for paediatric and neonatal patients recommend the two-thumb encircling-hands chest-compression technique [53]. This manner of resuscitation requires encircling the child's chest with the hands, with the fingers are placed on the back to provide posterior stability and the thumbs placed on the lower half of the sternum to apply compression in an AP direction (Figure 2.5.B) [4, 27]. The two-thumb CPR technique resembles the method postulated in injury scenarios resulting from SPA (i.e., abusive compression of an infant's chest). The recommended two-thumb CPR method may pose a greater risk of causing rib fractures in infants than the two-finger CPR method [27] because the two-thumb method may provide a greater magnitude of force and deflection to the infant's chest than the two-finger method. There is debate in the literature about the occurrence of rib fractures from the two-thumb CPR method [4]. Although it has been reported that rib fractures associated with the two-thumb CPR method are uncommon [4, 54, 55], they can occur, typically in the anterior location [55-57].

Posterior rib fractures are uncommon with either the two-finger [4, 58] or two-thumb [4, 54] CPR method. Despite resembling the method used to inflict rib fractures, the two-thumb CPR method is less likely to cause posterior fractures, because trained CPR providers apply pressure to the sternum using the thumbs and employ the other fingers as support to maintain back stability. In contrast, the perpetrator pushing the sternum inwards in abusive compression pushes the posterior part of the ribs from the posterior to the anterior direction, which may lead to leveraging the ribs over the transverse processes [4].

Some studies that have assessed the occurrence of CPR-related rib fractures in children used conventional radiography as a diagnostic imaging method [54, 55, 59]. Arguably, conventional radiography is limited in detecting subtle acute rib fractures [60-62]; using more sensitive imaging tools, such as computed tomography (CT), could provide accurate data regarding the occurrence of rib fractures from CPR in children.

To differentiate between rib fractures resulting from SPA and those related to CPR in infants and young children, a comprehensive history of the CPR procedure is necessary. This history should include details about who performed the CPR, the CPR method used, and where it occurred (at home, during transportation or in a hospital) [4]. Additionally, histological dating of rib fractures in post-mortem (PM) children with SPA facilitates differentiating resuscitation injuries from injuries resulting from SPA [4, 63].

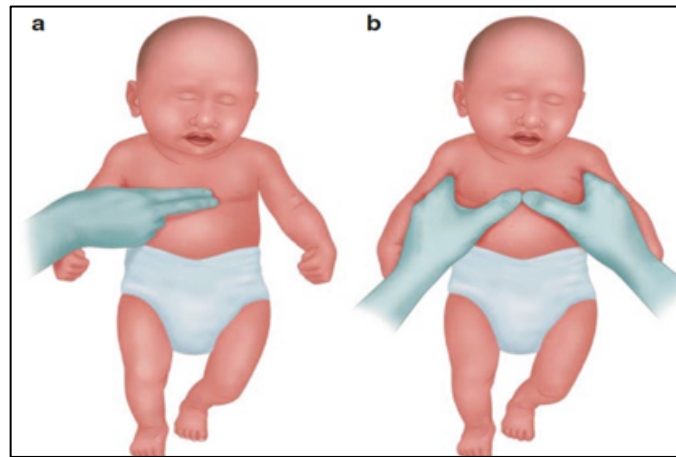


Figure 2.5. Graphic representation of cardiopulmonary resuscitation (CPR) techniques in infants: (A) two-finger CPR technique and (B) two-thumb encircling hands chest compression CPR technique (Reproduced with permission from Bilo et al. [4]).

2.3.2 Diagnosis

No single injury is diagnostic of physical abuse [10, 24, 64]. Diagnosing physical abuse is complex and requires a cooperative multidisciplinary approach [28, 50, 65, 66], including an accurate history and detailed evaluation of any incident, a thorough clinical evaluation of the child and imaging following recommended guidelines where available [1, 10, 28, 65, 67].

Rib fractures are highly associated with physical abuse [13, 22, 31, 33, 34]. Deciding whether a patient has a rib fracture or not is crucial in influencing further evaluation of the child, with the potential initiation of legal proceedings. Accurate diagnosis is therefore critical. Missing fractures puts the child at risk of returning to an abusive home, with potentially catastrophic results [64]. In contrast, however, the incorrect diagnosis of fractures can result in needlessly subjecting the child and their family to child protection investigations [64]. The assessment of abuse in children is a broad topic; thus, this thesis focuses on the currently recommended imaging investigations for diagnosing rib fractures in children being investigated for SPA.

2.3.2.1 History

Obtaining a detailed medical, social and developmental history is essential when there are suspicions of physical abuse [10, 21, 65-67]. When a child has presented with an injury, a detailed explanation of the mechanism and timing of that injury should be obtained from parents or caregivers in a nonaccusatory manner [10, 21, 65-67]. The consistency of any explanation must be evaluated in combination with both the clinical and radiological findings [66]. Certain features should raise suspicion for physical abuse, including discordance between the offered history and type of injury, fractures inconsistent with the

developmental level of the child, multiple fractures at different stages of healing or the presence of fractures commonly associated with physical abuse, including high-specificity fractures such as metaphyseal and rib fractures [1, 10, 22, 25, 28, 65-67].

2.3.2.2 Physical examination

Clinical signs of physical abuse can manifest in any area of the body, with some injuries being more common than others [1, 28, 66]. Bruises are common in physical abuse and may be solitary or multiple [1, 28, 66]. Any bruise in a non-ambulatory child is regarded as highly suspicious for physical abuse [1, 28, 66]. Rib fractures are typically clinically occult [64]. Fingertip bruising may be seen but is unusual and does not necessarily occur at the location of fractures [4, 45]. Palpable swelling associated with rib fractures is uncommon, as rib fractures rarely exhibit significant displacement due to relative rigidity of the rib cage and strong intercostal muscles [45]. Rib fractures can be painful; they force infants to breathe shallowly and rapidly to minimise pain [45]. However, carers may not recognise such pain and may believe it stems from childhood physiology or illnesses, such as teething or colic [45].

2.3.2.3 Radiological imaging

Medical imaging plays a crucial role in assessing children who may have been physically abused because injuries are often clinically occult, and the history offered is often misleading or incomplete. In 1946, American paediatric radiologist John Caffey gave the first radiological description of physical abuse, in which he described multiple long bone fractures in infants with subdural hematomas [68].

Among the available guidelines on imaging children investigated for SPA, those of the American College of Radiology and the Society for Pediatric Radiology (ACR-SPR) [69] and the Royal College of Radiologists and the Society and College of Radiographers (RCR-SCoR) [70] are the widely recognised and implemented internationally across various healthcare systems [71]. In Europe, the European Society of Paediatric Radiology (ESPR) adopted the RCR-SCoR guideline as the gold standard for imaging children with SPA [72].

2.3.2.3.1 Conventional radiography

Conventional radiography is the imaging modality of first choice to evaluate the presence of fractures [11, 73]. Both guidelines (ACR-SPR and RCR-SCoR) recommend skeletal surveys (SkS) as the primary imaging method to assess skeletal injuries in children with SPA (Table 2.1) [69, 70]. The SkS is a

systematically performed series of radiographic images that encompass the entire skeleton to identify occult fractures, differentiate them from developmental variants and identify focal and diffuse abnormalities of the skeleton. The SkS is recommended for all children under 2 years of age where physical abuse is suspected and should also be considered on a case-by-case basis for children older than 2 years of age [69, 70]. A follow-up limited SkS should be performed 11-14 days after the initial SkS [70]. The rationale behind follow-up imaging is to improve detection of fractures that were radiographically subtle or occult (invisible) on the initial survey, becoming visible only with the onset of bone healing, and to assist in fracture dating [70].

As part of the SkS, chest radiography is the standard imaging tool to assess the chest [69, 70]. However, acute rib fractures are often invisible on chest radiographs (CXR) [60-62, 74, 75], as fractures are often non-displaced or incomplete [38], and fracture lines may be obscured by overlying ribs, vertebrae and soft-tissue [45, 47, 76]. The addition of right and left oblique projections to the AP chest has been shown to improve the detection of rib fractures [77-79]. However, rib fractures are the most commonly missed fracture on the initial SkS but are identified at the follow-up SkS [80-84]. Therefore, the CXRs—including the AP and right and left oblique views—are recommended as part of the follow-up imaging standard SkS (Figure 2.6) [70].

Rib fractures might be the sole skeletal abnormality in a third of abuse cases [32]. The accurate and prompt detection of rib fractures is crucial when there are suspicions of physical abuse. Although follow-up CXR performed 11-14 days after the initial SkS improve the detection of rib fractures, this results in a delay in diagnosis and ultimately, in safeguarding the child, and legal decisions. Additionally, ensuring that a child returns for follow-up imaging can be challenging and is not always guaranteed [84, 85]; this may result in increased risk to the child with the potential for additional injury.

Table 2.1. Imaging guidelines for skeletal survey in suspected child physical abuse

ACR-SPR [69]	RCR-SCoR [70]
Initial skeletal survey	
Skull - Skull ^a (AP and lateral), additional views when indicated: oblique or Towne view Spine - Cervical spine (AP and lateral) - Lateral lumbosacral spine Chest - Chest (AP, lateral, right and left obliques), to include ribs and thoracic and upper lumbar spine	Skull - Skull (AP and lateral) Spine - Lateral spine (cervical, thoracic and lumbar): ▪ Children < 1 year (small children): one view for the whole spine if possible ▪ Children > 1 year and larger children: separated views of the spine are required Chest - AP chest (to include the shoulders) and left and right oblique (to include all ribs)

Abdomen/pelvis -AP abdomen and pelvis, to include the thoracolumbar spine and sacrum Upper extremities - AP humerus - AP forearm - PA hand Lower extremities - PA femur - AP tibia and fibula - AP foot	Abdomen/pelvis - AP abdomen and pelvis Upper extremities - In small children, where possible: ▪ AP of the whole arm (centred at the elbow if possible) ▪ PA hand and wrist ▪ Coned lateral elbow ▪ Coned lateral wrist - In large children: ▪ AP humerus (including the shoulder and elbow) ▪ AP forearm (including the elbow and wrist) ▪ Coned lateral elbow ▪ Coned lateral wrist ▪ PA hand and wrist Lower extremities - In small children, where possible: ▪ Whole AP lower limbs, hip to ankle ▪ Coned lateral knee ▪ Coned AP ankle (mortise view) ▪ PA foot In large children: ▪ AP femur ▪ AP tibia and fibula ▪ AP knees ▪ AP ankle ▪ Coned lateral knee ▪ Coned lateral ankle ▪ PA foot
Follow-up skeletal survey	
Case-by-case basis: ‘a complete repeat examination is appropriate, though a limited follow-up examination could also be considered’	-Any of the abnormal or suspicious areas on the initial skeletal view plus the following views: Chest - AP chest (to include the shoulders) and left and right oblique (to include all ribs) Upper extremities - In small children, where possible: ▪ AP of the whole arm (centred at the elbow if possible) - In larger children: ▪ AP humerus (including the shoulder and elbow) ▪ AP forearm (including the elbow and wrist) Lower extremities - In small children, where possible: ▪ Whole AP lower limb, hip to ankle - In larger children: ▪ AP femur ▪ AP tibia and fibula

^aIf a contemporaneous head CT was performed before the skeletal survey with sufficient resolution to provide high-quality multiplanar 2D reconstructions and surface-rendered 3D skull reconstruction, the radiologist may exclude the AP and lateral views of the skull from the skeletal series.

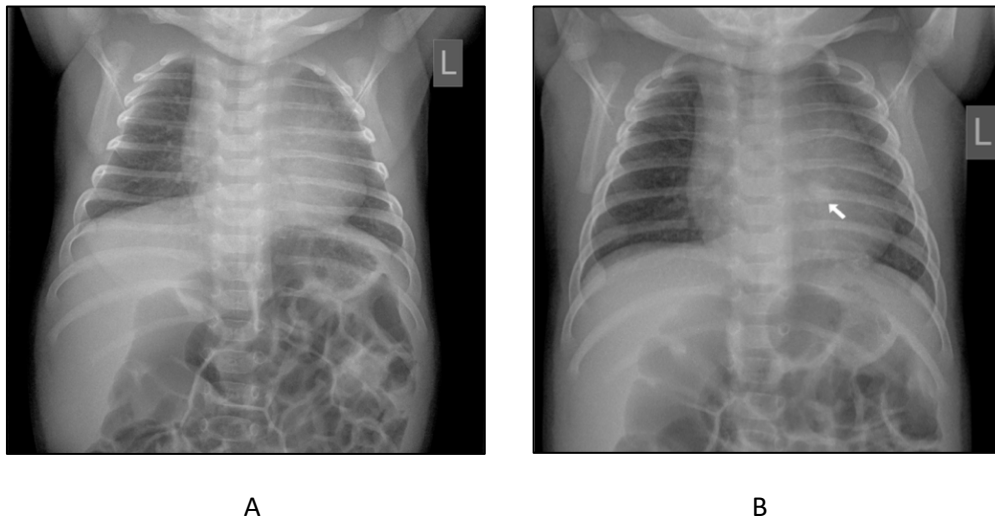


Figure 2.6. Skeletal survey of a one-month-old girl.

(A) Initial AP chest radiograph did not reveal any rib fractures. (B) Follow-up chest radiograph two weeks later shows a healing left 7th posterior rib fracture (arrow).

2.3.2.3.2 Bone scintigraphy

Bone scintigraphy is a nuclear medicine imaging procedure in which the patient is injected with a small amount of radioactive material (Tc-99m-methylene diphosphonate [MDP]), which binds to sites of active bone turnover that occurs due to a range of causes, such as bone growth, metastases, infection and fracture healing [86]. Historically, Tc-99m MDP bone scintigraphy has been used as a complementary tool to chest radiography for detecting rib fractures in children with SPA when the initial CXR is negative or equivocal but clinical suspicion remains high [87].

The use of Tc-99m MDP bone scintigraphy in children with SPA has decreased over the last two decades [11]. A recent review by Lawson *et al.* [11] reported that no recent studies have compared bone scans to SkS. Most studies were published between 1980 and 2000 [30, 88-91] and reported that Tc-99m MDP bone scintigraphy had a higher sensitivity for detecting rib fractures than initial CXR SkS. However, in 2003, a study by Mandelstam *et al.* [92] contradicted previous results, reporting that CXR acquired as part of the initial SkS detected 73% of rib fractures, whereas bone scans detected 63%. In 2006, a systematic review conducted by Kemp *et al.* [93], concluded that bone scans were more sensitive than initial CXR in detecting acute rib fractures.

Advances in nuclear medicine technology have improved accuracy in detection of occult fractures in children and adults [86]. Fluorine-18 sodium fluoride (F18-NaF) positron emission tomography (PET) has multiplanar reconstruction capabilities and enhances spatial resolution, which may increase the detection of occult fractures in children with SPA [86]. In 2010, Drubach *et al.* [94] reported 18F-NaF PET to have a higher sensitivity (93%) than initial CXR SkS (73%) in detecting posterior rib fractures, using the

initial and follow-up SkSs as a reference standard in 22 children under 2 years of age investigated for SPA.

However, there are several of disadvantages to the routine use of Tc-99m MDP bone scans or F18-NaF PET for assessing the presence of rib fractures in children investigated for SPA. First, both Tc-99m MDP bone scan and 18F-NaF PET are associated with a high radiation burden, with an estimated absorbed dose of approximately 3.1 millisieverts (mSv) and 3.4 mSv, respectively, for a 10-kg infant [95]. Second, these examinations are lengthy, and sedation or general anaesthesia is generally necessary to obtain high-quality images [22, 94, 95]. Third, trained radiographers and expert radiologists are need to perform and report these examinations [64]. Fourthly, Tc-99m MDP bone scans can remain positive for up to 1 year after trauma, impairing their usefulness for dating rib fractures [64, 93]. Finally, Tc-99m MDP bone scans and 18F-NaF PET have limited availability [64], and they are expensive compared to SkS [95].

In the UK, the RCR-SCoR guidelines for Imaging children investigated for SPA do not recommend bone scintigraphy [70], whereas the ACR-SPR guidelines state that bone scintigraphy can be used as complementary imaging where there is a focal area of concern [69].

2.3.2.3.3 Computed tomography

CT is a computerised x-ray imaging procedure that acquires cross-sectional (axial) images of the body which can be stacked together to form a three-dimensional (3D) image and reconstructed in the axial, sagittal and coronal planes. CT scans are used predominantly to identify disease or injury within regions of the body such as the head, chest, abdomen and pelvis. CT is also used for musculoskeletal and bone imaging in trauma patients because of its high speed and increased accuracy compared to conventional radiographs. Studies have shown CT to be more sensitive than CXR in identifying rib fractures in adults and children with blunt chest trauma. A study by Chapman *et al.* [96] on blunt trauma in adult patients found that approximately 74.5% (1467/1969) of rib fractures observed on chest CT were missed on CXR. In a study comparing chest radiography with CT scans in 1,235 paediatric patients following blunt chest trauma, chest radiography detected 80 rib fractures whereas CT detected 219 rib fractures [97]. Another study by Renton *et al.* [98] reported that CT revealed 31 additional thoracic injuries in 18 of the 45 paediatric blunt trauma patients, which were missed on chest radiography. Two of the 31 thoracic injuries were rib fractures. Furthermore, Golden *et al.* [99] reported evaluating 139 paediatric blunt trauma patients with both chest radiography and chest CT. Chest CT detected an additional 4 fractures that were missed on chest radiography. It has been suggested that chest CT can be used as a

complementary tool for chest radiography for the evaluation of suspected rib fractures in minor blunt trauma patients [100].

Chest CT has been proposed as a complementary tool for detecting rib fractures in children investigated for SPA when initial CXR SkS are negative or inconclusive (Figure 2.7) but suspicion of abuse is high [61]. A recent systematic review and meta-analysis by Alzahrani *et al.* [101] assessed the performance of chest CT in the diagnosis of rib fractures in children with suspected or confirmed physical abuse using either CXR SkS or autopsy as the reference standard. This systematic review includes four studies: two in live children [61, 102], and two in PM children [38, 60]. The latter studies were included in the meta-analysis. They showed that chest CT is superior to initial CXR SkS for detecting rib fractures in live children. The two studies that compared post-mortem CT (PMCT) with autopsy as a reference standard for detection of rib fractures were grouped ($n=81$) and indicated that PMCT had an overall sensitivity of 34% and specificity of 99%. PM CXR were not pooled due to the differences in the projections acquired; they had a sensitivity of 13.5% and 28% and specificity of 97% and 99%. The search period for eligible studies in the published systematic review [101] was from January 1980 to April 2020; thus a repeat database search was conducted to identify potential further studies from April 2020 to June 2024. Two eligible studies (on live children) were identified: those by Pomeranz *et al.* [75] and Karmazyn *et al.* [103], published in 2022. Table 2.2 summarises the included studies in the systematic review and the additional retrieved studies.

A recent study assessed the accuracy of multiple diagnostic imaging methods, including magnetic resonance imaging (MRI), SkS and ultrasound, for detecting CCJ fractures using CT as the reference standard in 22 children under 4 years of age [104]. A total of 109 CCJ fractures were found. CT performed in 18 of 22 children detected 92 CCJ fractures. In 15 patients who underwent CXR SkS and CT examinations within three days of each other, CXR SkS had a sensitivity of 32.5% and a specificity of 99.2%. In four patients who underwent CT and MRI, MRI had a sensitivity of 42.9% and specificity of 98.1% (the time between examinations was not reported). In one patient who underwent ultrasound and CT (the time between examinations was not reported), ultrasound detected the four CCJ fractures identified by CT. The sensitivity and specificity of the ultrasound were not calculated, because only one child had both an ultrasound and CT (reference standard).

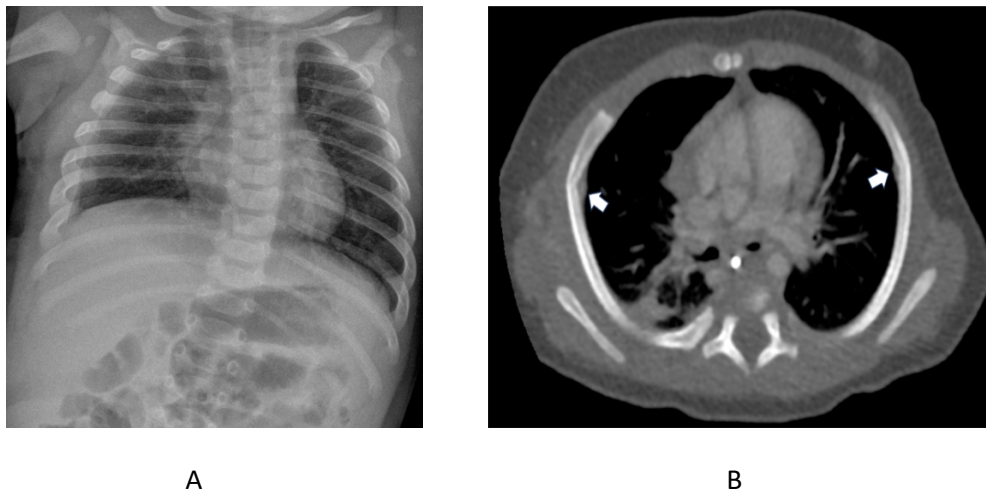


Figure 2.7. Comparison of chest radiography and CT of an 11-week-old boy.

(A) Initial AP chest skeletal survey and (B) axial unenhanced chest CT performed within three days of the skeletal survey, shows bilateral acute 3rd anterior rib fractures (2 and 10 o'clock, arrows) not demonstrated in the initial chest skeletal survey.

In addition to the improved accuracy of chest CT for detecting rib fractures in children with SPA, which aids in timely safeguarding, another advantage of chest CT is the potential ability to evaluate other high-specificity fractures such as scapular and spinous process fractures [61]. Additionally, CT has the ability to provide 3D images of the rib cage, which could potentially be used by expert radiologists to demonstrate the injuries in the courts [11, 24, 25, 105].

The potential risk of radiation from CT prevents this technology from being widely implemented in clinical practice for detecting rib fractures in children with SPA. The potential risks of CT radiation must be evaluated, considering the risks of misdiagnosing child abuse. Improvements in CT technology, including use of iterative reconstruction algorithms [106], the introduction of emerging photon counting detectors [107] and improved protocols [106], have significantly reduced the radiation dose burden of CT examinations without compromising the diagnostic image quality. The possibility of developing a low-dose chest CT examination to diagnose rib fractures in children with SPA has been reported [103, 108]. Sanchez *et al.* [108] reported that the average dose of four CXR projections (AP, lateral and two oblique projections) was 0.29 mSv, while optimised chest CT protocol resulted in an average effective dose of 0.56 mSv in children up to 4 months in age, which was less than twice the dose of the four projections of CXR. A study by Karmazyn *et al.* [103] reported the development of a low-dose CT (LDCT) chest protocol with an effective dose of 0.17 mSv, which approaches the average effective dose of the standard set of initial and follow-up skeletal survey CXRs (6 projections [AP and right and left oblique views], 0.1 mSv) [109, 110].

Table 2.2 Summary of published studies assessing accuracy of chest CT in detecting rib fractures in children with SPA

Study	Author (year)	Study design (recruitment start and end dates)	Sample size / Number of reviewed ribs	Mean age (range)	Reference test	CT imaging protocol	Time interval between the reference standard and CT imaging	The study's primary outcome
1	Wootton-Gorges <i>et al.</i> [102]	Retrospective (between 1999 and 2004)	12 / 225 ribs	Mean age 2.5 months (range 1.2 to 5.6 months)	Initial CXR (AP and lateral projections)	Not reported	1 day	- Chest CT=131 rib fractures - CXR=79 rib fractures - CT more sensitive in the detection of rib fractures based upon anatomical position than CXR in the detection of rib fractures at all anatomical positions ($p<0.01$), except in lateral location - Two radiologists reviewed the chest CT studies
2	Hong <i>et al.</i> [38]	Retrospective (between January 2007 and October 2009)	56 / 1318 ribs reviewed at primary (clinical) interpretation and 298 ribs reviewed at research radiologist's interpretation	Mean age 12 months (range 8 days to ~93 months); 46 children < 24 months)	Autopsy	8 multi-slice helical CT (GE), 128-slice MDCT (GE) or 16-slice CT (Philips) 120 kV, 320 and 355 mA, 0.53 and 0.93 mm pitch, rotation time 0.75 & 0.80 s - Slice thickness reconstruction 0.80–0.62 mm 3D reconstruction	Not reported	101 rib fractures at autopsy (standard) - Two image interpretation methods were used for the detection rib fractures by fracture locations: A. Primary (clinical) interpretation=chest CT showed sensitivity 51.5% and specificity 99.7% for detecting rib fractures by fracture locations - PM CXR for detection of rib fractures: at specified locations=sensitivity 28.9% and specificity 99.9%; the sensitivity and specificity of PM CXR at specific locations along rib arc^a was 8% and 99% at anterior; 80% and 100% at lateral; 29% and 98% at posterior B. Radiologist interpretation=13 children: 12 with rib fractures at autopsy and 1 false positive at chest radiograph primary interpretation; chest CT showed sensitivity 85.1% and specificity 99.4% for detecting rib fractures by fracture locations - Two radiologists reviewed chest CT (3 studies reviewed by one radiologist) at primary (clinical) interpretation; radiologist interpretation performed by one radiologist only

Study	Author (year)	Study design (recruitment start and end dates)	Sample size / Number of reviewed ribs	Mean age (range)	Reference test	CT imaging protocol	Time interval between the reference standard and CT imaging	The study's primary outcome
3	Sanchez <i>et al.</i> [61]	Retrospective (between January 2008 and January 2012)	16 (only 5 had both CXR and chest CT) / Not reported	Mean age 6 months (range 1 to 11 months)	Initial CXR (AP, lateral, right and left oblique projections)	• 100 kV, 15 mA, 1 mm pitch, rotation time 0.5 s • Adaptive iterative reconstruction blend of 20%	1 day	• Chest CT=11 rib fractures all missed on initial CXR • 7 rib fractures identified on follow-up CXR (1-2 weeks) in patients who did not have chest CT • The number of radiologists who reviewed chest CT was not reported
4	Shelmerdine <i>et al.</i> [60]	Retrospective (between January 2012 and January 2017)	25 / 600 ribs (12 pairs of ribs in 25 children)	Median age 4 months (range 17 days to 7 years)	Autopsy	• 64-slice MDCT (Siemens) • 120 kV, 200–350 mA, 1 mm pitch, and 0.62 mm collimation • Slice thickness reconstruction (1 mm)	Median 2 days (range 0 to 5 days)	• 136 rib fractures at autopsy (standard) • Chest CT for detection of rib fractures: at specified locations= sensitivity 44.9% and specificity 97% • PM CXR for detection of rib fractures: at specified locations= sensitivity 13.5% and specificity 97.9%; the sensitivity and specificity of PM CXR at specific locations along rib arc was 15% and 97% at anterior, 0.8% and 98% at lateral, 27% and 98% at posterior, respectively • Thirty-five radiologists reviewed the CT chest studies and thirty-eight reviewed the CXR studies
5	Pomeranz <i>et al.</i> [75]	Retrospective (between January 2009 and July 2017)	57 / Not reported	Mean age 14.4 months (range 0 to 8 years)	Initial CXR (AP, lateral, right and left oblique projections)	• 64-slice MDCT (Siemens) • 1.0–1.5 mm pitch, rotation time 0.28 s, 0.6 mm collimation, temporal resolution 130–150 ms, and automated kV and mA were used depending on the patient's size and age. • Slice thickness reconstruction (5–3mm)	Mean 3 days (range 0 to 29 days)	• Chest CT=225 rib fractures • CXR=187 rib fractures • CT more sensitive than initial CXR in the detection of rib fractures at all anatomical positions • A paediatric radiology fellow reviewed CXR and CT studies, with interpretations integrated with original reports by other radiologists

Study	Author (year)	Study design (recruitment start and end dates)	Sample size / Number of reviewed ribs	Mean age (range)	Reference test	CT imaging protocol	Time interval between the reference standard and CT imaging	The study's primary outcome
6	Karmazyn <i>et al.</i> [103]	Retrospective (between January 2010 and December 2019)	50 / Not reported	Mean age 9.7 months (range 8 days to 2.8 years)	Two reference standard method were used: A. Initial CXR only in 50 patients (AP, lateral, right and left oblique projections) B. Follow-up CXR only in 27 of 50 patients (AP, lateral, right and left oblique projections)	• 256-slice CT (Philips) with a kV of 80 or 384-slice CT (Siemens) with automated kV selection (100 kV as the reference, using a tin filter) • Slice thickness reconstruction (4–2mm) • 3D reconstructions per radiologist request	• Mean 0.9 days (range 0 to 3 days) for CT vs initial CXR • Mean 17.1 days from initial CXR (range 13 to 25 days) for CT vs follow-up CXR	• CT vs initial CXR in 50 patients: - Chest CT=112 rib fractures - Initial CXR=42 rib fractures - CT more sensitive than initial CXR in the detection of rib fractures at all anatomical positions -In 10 children with negative initial CXR, radiologists were suspicious of a rib fracture. CT demonstrated rib fractures in 4 patients and was negative in other 6 patients; 4 of 6 patients had negative follow-up CXR • CT vs follow-up CXR in 27 patients: -Chest CT=93 rib fractures -Follow-up CXR=49 rib fractures -CT more sensitive than follow-up CXR in the detection of rib fractures at all anatomical positions, except in lateral location -CT missed fractures in only one child who had nondisplaced acute anterior rib fractures • Two radiologists reviewed the chest CT and CXR studies • The interobserver agreement was substantial for initial CXR (k=0.72) and almost perfect for chest CT (k=0.82) and follow-up CXR (k=1.00)

^athe location of the rib fractures was divided into three segments: anterior fracture including costochondral, anterior and anterolateral; posterior fracture including costovertebral, posterior and posterolateral; and lateral. Calculated as follows [anterior = (anterior + anterolateral) / 2].

(Adapted with permission from Alzahrani *et al.* [101])

2.3.2.3.4 Ultrasound

Ultrasound uses high-frequency sound waves to produce images of body structures. Ultrasound has excellent temporal and spatial resolution, especially for superficial structures, and it can be useful in an emergency clinical setting for evaluation of traumatic injuries of the ribcage and pleural fluid accumulation [111, 112]. Ultrasound has been reported to have high sensitivity in detecting ribcage fractures in adult patients [112-118]. Griffith *et al.* [114] found that ultrasound was more sensitive than chest radiography in detecting acute rib fractures in 50 patients with clinical suspicion of rib fracture. Chest radiography revealed 8 rib fractures in 6 out of 50 (12%) patients, while ultrasound detected 83 rib fractures in 39 out of 50 (78%) patients. Of these 83 fractures, 74 (89%) were of the rib, 4 (5%) at the CCJ and 5 (6%) in the costal cartilage. Turk *et al.* [117] reported that ultrasound detected 26 rib fractures, initially undetected on chest radiography, in 18 (90%) of 20 patients with minor blunt chest trauma. A fracture at the CCJ was observed in one patient. Additionally, it has been reported that ultrasound can be useful not only for detecting costal cartilage fractures and CCJ fractures but also for detecting sternal fractures [119, 120].

The thorax is only partially ossified in infants and young children, offering more acoustic windows for evaluation of suspicious chest injuries [111, 121]. The sternal cartilage and costal cartilage ossify over time, reducing acoustic accessibility [111, 121]. Costal cartilage fractures in infants and young children can be missed on chest radiography due to the lack of ossification [116]. On ultrasound, the costal cartilage appears hypoechoic, while the osseous rib is hyperechoic [111, 112]. Ultrasound can directly show the costal cartilage and ribs, enabling the evaluation of costochondral and rib fractures [122].

In children investigated for SPA, the RCR-SCoR guidelines recommend ultrasound imaging may help diagnose equivocal rib fractures [70]. However, the role of ultrasound imaging as an adjunctive tool for evaluating rib fractures and costochondral cartilage fractures in children with SPA has not been widely explored [11, 22]. Smeets *et al.* [123] reported the value of ultrasound in diagnosing costochondral dislocation in a 9-month-old infant with multiple rib fractures and focal soft-tissue swelling over the left lateral thoracic wall. A further case report by Kelloff *et al.* [124] used ultrasound as a complementary tool to evaluate the cause of chest wall crepitus in a 9-week-old infant when the initial three-view CXRs were negative. Ultrasound demonstrated the presence of acute rib fractures, which were confirmed on the follow-up CXRs performed 14 days after the initial SkS. Safeguarding proceedings were initiated following the ultrasound and the child was taken into a place of safety. Both of these case reports

demonstrate the potential role of ultrasound to assist the diagnosis of focal abnormal clinical findings. However, using ultrasound routinely to diagnose rib fractures in children with SPA is not practical because imaging of all individual ribs would be required, which is time-consuming [11]. In addition, ultrasound is operator-dependent and requires sonographers or radiologists with musculoskeletal ultrasound experience to perform such examinations.

2.3.2.3.5 Magnetic resonance imaging

MRI uses magnetic fields and radio waves to produce images of the internal body structures. The literature on the ability of MRI to detect rib fractures in SPA is limited [11]. Published studies report that MRI has a low sensitivity in the detection of rib fractures in cases of SPA but a greater sensitivity in the detection of oedema and soft-tissue swelling associated with rib fractures [125, 126]. Perez-Rossello *et al.* [126] found that whole-body MRI (WB-MRI) has low sensitivity (57%) for identifying rib fractures compared to two standard SkS (i.e., initial and follow-up). A recent study by Proisy *et al.* [125] reported that WB-MRI had low sensitivity (58.8%) for detecting rib fractures using the consensus results of all modalities (the initial SkS, bone scintigraphy and WB-MRI) as a reference standard. In addition to the low sensitivity of MRI in detecting rib fractures in cases of SPA, disadvantages to the routine use of MRI in SPA include the need for sedation or general anaesthesia and a long scanning time [125, 126]. The RCR-SCoR guidelines recommend use of MRI as a complementary tool for identifying equivocal skeletal injuries and associated soft-tissue injuries [70].

2.3.2.3.6 Radiological dating of fractures

In cases of SPA, explanation offered by caregivers is often misleading or incomplete and the injuries are usually unwitnessed [127, 128]. Radiologists are therefore often asked by the clinicians caring for the child to estimate the age of the fractures [128], to assist them in assessing any discrepancies between the provided history and the timing of the injury [127-129]. From a legal perspective, estimating the age of fractures is often important to help the court in the identification and elimination of a potential pool of perpetrators and aids in decision-making regarding the optimum placement of the child [127-129].

It has been suggested that the healing pattern of long bone (diaphyseal) fractures applies to rib arc fractures due to their similar tubular morphology [42, 47, 50]. Generally, the healing pattern of long

bone fractures (including rib fractures) follows a predictable course which can be manifested radiologically and used by radiologists to estimate the age of fractures. The healing phases of the fractures as seen on radiographs traditionally can be divided into different phases [4, 42]. The first phase is soft tissue swelling, which depends on fracture location [4]. For example, soft-tissue swelling is generally more distinct around a femoral fracture than a foot's phalanx fracture. Soft tissue swelling is rarely seen with rib fractures but may manifest radiologically as pleural thickening [4]. The second phase is periosteal reaction, also known as subperiosteal new bone formation (SPNBF), is the first radiological indicator of bone healing and can be seen radiologically as a thin layer of bone along the original cortex [4, 42]. The third phase is soft callus formation and can be seen radiologically as a faint mineralisation (fluffy) appearance at and around the fracture site [4, 42]. The fourth phase is hard callus formation, is where soft callus becomes mineralised and increases in density. This phase can be seen radiologically as well-demarcated new bone surrounding the fracture site with a density comparable to cortical bone [4, 42]. Remodelling is final phase of fracture healing in which fracture healing is complete, and the medullary cavity has been reconstituted and the cortex resembles the shape of the cortex of the adjacent bone [4, 42].

It should be noted that CCJ fractures do not heal like rib arc and diaphyseal fractures [47, 130]. CCJ fractures often heal with no periosteal reaction and therefore pose a challenge in detecting and dating on chest radiography [47, 130]. A study by Tsai *et al.* [130] found that CCJ fractures in children with SPA may follow a predictable course of healing on chest radiography as follows: a bucket-handle appearance is the primary pattern, growth disturbance of the rib end is the secondary pattern and bony sclerosis is the final pattern.

The literature has several studies on dating fractures in children. Messer *et al.* [129] published a recent systematic review on the radiologic features of paediatric fracture healing with associated timelines. A total of 10 studies were included; these showed that the radiological timeline of fracture healing parameters varied significantly amongst the studies [129]. This is because these studies have not considered factors affecting the rate of fracture healing; therefore, it is difficult to apply the suggested fracture healing timelines to all cases of children with SPA. Age is a factor that might affect the rate of fracture healing. It has been reported that fractures in infants appear to heal faster than in older children [129, 131]. Some studies have assessed the patterns of fracture healing in older children or in a wide range of ages [132, 133] rather than in children under 2 years of age who are at the most risk of physical

abuse [10, 11, 13]. Fracture location is another factor that might affect the rate of fracture healing. It has been reported that upper limb fractures are likely to heal faster than lower limb fractures [131]. Furthermore, fracture healing is influenced by immobilisation which is known to promote fracture healing [129]. Moreover, most of studies did not mention the types of fractures (i.e., displaced, complete or incomplete), which may affect the healing process [129]. A study by Warner *et al.* [134] found a difference in healing between incomplete and complete long bone fractures in 40 infants. Application of healing timelines derived from children with accidental trauma to those with SPA requires caution. This is because children with fractures due to accidental trauma may be in overall have good health and receive prompt medical treatment while abused children may suffer from malnutrition, multiple injuries and additional stressors [4, 129]. Thus, the presence of comorbidities in children experiencing physical abuse may result in altered or delayed fracture healing [4, 129].

Because of these limitations in current literature regarding the fracture dating in children, especially when reporting radiological imaging in cases of SPA, reporting general and non-expert paediatric radiologists are often advised to offer a broad timeframe (acute vs. healing) of fractures instead of specific timescales [128]. Such radiologists may be less aware of the weaknesses and strengths of the published studies on dating fractures in the paediatric population unless they have particular interest or expertise in interpreting imaging performed for children with SPA. Reporting radiologists who offer specific timescales of fractures may risk being called to appear in court to justify their opinion, especially when there is a disagreement with an appointed expert paediatric radiologist who provides the most likely broad timeline (in weeks) for the fractures [128].

Further studies are needed on the radiological dating of fractures in children with SPA. An area that requires investigation is the effect of patient age on aspects of fracture healing (such as SPNBF and callus formation) in young patient age cohorts (0–1 year and 1–2 years) [129]. Another area that requires investigation is the assessment of variations in fracture healing between different locations, beginning broadly from fractures in different bone locations such as the upper and lower limbs and narrowing within the same bone locations such as the upper and lower ribs [129]. There is also a need for future research focusing on the radiological dating of the highly specific fractures for abuse such as rib fractures, taking into account the factors affecting the healing process such as patient age, rib fracture location and fracture type (buckle, complete and fracture with/without dislocation).

2.3.4 Differential diagnosis

Although rib fractures have a high specificity for physical child abuse, they also can result from different scenarios. Therefore, a wide range of differential diagnoses should be considered before diagnosing injuries in infants and young children with SPA.

Rib fractures may result from birth trauma due to difficult vaginal deliveries in cases of large babies and may be associated with clavicular fractures [31, 50]. However, birth-related rib fractures are rare [135, 136]. The clinical and birth history, including mode of delivery, should be considered in rib fractures in infants younger than 3 months, given that a birth-related injury would be healed after 3 months [50].

Generally, bone fragility diseases, such as osteopetrosis, rickets and osteogenesis imperfecta, may cause rib fractures [50, 137]. Although rib fractures in children may be due to such underlying medical conditions, these causes are rare [28, 138]. Osteopetrosis is a bone disease that makes the bones brittle and susceptible to fracture [139]. Rickets can cause enlargements at the anterior ends of the ribs (observed radiographically as a bulbous appearance at CCJ, known as a ‘rachitic rosary’), which may be mistakenly diagnosed as healing rib fractures [50, 137]. Osteogenesis imperfecta (“brittle bone disease”) is a rare genetic disease that increases bone fragility [25, 31]. Differentiating osteogenesis imperfecta from abuse is challenging because of the variability and complexity of this disorder [25]. Rib fractures generally occur in cases with severe osteogenesis imperfecta and tend to be lateral [25]. In the diagnosis of children with rib fractures, it is important to consider not only SPA but also other diseases or disorders that cause bone fragility. It is important to note that the presence of a rib fracture in a child suffering from a medical condition does not imply exclude physical abuse. The clinical and family history, laboratory results and radiological examinations should be considered in diagnosing rib fractures in children without a clear history of trauma [4, 24].

Some normal variants that may mimic rib fractures and could be misinterpreted as pathology in the child abuse evaluation setting. Sternal segments (ossification centres) superimposed on the ribs on oblique CXRs may be mistaken for healing fractures [50, 137, 140]. Additionally, the thickening appearance resulting from superimposing the transverse process of the spine over the rib head or neck may be misinterpreted as a healing rib fracture [140].

2.4 Summary

Rib fractures are highly specific injuries for physical child abuse. Chest radiography, as part of an SkS, is the current standard imaging for assessing rib fractures in children with SPA. However, chest radiography is limited in detecting acute non-displaced rib fractures; therefore, a follow-up chest radiography after 11–14 days of the initial SkS is required to be performed to detect rib fractures not previously observed in the initial SkS imaging. The time interval between the initial and follow-up SkS imaging is crucial to making decisions regarding the management and safety of a child, and ensuring that the child attends the follow-up imaging is challenging.

Chest CT improves the detection of acute and healing rib fractures and could offer immediate evidence of rib fractures resulting from SPA, rendering the need for chest radiography as part of the SkS redundant and facilitating the safeguarding procedures for a child. The relatively high radiation dose associated with chest CT examinations compared to chest radiography is of concern in using chest CT in routine clinical practice. However, the current advancements in CT technology have significantly reduced radiation exposure. Current studies have found that chest CT is superior to the initial CXR SkS or follow-up CXR SkS in detecting rib fractures in live children with SPA. However, the accuracy of chest CT needs to be evaluated against the current standard method used in clinical practice (i.e., initial and follow-up CXRs together). Additionally, if chest CT could replace chest radiography as part of the initial and follow-up SkS, the possibility of dating the rib fractures using CT must be evaluated, and the radiation dose for the chest CT must be optimised.

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Chapter Three

The diagnostic performance of chest computed tomography in the detection of rib fractures in children investigated for suspected physical abuse: a systematic review and meta-analysis

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3. The diagnostic performance of chest computed tomography in the detection of rib fractures in children investigated for suspected physical abuse: a systematic review and meta-analysis

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- Wrote the initial draft of the study protocol: **N.M.A.**
- Review of study protocol: A.C.O and A.J.
- Registered the protocol on PROSPERO: **N.M.A.**
- Performed the database searches: **N.M.A.**
- Screened for eligible studies: **N.M.A.**
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- Designed the data collection form and extracted the data: **N.M.A.**
- Statistical analysis:
 - Calculated the accuracy measures (true positive, true negative, false positive and false negative) from the included studies: **N.M.A.**
 - Cleaned and tabulated the data for analysis: **N.M.A.**
 - Chose the appropriate tests and ran the analysis: **N.M.A.** and F.A.
- Wrote the initial draft of the manuscript: **N.M.A.**
- Reviewed and approved the final draft of the manuscript and replied to the journal's comments: **N.M.A.**, A.C.O., A.J. and M.P.

3.1 Abstract

Objective

To assess the diagnostic performance of chest CT in the detection of rib fractures in children investigated for suspected physical abuse (SPA).

Methods

Medline, Web of Science and Cochrane databases were searched from January 1980 to April 2020. The QUADAS-2 tool was used to assess the quality of the eligible English-only studies following which a formal narrative synthesis was constructed. Studies reporting true positive, false positive, true negative, and false negative results were included in the meta-analysis. Overall sensitivity and specificity of chest CT for rib fracture detection were calculated, irrespective of fracture location, and were pooled using a univariate random-effects meta-analysis. The diagnostic accuracy of specific locations along the rib arc (anterior, lateral or posterior) was assessed separately.

Results

Of 242 identified studies, 4 met the inclusion criteria. Of these, 2 were included in the meta-analysis. Chest CT identified 142 rib fractures compared to 79 detected by initial skeletal survey chest radiographs in live children with SPA. Post-mortem CT (PMCT) has low sensitivity (34%) but high specificity (99%) in the detection of rib fractures when compared to the autopsy reference standard. PMCT has low sensitivity (45%, 21% and 42%) but high specificity (99%, 97% and 99%) at anterior, lateral and posterior rib locations, respectively.

Conclusions

Chest CT detects more rib fractures than initial skeletal survey chest radiographs in live children with SPA. PMCT has low sensitivity but high specificity for detecting rib fractures in children investigated for SPA.

3.2 Introduction

Physical child abuse is one of the leading causes of child morbidity and mortality worldwide [1, 2]. Physical abuse is defined by the World Health Organisation as "acts that cause actual physical harm or have the potential for harm" [3]. In 2013, the prevalence of physical child abuse in the European Region was approximately 23% (44 million children) [4]. Physical abuse is more common in children aged less than 2 years [5, 6], in particular children less than 12 months, who are typically pre-ambulant (those who will typically go on to walk in the future) or non-ambulant (those who will never walk e.g., wheelchair bound) who are unable to localise their pain or communicate a history of injury [6, 7].

Following cutaneous injuries, fractures are the second most common finding associated with physical abuse [8]. Rib fractures are strongly associated with physical abuse in infants and young children [9-12] with positive predictive values (PPVs) of 95% and 66% in children under 3 [13] and 4 years of age [14], respectively. Rib fractures are uncommon following accidental trauma in children under the age of 3 years due to the plastic nature of the thoracic cage in this age group [13, 15].

Radiological imaging is an essential tool in the investigation of suspected physical abuse (SPA) in children where the history provided is considered to be inconclusive or incongruent with the clinical examination [16]. International guidelines for skeletal surveys (SkS) have been published by: the American College of Radiology (ACR) and the Society for Pediatric Radiology (SPR) [17]; and the Royal College of Radiologists (RCR) and the Society of College of Radiographers (SCoR) endorsed by Royal College of Paediatrics and Child Health (RCPCH) [18], recognised by the European Society of Paediatric Radiology (ESPR) as the gold standard for the investigation of SPA across Europe [19].

These guidelines state that chest radiography is the standard imaging modality employed in the evaluation of the thorax in children suspected of having been physically abused [17, 18]. However, initial chest radiographs (CXR) are often unable to detect acute, non-displaced and incomplete rib fractures [20]. Sanchez *et al.* [21] found that 17% of rib fractures studied (total 105 fractures) in cases of SPA were not visualised on CXR. Recent studies have shown that oblique projections of the thorax have improved the detection of rib fractures in SPA [22-24], both on initial (acute) and follow-up (healing) SkS. However, even with additional oblique views of the thorax, acute rib fractures are often difficult to detect [6, 25] due to fracture lines potentially being masked by overlying lung and vascular markings [26, 27], in addition to being superimposed over other anatomical structures [20]. The rationale behind the

inclusion of the CXR as part of the follow-up SkS 11-14 days after the initial SkS relates to the formation of callus associated with rib fracture healing [7], thereby increasing their conspicuity and improving the detection of those fractures not visualised on the initial SkS [28-30].

It has been shown that chest computed tomography (CT) improves the detection of acute and healing rib fractures in live [31] and post-mortem (PM) children [26]. Unlike CXR, chest CT can more accurately diagnose acute rib fractures and could offer immediate evidence of inflicted injury. The use of chest CT may avoid follow-up CXR at possibly comparable radiation doses [21, 32].

We systematically reviewed the available evidence concerning the diagnostic performance of chest CT in the detection of rib fractures in live and post-mortem children with suspected or confirmed physical abuse in comparison to the established reference standard of CXR and/or autopsy. The primary objective was to evaluate whether the diagnostic performance of chest CT is comparable to other established standard methods of diagnosing rib fractures in children with SPA. The second objective was to assess the diagnostic accuracy (sensitivity and specificity) of chest CT in the detection of rib fractures at different anatomical locations (anterior, lateral, and posterior) along the rib arc.

3.3 Methods

The study protocol for this systematic review was registered on PROSPERO (registration number: CRD42020179550) and the study was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement guidelines [33].

3.3.1 Data sources and searches

Medline, Web of Science and Cochrane databases were searched for eligible articles published in English between January 1980 and April 2020. The search strategy and terms used are provided in the Appendix 1. The reference lists of all included articles were searched for additional articles not captured in the initial search.

3.3.2 Study selection

Study inclusion and exclusion criteria were developed based on population, intervention, comparator, and outcomes (PICO) criteria:

P: children (0–18 years [34]) with suspected or known rib fractures resulting from confirmed or SPA.

I: chest CT imaging.

C: CXR and/or autopsy.

O: diagnostic accuracy of CT in the detection of rib fractures in children resulting from confirmed or SPA.

Studies satisfying the following criteria were included: (1) study participants aged up to 18 years old with suspected or known rib fractures resulting from physical abuse; (2) chest CT used as a diagnostic tool to detect rib fractures; (3) the diagnostic performance of chest CT compared to the reference standards of either CXR and/or autopsy was reported; (4) for meta-analysis, the absolute numbers of true positives (TP), true negatives (TN), false positives (FP), and false negatives (FN) were reported or could be derived to calculate sensitivity and specificity. We excluded: (1) studies performed on animals and/or phantoms; (2) studies where the manuscript body was not in English; (3) case reports, review articles, editorial/comment papers, and abstracts of conference meetings. Following the removal of duplicates, study titles and abstracts were screened by one reviewer (N.M.A). Full-text screening of potentially eligible studies was then performed to further confirm eligibility. A consensus opinion was sought by two reviewers (A.M.J and A.C.O) to resolve any uncertainties.

3.3.3 Data extraction and quality assessment

Data were extracted from the eligible studies using a predesigned data collection form which included: author; publication year; study design; sample size and number of ribs reviewed; mean age; reference test; CT imaging protocol; the time interval between the reference standard and CT imaging; and the study primary outcome. For this systematic review, the acceptable time intervals between the index test (chest CT) and the reference standards were ≤ 48 hours (CXR) and/or $\leq$ one week (autopsy). For meta-analyses, TP, TN, FP, and FN were derived and pooled from the included studies to assess the diagnostic performance of chest CT. Four reviewers (N.M.A., A.M.J., M.P., A.C.O.) independently assessed the quality of the included studies using the Quality Assessment of Diagnostic Accuracy Studies 2 (QUADAS-2) tool [35]. Discrepancies between reviewers were resolved by consensus.

3.3.4 Data synthesis and analysis

We performed a formal narrative synthesis of the findings from the eligible studies which included a summary of the study characteristics and outcome measures regarding the diagnostic performance of

chest CT. To perform a meta-analysis, summary measures of TP, FP, TN, and FN rates were calculated for individual studies to express the diagnostic performance of chest CT imaging in terms of sensitivity, specificity, PPV, and negative predictive value (NPV) with respect to the detection of rib fractures. To assess the overall diagnostic performance of chest CT against the reference standards, the diagnostic accuracy measures reported for all rib fractures in each study were pooled with those that utilised the same reference standard. Separately, to assess the diagnostic accuracy of chest CT in the detection of rib fractures based on specific locations along the rib arc (anterior, lateral and posterior), the diagnostic accuracy measures reported in studies were pooled with those using the same reference standard for each location. A meta-analysis was performed when at least two studies met the criteria.

Forest plots estimating the sensitivity and specificity with 95% confidence intervals (CIs) were created using a univariate random-effects model. Moreover, a receiver operator characteristic (ROC) curve was generated to calculate the area under the curve (AUC).

Heterogeneity between studies included in the meta-analysis was assessed using the I^2 statistic with heterogeneity categorised by low (0%–40%), moderate (50%–75%), and high (>75%) [36]. Meta-analyses were performed using STATA 14 package metandi (STATA Corporation, TX, USA).

3.4 Results

3.4.1 Search strategy

Of 242 articles identified, 42 duplicates and 178 articles were excluded on the basis of title and abstract. Of the 22 full text articles extracted, 18 did not fulfil the inclusion criteria. The remaining 4 articles were included for qualitative synthesis. Of these, two studies [21, 31] were excluded from the meta-analysis because the TP, TN, FP, and FN values were not reported or could not be derived. Figure 3.1 illustrates the search strategy and study selection process.

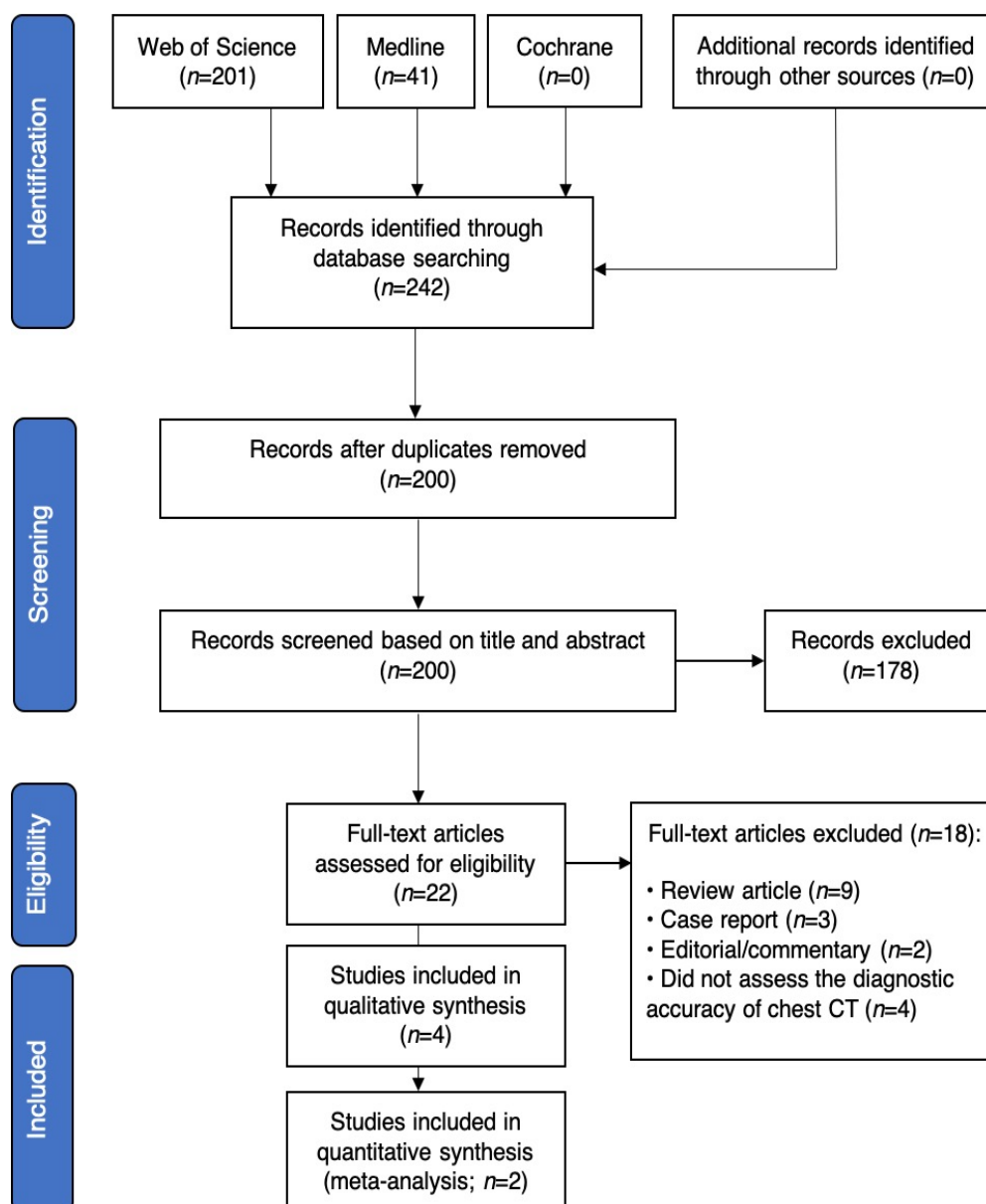


Figure 3.1. Flowchart of the study selection process

3.4.2 Study characteristics and quality assessment

The characteristics and main findings of the included studies are summarised in Table 3.1. These observational retrospective studies included a total of 109 children. The mean age per study ranged from 2.5 months to 12 months, with a mean age of 6 months across all studies. The reference standards against which chest CT was compared were: CXR from initial SkS in two studies (time interval 1 day); and autopsy in the remaining two (time interval 0 to 5 days, median 2 days). The tube voltage (kilovolts, kV)

and current (milliampere, mA) settings for chest post-mortem CT (PMCT) were 120 kV and 200–355 mA, and 100 kV and 15 mA in live children, respectively.

Table 3.2 summarises the results of the quality assessment of the 4 included studies. In the patient selection domain, three studies [21, 25, 31] were assessed as having an unclear risk of bias due to poor sampling procedure reporting. One study [21] was scored as having an unclear risk of bias in the index test domain as it was unclear whether the chest CT results were interpreted without knowledge of reference standard results. In the reference standard domain, two studies [21, 26] were judged as having an unclear risk of bias because they did not offer information on whether the reference standard was interpreted without knowledge of the results of the index test. Regarding applicability concerns, one study [21] had a high risk of concern in the index test domain because chest CT was only performed in children with normal initial CXR: this affects the diagnostic accuracy as all children with positive and negative initial CXR were supposed to have chest CT. Additionally, one study [31] had an unclear risk of concern in the patient selection domain because information about the clinical indication for patients who underwent CT examinations was not provided.

Table 3.1. Characteristics and main findings of included studies.

Study	1	2	3	4
Author (year)	Wootton-Gorges <i>et al</i> [31]	Hong <i>et al</i> [26]	Sanchez <i>et al</i> [21]	Shelmerdine <i>et al</i> [25]
Study design (recruitment start and end dates)	Retrospective (between 1999 and 2004)	Retrospective (between January 2007 and October 2009)	Retrospective (between January 2008 and January 2012)	Retrospective (between January 2012 and January 2017)
Sample size / Number of reviewed ribs	12 / 225 ribs	56 / 1318 ribs reviewed at primary (clinical) interpretation and 298 ribs reviewed at research radiologist's interpretation	16 (only 5 of whom had both CXR and chest CT) / Not reported	25 / 600 ribs (12 pairs of ribs in 25 children)
Mean Age (range)	Mean age 2.5 months (range 1.2 to 5.6 months)	Mean age 12 months (range 8 days to ~93 months); 46 children < 24 months)	Mean age 6 months (range 1 to 11 months)	Median age 4 months (range 17 days to 7 years)
Reference test	Initial CXR (AP and lateral projections)	Autopsy	Initial CXR (AP, lateral, right and left oblique projections)	Autopsy
CT imaging protocol	Not reported	• Either 8 multi-slice helical CT (GE), 128-slice MDCT (GE) or 16-slice CT (Philips) • 120 kV, 320 and 355 mA, 0.53 and 0.93 mm pitch, rotation time 0.75 & 0.80 s • Slice thickness reconstruction 0.80–0.62 mm • 3D reconstruction	• 100 kV, 15 mA, 1 mm pitch, rotation time 0.5 s • Adaptive iterative reconstruction blend of 20%	• 64-slice MDCT (Siemens) • Collimation 0.62 mm • 120 kV, 200–350 mA, 1 mm pitch • Slice thickness reconstruction (1 mm)
Time interval between the reference standard and CT imaging	1 day	Not reported	1 day	Median 2 days (range 0 to 5 days)

The study primary outcome	• Chest CT=131 rib fractures • CXR=79 rib fractures • CT more sensitive in the detection of rib fractures based upon anatomical position than CXR in the detection of rib fractures at all anatomical positions (p<0.01), except in lateral location • Two radiologists reviewed the chest CT studies	• 101 rib fractures at autopsy (standard) • Two image interpretation methods were used for the detection rib fractures by fracture locations: A. Primary (clinical) interpretation=chest CT showed sensitivity 51.5% and specificity 99.7% for detecting rib fractures by fracture locations • PM CXR for detection of rib fractures: at specified locations=sensitivity 28.9% and specificity 99.9%; the sensitivity and specificity of PM CXR at specific locations along rib arc* was 8% and 99% at anterior; 80% and 100% at lateral; 29% and 98% at posterior B. Radiologist interpretation=13 children: 12 with rib fractures at autopsy and 1 false positive at chest radiograph primary interpretation; chest CT showed sensitivity 85.1% and specificity 99.4% for detecting rib fractures by fracture locations • Two radiologists reviewed chest CT (3 studies reviewed by one radiologist) at primary (clinical) interpretation; radiologist interpretation performed by one radiologist only	• Chest CT=11 rib fractures all missed on initial CXR • 7 rib fractures identified on follow-up[†] CXR (1-2 weeks) in patients who did not have chest CT • The number of radiologists who reviewed chest CT was not reported	• 136 rib fractures at autopsy (standard) • Chest CT for detection of rib fractures: at specified locations= sensitivity 44.9% and specificity 97% • PM CXR for detection of rib fractures: at specified locations= sensitivity 13.5% and specificity 97.9%; the sensitivity and specificity of PM CXR at specific locations along rib arc was 15% and 97% at anterior, 0.8% and 98% at lateral, 27% and 98% at posterior, respectively • Thirty-five radiologists reviewed the CT chest studies and thirty-eight reviewed the CXR studies
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**the location of the rib fractures was divided into three segments: anterior fracture includes costochondral, anterior and anterolateral; posterior fracture includes costovertebral, posterior and posterolateral; and lateral. Calculated as follows [anterior = (anterior + anterolateral) / 2].*

[†]follow-up skeletal

Table 3.2. Quality assessment of included studies.

Study	Risk of bias				Applicability concerns		
	Patient selection	Index test	Reference standard	Flow and timing	Patient selection	Index test	Reference standard
Hong <i>et al</i> [26]	1	1	2	1	1	1	1
Sanchez <i>et al</i> [21]	2	2	2	1	1	3	1
Shelmerdine <i>et al</i> [25]	2	1	1	1	1	1	1
Wootton-Gorges <i>et al</i> [31]	2	1	1	1	2	1	1

Low risk =1; unclear risk = 2; high risk =3.

3.4.3 Diagnostic performance of chest CT

Two retrospective studies [21, 31] demonstrated superior diagnostic accuracy of chest CT in the detection of rib fractures compared to initial CXR. Sanchez *et al.* [21] reported that chest CT detected 11 rib fractures that were missed on initial CXR. Wootton-Gorges *et al.* [31] observed 131 rib fractures on chest CT compared to 79 on CXR. Additionally, Wootton-Gorges *et al.* [31] reported that chest CT performed better in detecting rib fractures along the rib arc ($p<0.01$), except for lateral locations.

The retrospective studies by Hong *et al.* [26] and Shelmerdine *et al.* [25] compared the diagnostic accuracy of chest CT to autopsy in the detection of rib fractures. Chest CT reported sensitivity (51.5% and 44.9%, respectively) and specificity (99.7% and 97.0%, respectively) in the detection of rib fractures at specific locations. Hong *et al.* [26] noted that the sensitivity for detecting rib fractures at specific locations increased from 51.5% at primary (clinical) interpretation to 85.1% following radiologist interpretation.

We grouped two studies ($n=81$ children) regarding the diagnostic performance of chest CT as compared to autopsy in the detection of rib fractures: Table 3.3 presents the sensitivity and specificity of chest CT. Forest plots for overall chest CT diagnostic performance demonstrated sensitivity 34% (95% CI 18–55%) and specificity 99% (95% CI 94–100%) (Figure 3.2), and PPV 95% (95% CI 91–100%), NPV 59% (95% CI 58–61%) and AUC 79% (95% CI 75–82%). Significant heterogeneity existed for both sensitivity and specificity ($I^2=99\%$). The pooled diagnostic sensitivity and specificity of chest CT in the detection of rib fractures along the rib arc was: 45% and 99% at anterior locations; 21% and 99% at lateral locations; and 42% and 97% at posterior locations, respectively.

Table 3.3. Diagnostic performance measures (sensitivity and specificity) of chest CT in the detection rib fractures.

Study	Reference test	Fracture location along rib arc*	Number of ribs included in analysis	Number of observations	Number of rib fractures identified by the reference test	TP	TN	FP	FN	Sensitivity %	Specificity %
Hong <i>et al</i> [26]	Autopsy	Anterior	1318	N/A	49	16	2587	3	33	33	100
		Lateral			5	0	1313	3	5	0	100
		Posterior			47	36	2589	12	11	77	100
Shelmerdine <i>et al</i> [25]	Autopsy	Anterior	600	21 000 [†]	111	1769	15 783	1332	2116	46	92
		Lateral			10	164	19 574	901	361	31	96
		Posterior			15	164	6479	1081	1011	14	86

*the location of the rib fractures was divided into three segments: anterior fracture includes= costochondral, anterior and anterolateral; posterior fracture includes= costovertebral, posterior and posterolateral; and lateral.

[†]calculated as 25 cases × 24 ribs × 35 reporters.

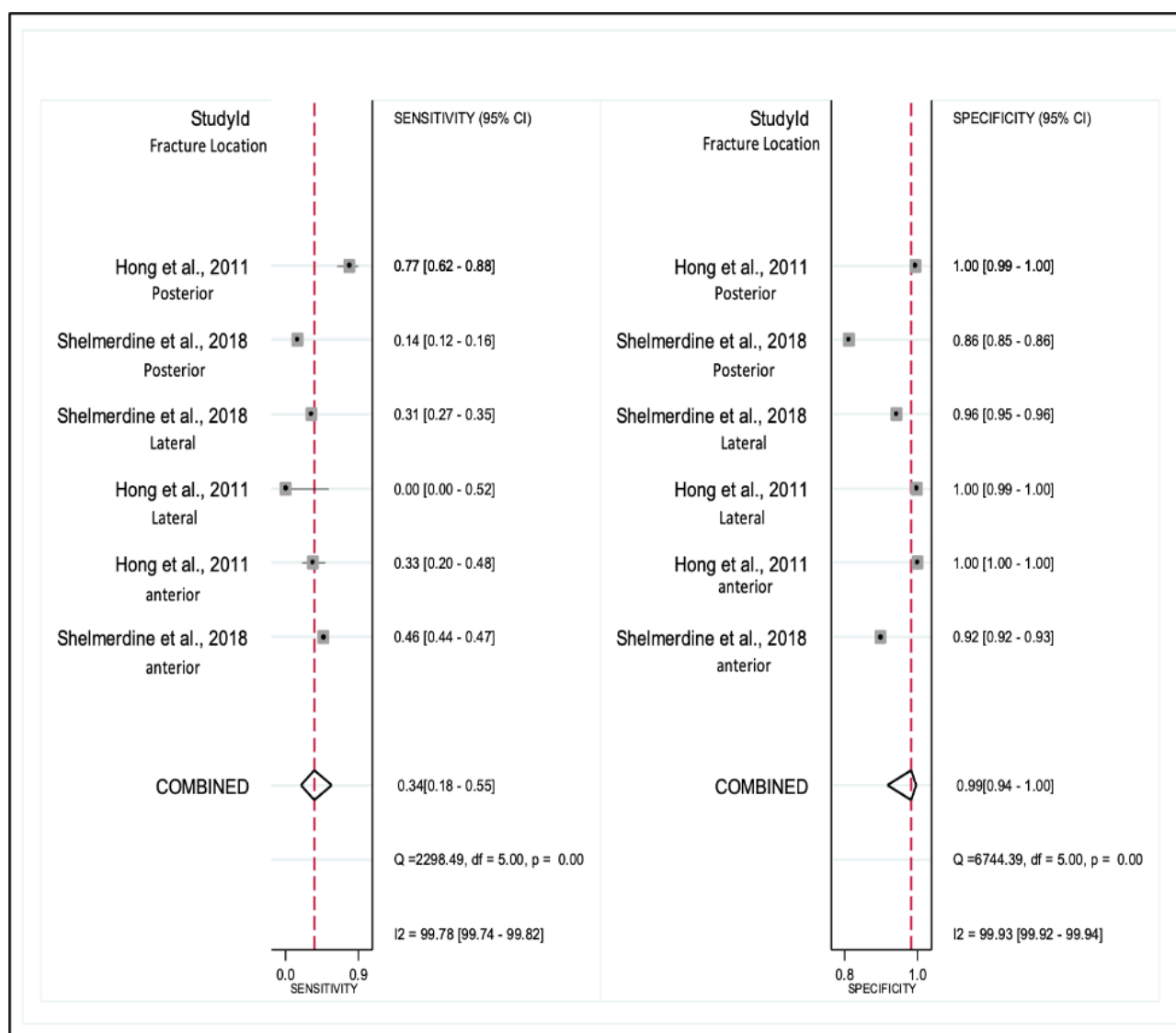


Figure 3.2. Forest plot of overall sensitivity and specificity with 95% confidence intervals of chest CT in the detection of rib fractures.

3.5 Discussion

This systematic review and meta-analysis provides an overview of the diagnostic performance of chest CT in the detection of rib fractures in children with SPA. This study demonstrates that chest CT detects more rib fractures than initial CXR. The overall diagnostic performance of PMCT is 34% sensitivity and 99% specificity in the detection of rib fractures when compared to autopsy, while PM CXR showed a sensitivity of 13.5% and 28%, and specificity of 97% and 99% [25, 26]. Overall, PMCT exhibited the lowest sensitivity for lateral rib fracture locations, with sensitivities of 45%, 21%, and 42% at anterior, lateral and posterior locations, respectively. The diagnostic performance of PM CXR at specific rib fracture

locations reported in two of the included studies [25, 26] was sensitivity: 8% and 15.8% at anterior; 80% and 0.8% at lateral; and 29% and 27% at posterior rib fracture locations, respectively. PM CXR pooled sensitivities, specificities and meta-analyses were not performed due to the different projections obtained in the included studies: 3 projections (AP, right and left obliques) were utilised by Shelmerdine *et al.* [25] whereas only 2 projections (AP and lateral) were used by Hong *et al.* [26]. It has been reported by Hong *et al.* [26] that PM CXR missed 42 anterior rib fractures while 27 anterior rib fractures were missed on CT in children who underwent cardiopulmonary resuscitation.

Notably, chest CT detected more rib fractures than initial CXR in abused live children. In 2 studies, chest CT identified 142 rib fractures compared to 79 detected by initial CXR [21, 31]. This is because CT provides high resolution cross-sectional images of the thoracic cage with volumetric and multi-planar reconstructions [37] eliminating the contributing factors which obscure rib fractures on CXR; in particular, acute and/or non-displaced fracture where callus formation, indicative of healing, is not present [7].

The overall low sensitivity (34%) and high specificity (99%) of PMCT in this systematic review are consistent with the results of a study validating PMCT against autopsy in the detection of rib fractures in adults (low sensitivity of 58% and high specificity of 97%) [38]. A possible explanation of this low sensitivity is that PMCT may not accurately detect reattached rib fracture edges on autopsy [38]. Moreover, autopsy is not a perfect reference standard due to its fallibility with respect to partial rib fractures which are more easily detected by PMCT [38]. Interestingly, Hong *et al.* [26] observed that PMCT sensitivity increases from 51.1% at primary (clinical) interpretation to 85.1% at radiologist interpretation: not an unexpected result given that the interpretation was performed by an experienced radiologist (22 years' experience). High heterogeneity in reported sensitivity and specificity was observed among the included studies which could be secondary to the differences in radiologists' experience and the imaging protocols employed.

Concerns regarding the relatively high radiation exposure of chest CT [39, 40] have traditionally made chest CT a less desirable option in the routine clinical investigation of SPA in live children [41]. It is well-documented that children are more vulnerable to the effects of ionising radiation and potential future risk of radiation-induced cancer than adults, in addition to a greater time over which the consequences of radiation exposure may be borne out [42-45]. However, adjusting the scanning parameters (e.g. mA, kV and pitch) and the use of iterative reconstruction reduces the radiation dose and the consequent

potential risk and concerns regarding radiation-induced cancers [46, 47]. Recently, a developed low-dose chest CT (LDCT) protocol for the detection of rib fractures in children with SPA employed radiation doses approaching those of standard CXR without compromising diagnostic quality [32]. Sanchez *et al.* [32] reported an optimised chest CT protocol for detecting rib fractures in children with SPA aged up to 4 months old with an effective dose of 0.56 millisieverts (mSv), compared to the dose of 0.29 mSv of the initial standard four views of CXR (anteroposterior, lateral and two oblique projections) performed at their institution.

The risk of exposure to ionising radiation in the case of chest CT should be balanced against the risk of missed diagnoses of physical child abuse, in particular, missing occult acute rib fractures on initial SkS CXR [21]. Given that follow-up SkS imaging is not guaranteed (as children are reliant on their caregiver/parent to return them to hospital for follow-up imaging), children may remain in an abusive environment, which risks sustaining a further, potentially fatal, injury [48]. Chest CT demonstrates a higher sensitivity in the detection of acute rib fractures in live children who may have been abused, thus potentially rendering the initial and follow-up SkS CXR redundant. Moreover, this would result in an overall reduction in radiation burden if LDCT protocols are utilised and may facilitate more prompt and appropriate management in cases of child protection.

This study has several limitations. First, a small number of studies ($n=2$) were included in the meta-analysis which is insufficient to accurately evaluate the diagnostic performance of PMCT in the detection of rib fractures. Therefore, the results of the meta-analysis should be interpreted cautiously. Notably, the results of this meta-analysis should be restricted to the diagnostic performance of chest CT in PM children. The image quality of chest PMCT examinations may be higher than in live children (given that dose restrictions are not a consideration) which may increase its diagnostic accuracy. Second, all included studies were retrospective. Third, whilst the reference standards used to assess the accuracy of the chest CT in the detection of rib fractures and skill of the radiologist reading them are those used in current clinical practice, they themselves are imperfect. Fourth, although physical abuse is not common over the age of 2 years, our search criteria included participant age up to 18 years to ensure that we captured all relevant papers. In total, 13 children (11.9%) were over the age of 2 years, with a mean age of 6 months across all 4 papers; therefore, we believe the results of this review are applicable to cases of SPA. Finally, this systematic review might be prone to publication bias given that the literature search was restricted to English language studies only.

Although chest CT shows promising results in the detection of acute and healing rib fractures, further research is required to better elucidate its diagnostic performance. Ideally, the diagnostic accuracy of chest CT (compared to a reference standard of initial and follow-up CXR from SkS) should be evaluated in a prospective study with a large cohort of live children. Additionally, to adhere to the as low as reasonably achievable (ALARA) principle, evaluation of a LDCT chest protocol to reduce exposure to ionising radiation could be conducted prior to formal implementation in clinical practice.

3.6 Conclusion

The diagnostic performance of chest CT for detecting rib fractures in children suspected of having been physically abused has not previously been systematically evaluated in the literature. Chest CT detects more rib fractures than initial CXR in children with SPA. PMCT has a low sensitivity but high specificity for detecting rib fractures (especially in lateral locations) compared to autopsy.

3.7 References

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3.8 Systematic review update April 2020- June 2023

This section reviews the studies published since the publication of the systematic review. The systematic review literature search was updated to include studies from April 2020 to June 2024. Two additional studies (on live children) were identified that met the inclusion criteria: those by Pomeranz *et al.* [1] and Karmazyn *et al.* [2]. The results of the quality assessment of the two studies are summarised in Table 3.4.

Table 3.4. Quality assessment of eligible studies following search update (April 2020- June 2024).

Study	Risk of bias				Applicability concerns		
	Patient selection	Index test	Reference standard	Flow and timing	Patient selection	Index test	Reference standard
Pomeranz <i>et al.</i> [1]	2	3	3	3	1	1	1
Karmazyn <i>et al.</i> [2]	2	1	1	1	1	1	1

Low risk =1; unclear risk = 2; high risk =3.

Pomeranz *et al.* [1] compared initial CXR and chest CT in detecting rib fractures in 57 children with suspected and confirmed physical abuse. Chest CT detected more rib fractures (225 fractures) than initial CXR (187 fractures). Of 38 missed fractures on initial CXR but seen on CT, 24 rib fractures were acute and 14 fractures were healing. To the best of my knowledge, the study by Pomeranz *et al.* [1] is the largest published study to date that compares CT to CXR SkS in detecting rib fractures in live children investigated for SPA. However, this study has several limitations. First, the initial CXR and CT images were reviewed by a paediatric radiology fellow who was not blinded to the original reports by the reporting radiologists. Second, included cases had a broad time interval between initial CXR and chest

CT (<30 days), which is more likely to increase fracture detection on CT due to development of the healing response of fractures. Third, CT was compared only to initial CXR which does not reflect the reference standard used in clinical practice (i.e., initial and follow-up CXR SkS).

Karmazyn et al. [2] assessed the yield of chest CT in detecting rib fractures compared to chest radiography as part of the SkS in 50 children with SPA. Chest CT performed within 3 days of initial CXR and CT revealed significantly more rib fractures (112 fractures) than initial CXR (42 fractures). Of 50 children, 27 (54%) had follow-up CXR performed an average of 17 days (range 13–25 days) after the initial CXR; follow-up CXR demonstrated 49 rib fractures while chest CT revealed 93 rib fractures. Out of 50 patients, 10 had negative initial CXR. Of these, CT revealed rib fractures in 4 patients and was negative in the other 6 patients; 4 of these 6 patients had negative follow-up CXR. The study by *Karmazyn et al.* [2] has some limitations. There was a lack of a reference standard. In the study, chest CT was compared to either initial CXR only or follow-up CXR only; this does not reflect clinical practice where the final radiological diagnosis of rib fractures in SPA cases is based on reading initial and follow-up CXR together. Furthermore, only 27 of 50 children had follow-up CXR. Moreover, the number of reporters was limited (2 radiologists with 9 and 15 years of experience).

In conclusion, the results of these studies support the key conclusion of the systematic review, that chest CT is superior to initial CXR in detecting rib fractures in live children investigated for SPA.

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Chapter Four

Rib fracture diagnosis in suspected abuse: Computed Tomography Or Radiographs (RECEPTOR)? A multicentre diagnostic accuracy observational study

The paper is in preparation for publication

4. Rib fracture diagnosis in suspected abuse: Computed Tomography Or Radiographs (RECEPTOR)? A multicentre diagnostic accuracy observational study

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- Review of study protocol: A.C.O., A.J. and M.P.
- Sought national R&D ethical approval (IRAS application) and for 13 participating centres across Europe: **N.M.A.**
- Contacted collaborators regarding eligibility of cases, explained the study and responded to the inquiries of readers: **N.M.A.**
- Anonymised the images: **N.M.A.**
- Designed the report proforma: **N.M.A.**
- Data collection: **N.M.A.**
- Statistical analysis:
 - Cleaned and tabulated the data for analysis of 19 readers for all 3 phases of the study: **N.M.A.**
 - Chose the appropriate tests: **N.M.A.** and A.R.
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 - Supervised the statistical analysis: A.R.
- Wrote the initial draft of the manuscript: **N.M.A.**
- Reviewed and approved the final draft of the manuscript: **N.M.A.**, A.C.O., A.J. and M.P.

Note—At the time of PhD thesis submission and up to the time of writing this statement letter, the RECEPTOR collaborators have ONLY been involved in this study as readers (reading images). In other words, the input of RECEPTOR collaborators is thus far limited ONLY to reading the images. The manuscript will be sent to them for approval prior to publication.

4.1 Abstract

Background

Rib fractures are strongly associated with physical abuse in children below the age of two years. Chest radiography is the current imaging standard used to diagnose rib fractures in children with suspected physical abuse (SPA). Studies have shown that chest computed tomography (CT) has a greater sensitivity than initial skeletal survey chest radiographs (CXRs) for detecting acute and healing rib fractures in children with SPA.

Objective

To assess the diagnostic performance of chest CT for detecting rib fractures in children investigated for SPA using initial and follow-up CXRs as the reference standard.

Methods

A retrospective 10-year (September 2011 to 2021) multicentre search was performed for children less than 2 years of age who received CXRs as part of the initial and follow-up skeletal surveys and chest CT for SPA. Radiologists were recruited voluntarily as reporters via the membership database of the Child Abuse Taskforce of the European Society of Paediatric Radiology. Radiologists independently read the images in three separate reads: Read 1 (initial CXRs only), Read 2 (CTs only) and Read 3 (initial and follow-up CXRs) performed at least one month apart. The order of Reads 1 and 2 were varied between reporters but no reporter performed Read 3 before Read 1 or 2. Radiologists reported the presence of rib fractures, fracture age, fracture location and their interpretation confidence level. The diagnostic performance of CT was calculated for per patient, per rib and per specific location along the rib arc.

Results

A total of 64 patients (36 male) with a median age of two months were included and independently assessed by 19 consultant radiologists. In the patient analysis, sensitivity of CT was 90.61% (95% confidence interval [CI]: 88.21–92.66) and specificity was 74.26% (95% CI: 70.26–78.00). In the rib analysis, sensitivity of CT was 85.63% (95% CI: 84.17–87.01) and specificity was 94.16% (95% CI: 93.88–94.44). In the location analysis, sensitivity of CT was 75.75% (95% CI: 74.04–77.40) and specificity was 97.09% (95% CI: 96.98–97.21).

Conclusion

Chest CT confers accurate rib fracture detection in live children with SPA, potentially rendering the current recommended standard of the six view CXRs acquired as part of the skeletal survey redundant.

4.2 Introduction

Rib fractures are one of the most common and highly specific skeletal injuries for physical abuse in infants and young children [1-6]. Rib fractures in children under the age of 3 years have a reported 95% positive predictive value for physical abuse [7]. Diagnostic imaging plays a crucial role in the assessment of children with suspected physical abuse (SPA) given that any proffered history may be misleading, absent or incongruent with the clinical examination [8, 9].

Currently, chest radiography (anteroposterior and right and left oblique projections) as part of a skeletal survey (SkS) is the recommended standard imaging method for detecting rib fractures in children investigated for SPA [10, 11]. However, acute rib fractures are often undetected on initial chest radiographs (CXRs) [12-14] because they are often minimally displaced, incomplete [15] and may be obscured by overlying structures [13, 14]. CXRs as part of a follow-up SkS performed 11 to 14 days after the initial SkS are advocated, because interval bone healing with callus formation increases the conspicuity of rib fractures, improving their detection [16-19]. However, there are limitations of chest radiography in rib fracture detection in cases of SPA: the presence or absence of abusive rib fractures cannot always be confirmed until at least 11 days after initial CXRs have been performed, which risks exposing the child to further potential harm. There is also no guarantee that the child will be returned for follow-up imaging and thus, physical abuse could potentially be missed. Furthermore, posterior costovertebral fractures and costochondral junction fractures can be missed, both on initial and follow up CXRs due to their posterior location adjacent to the spine, and the tendency of costochondral fractures to heal without callus or subperiosteal new bone formation (SPNBF) [20].

Chest computed tomography (CT) has been shown to be more sensitive than CXRs in detecting rib fractures in adult trauma [21] and also in live [12-14, 22] and post-mortem (PM) [15, 23] children with SPA. Although a few studies have assessed accuracy of CT in detecting rib fractures in live children with SPA [12-14, 22], these studies had few reporters, small sample sizes or inadequate/inappropriate reference standards (initial CXR only). Our study aimed to assess the diagnostic performance of CT in

detecting rib fractures in live children with SPA, compared with the current recommended standard used in routine clinical practice (initial and follow-up CXRs) as the reference standard.

4.3 Methods

4.3.1 Study design and patient selection

This was a multicentre retrospective observational diagnostic accuracy study. The radiology information and picture archiving and communication systems of 13 European radiology departments were searched from September 2011 to 2021 (10 years) for children less than 2 years of age who underwent CXRs as part of initial and follow-up SkS and chest CT for SPA. Radiological reports were not reviewed. The CXRs from the SkS and chest CT data sets of eligible cases were anonymised and sent to the first author (N.M.A.) in the form of Digital Imaging and Communications Medicine (DICOM) images either 1) via a password protected file sharing website (Google Drive); or 2) via password protected USB flash or CD drives. The study was approved by the United Kingdom Health Research Authority (UK HRA; 21/HRA/2368) (Appendix 2) as well as by the research ethics committees of each participating centre. Due to the retrospective nature of the study and the use of anonymised patient data, the research ethics board waived the need for informed consent.

4.3.2 Reporter recruitment and image analysis

Radiologists were recruited as voluntary reporters via a call for participants from the Child Abuse Taskforce of the European Society of Paediatric Radiology (ESPR) membership database or from participating centres having expressed an interest. Only consultant radiologists (independent practising radiologists who had completed postgraduate clinical radiology speciality training) were recruited. The number of years of general and paediatric reporting experience for each radiologist was recorded.

The retrieved imaging was read in three rounds: Read 1, initial CXRs only; Read 2, chest CTs only; and Read 3, initial and follow-up CXRs. The order of Reads 1 and 2 varied between reporters, but no reporter performed Read 3 before Read 1 or 2. Each read round was performed over 2 months with a 1-month washout period between rounds to reduce recall bias (i.e., image recall and interpretation from the previous read). For Read 3 (initial and follow-up CXRs), reporters were given the results of their Read 1 (initial CXRs only), reflecting clinical practice: reporters were otherwise not provided with the results of their reads during the study period. Reporters were blinded to the results of other reporters. The anonymised CXRs and CT datasets were provided to the reporters in the form of DICOM files via a

password protected file sharing website (Google Drive). Reporters were advised to replicate their usual practice when reporting cases i.e., using diagnostic quality imaging displays, appropriate dim lighting, etc. Reminder emails were sent to reporters at fortnightly intervals prompting them to submit their analyses within the specified timeframes.

CXR were extracted from the SkSs. Anteroposterior abdominal projections were only included to view the lower ribs where the CXRs did not image the entire osseous thorax. The chest CT imaging was retrieved as either a standalone examination or extracted if part of a multipart examination (i.e., chest/abdomen/pelvis CT examination). The thinnest available axial CT slices were provided to the reporters. The median of CT slice thickness across the cases was 1 millimetre (mm), ranging from 0.5 mm to 3 mm. The slice thickness of CT images varied as follows: 0.5 mm in 3 cases (4.7%), 0.6 mm in 13 cases (20.3%), 0.7 mm in 3 cases (4.7%), 1 mm in 35 cases (54.7%), 1.5 mm in 1 case (1.6%), 2 mm in 6 cases (9.4%), 2.5 mm in 2 cases (3.1%) and 3 mm in 1 case (1.6%). The CT images were provided to the reporters with both bone and soft tissue windows in 48 patients (75%). Where chest CT images were available only in either soft tissue windows (6 patients, 9.4%) or soft and lung windows (10 patients, 16.6%), reporters were asked to read the images on bone windows (by manually selecting this window in their imaging software). Multiplanar reconstructions (MPR) and three-dimensional volume rendering (3DVR) were not retrieved from any centre or provided to reporters; however, reporters had the ability to perform MPR on their own imaging software as they would as part of their own clinical practice. The CXRs from the SkS and chest CT examinations were performed in different centres on machines from multiple vendors with different protocols.

A Google form was constructed to document the presence of rib fractures which was shared with the reporters via a password protected file sharing website (Google Drive). The form included fracture age (acute or healing), fracture locations (rib number, side and location), and the reporter's confidence level for the presence of fracture (a scale of 1 to 3: 1, not confident; 2, equivocal; and 3, confident). Acute fractures were defined as those with sharp margins and no evidence of healing, while healing fractures were those with periosteal reaction (even if subtle), and/or callus (soft or hard), and/or remodelling. The location of the rib fractures was divided into the following areas to standardise rib location reporting along the rib arc for CXRs: anterior, including costochondral, anterior and anterolateral; lateral; and posterior, including posterolateral, posterior and costovertebral. A separate reporting form was

constructed for the CT imaging on which additional questions were posed regarding MPR or 3DVR and whether they aided the detection of rib fractures.

For the chest CT examinations, the reporting clockface method utilised by Shelmerdine *et al.* [23] was used to standardise reporting of rib locations along the rib arc. This method allows reporters to record the rib fracture location around an imaginary clockface when the chest is viewed in an axial section. The rib fracture location is divided into three categories: anterior, lateral and posterior. At any given level, the 12 o'clock position is the sternum (not scorable), the 1 to 5 o'clock positions are located along the left rib, the 6 o'clock position is the vertebral column (not scorable), and the 7 to 11 o'clock positions are located along the right rib. The 1 and 11 o'clock positions refer to costosternal junction locations, and the 5 and 7 o'clock positions refer to costovertebral junction locations. Therefore, anterior fractures include the 1, 2, 10, and 11 o'clock positions; lateral fractures include the 3 and 9 o'clock positions; and posterior fractures include the 4, 5, 7, and 8 o'clock positions (Figure 4.1).

A rib fracture on both CXR and chest CT was defined as 'a rib with complete cortical breach, cortical irregularity or buckling, or the presence of healing around the bone' [23]. The initial and follow-up CXRs from the SkS were the reference standard in this study as this is current standard in clinical practice [10, 11]. The true positive for chest CT images was defined as the detection of a rib fracture reported by the majority of radiologists (i.e., >50% of reporters) when documenting their reads of the initial and follow-up CXR to establish a robust reference standard across reporters.

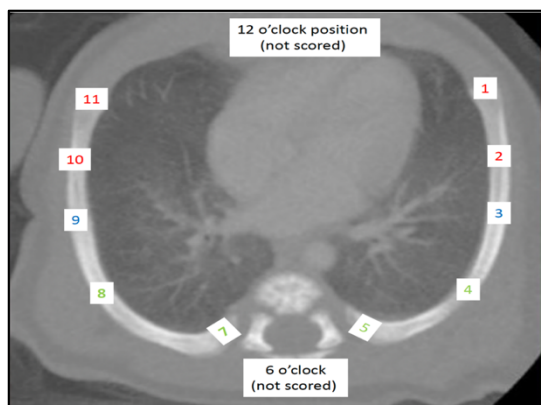


Figure 4.1 Axial computed tomography scan of the chest illustratrates the clockface method used for reporting the location of rib fractures.

Reconstruction parallel to each rib: a single rib identified through its entire length. Anterior fractures: 1, 2, 10, and 11 o'clock positions; lateral fractures: 3 and 9 o'clock positions; and posterior fractures: 4, 5, 7, and 8 o'clock positions (courtesy of Dr Maria Raissaki, Radiology Dept, University of Crete, Greece).

4.3.3 Statistical analysis

Continuous data are presented as the median and interquartile range (IQR), whereas categorical data are presented as frequency counts and percentages. The diagnostic performance of CT for diagnosing rib fractures was calculated on a per-patient, per-rib, and per-location basis and was determined using sensitivity, specificity, and accuracy with corresponding 95% confidence intervals (CIs). Table 4.1 lists the definitions of descriptive parameters at different diagnostic analysis levels. A Wilcoxon trend test was applied to assess whether the experience level of the reporters influenced the diagnostic accuracy of CT. The powered sample size calculation was based on a previously published study that compared CXRs against CT in detecting rib fractures in PM children [23] which reported that the estimated sensitivity of CXRs and CT as 64.7% and 81.5%, respectively. We assumed a power of 80% to detect a difference of 16.8% between the two modalities with an alpha confidence level of 5%, resulting in a required sample size of 108. The statistical analysis was performed using SPSS software (v.27; IBM, Armonk, NY), STATA software (v.14.2, StataCorp, Texas, United States) and Excel version 2016 (v.2016, Microsoft, Redmond, United States). A $P < 0.05$ was considered statistically significant.

Table 4.1. Definitions of descriptive parameters in diagnostic analyses

Analysis level	True positive	True negative	False positive	False negative
Per-patient	At least one fracture in a patient detected using CT and CXR* regardless of fracture location	No fracture in a patient detected using either CT or CXR* regardless of fracture location	At least one fracture in a patient detected using CT and no fracture detected using a CXR* regardless of fracture location	No fracture detected by CT and at least one fracture detected using a CXR* regardless of fracture location
Per-rib	At a given rib and side, at least one fracture detected using CT and CXR* regardless of fracture location (anterior, lateral or posterior)	At a given rib and side, no fracture detected using either CT or CXR* regardless of fracture location (anterior, lateral or posterior)	At a given rib and side, at least one fracture detected using CT and no fracture detected using CXR* regardless of fracture location (anterior, lateral or posterior)	At a given rib and side, no fracture detected using CT and at least one fracture detected using CXR* regardless of fracture location (anterior, lateral or posterior)
Per-location	At a given rib, side and fracture location, at least one fracture detected using CT and CXR*	At a given rib, side and fracture location, no fracture detected using CT or CXR*	At a given rib, side and fracture location, at least one fracture detected using CT and no fracture detected using CXR*	At a given rib, side and location, no fracture detected using CT and at least one fracture detected using CXR*

* by >50% of reporters (≥10/19 reporters)

4.4 Results

A total of 68 cases were collected from 13 hospitals across Europe. We excluded four cases because they had no initial CXRs (n=1) or follow-up CXRs (n=3). Of the 64 included cases, 36 (56.30%) were boys. The median age was 2 months (IQR: 69 days, range 13 days to 15 months). The median time between initial CXR and chest CT was 2 days (IQR:12 days, range 0 to 23 days). Of 64 patients, 46 had initial CXR and chest CT performed within 7 days (median: 1 day, IQR: 3 days, range: 0 to 7 days).

A total of 136 fractures were found at the reference standard (initial and follow-up CXRs), of which: 45 (33%) fractures were anterior; 23 (17%) were lateral; and 68 (50%) were posterior. There were 83 (61%) acute and 53 (39%) healing fractures.

4.4.1 Diagnostic performance of CT for detecting rib fractures

4.4.1.1 Comparison between chest CT and initial CXR versus the reference standard in 64 patients

The diagnostic performance of initial CXR and chest CT for rib fractures on patient-, rib- and location-based analyses is detailed in Table 4.2. The sensitivity, specificity, and accuracy of initial CXR and CT for detecting rib fractures in children with SPA for the following analyses were: per-patient, 63.58% (95% CI: 59.91–67.15) vs. 90.61% (95% CI: 88.21–92.66), 77.97% (95% CI: 74.13–81.49) vs. 74.26% (95% CI: 70.26–78.00) and 69.65% (95% CI: 66.98–72.23) vs. 83.72% (95% CI: 81.52–85.75), respectively; per-rib, 49.71% (95% CI: 47.69–51.73) vs. 85.63% (95% CI: 84.17–87.01), 97.33% (95% CI: 97.13–97.52) vs. 94.16% (95% CI: 93.88–94.44) and 93.42% (95% CI: 93.13–93.70) vs. 93.46% (95% CI: 93.17–93.74), respectively; and per-location were 35.77% (95% CI: 33.93–37.64) vs. 75.75% (95% CI: 74.04–77.40), 98.58% (95% CI: 98.50–98.66) vs. 97.10% (95% CI: 96.98–97.21) and 96.71% (95% CI: 96.59–96.83) vs. 96.47% (95% CI: 96.35–96.60), respectively.

Table 4.2. Diagnostic performance of initial chest radiographs and chest CT for the detection of rib fractures

Analysis level	Imaging study	TP	TN	FP	FN	Sensitivity (95% CI)	Specificity (95% CI)	Accuracy (95% CI)
Per-patient (n=1216)	Initial CXR	447	400	113	256	63.58 % (59.91–67.15)	77.97 % (74.13–81.49)	69.65% (66.98–72.23)
	CT	637	381	132	66	90.61% (88.21–92.66)	74.26% (70.26–78.00)	83.72% (81.52–85.75)
Per-rib (n=29184)	Initial CXR	1190	26074	716	1204	49.71% (47.69–51.73)	97.33 % (97.13–97.52)	93.42% (93.13–93.70)
	CT	2074	25200	1562	348	85.63% (84.17–87.01)	94.16% (93.88–94.44)	93.46% (93.17–93.74)

Analysis level	Imaging study	TP	TN	FP	FN	Sensitivity (95% CI)	Specificity (95% CI)	Accuracy (95% CI)
Per-location (n=87552)	Initial CXR	935	83735	1203	1679	35.77% (33.93–37.64)	98.58% (98.50–98.66)	96.71% (96.59–96.83)
	CT	1943	82522	2465	622	75.75% (74.04–77.40)	97.10% (96.98–97.21)	96.47% (96.35–96.60)

The total frequencies (positive and negative results) are calculated across all cases, rib locations (anterior, lateral, and posterior) for all readers. For example, total frequencies at the fracture per-location analysis is 87,552 = 64 cases × 24 ribs × three locations per rib × 19 readers

The sensitivity, specificity, and accuracy of initial CXR and CT for detecting anterior rib fractures were 34.25% (95% CI: 31.10–37.51) vs. 80.23% (95% CI: 77.40–82.85), 98.96% (95% CI: 98.84–99.08) vs. 97.34% (95% CI: 97.15–97.53) and 97.03% (95% CI: 96.83–97.22) vs. 96.84% (95% CI: 96.63–97.04), respectively; lateral rib fractures were 45.14% (95% CI: 40.38–49.97) vs. 54.07% (95% CI: 49.16–58.92), 98.56% (95% CI: 98.42–98.69) vs. 99.02% (95% CI: 98.90–99.13) and 97.77% (95% CI: 97.59–97.94) vs. 98.38% (95% CI: 98.23–98.52), respectively; posterior rib fractures were 33.69% (95% CI: 31.13–36.32) vs. 79.79% (95% CI: 77.50–81.96), 98.22% (95% CI: 98.06–98.38) vs. 94.86% (95% CI: 94.60–95.13) and 95.32% (95% CI: 95.07–95.56) vs. 94.20% (95% CI: 93.93–94.47), respectively (Table 4.3). The sensitivity of initial CXR and CT in the discernment of acute fractures was 24.35% (95% CI: 22.26–26.56) and 75.96% (95% CI: 73.76–78.04), respectively, while for healing fractures it was 54.71% (95% CI: 51.58–57.81) and 73.38% (95% CI: 70.52–76.07), respectively.

Table 4.3. Diagnostic performance of initial chest radiographs and chest CT by rib location (anterior, lateral and posterior)

	Imaging study	TP	TN	FP	FN	Sensitivity (95% CI)	Specificity (95% CI)	Accuracy (95% CI)
Anterior (n=29184)	Initial CXR	298	28020	294	572	34.25% (31.10–37.51)	98.96% (98.84–99.08)	97.03% (96.83–97.22)
	CT	686	27576	753	169	80.23% (77.40–82.85)	97.34% (97.15–97.53)	96.84% (96.63–97.04)
Lateral (n=29184)	Initial CXR	195	28338	414	237	45.14% (40.38–49.97)	98.56% (98.42–98.69)	97.77% (97.59–97.94)
	CT	226	28485	281	192	54.07% (49.16–58.92)	99.02% (98.90–99.13)	98.38% (98.23–98.52)
Posterior (n=29184)	Initial CXR	442	27377	495	870	33.69% (31.13–36.32)	98.22% (98.06–98.38)	95.32% (95.07–95.56)
	CT	1031	26461	1431	261	79.79% (77.50–81.96)	94.86% (94.60–95.13)	94.20% (93.93–94.47)

Out of 36 patients with negative initial CXR, CT demonstrated no fractures in 21 patients that were confirmed by reference standard (i.e., initial and follow-up CXRs). In the remaining 15 patients, CT detected at least one fracture; 12 of 15 patients were confirmed positive for fractures by the reference standard. Of the 28 patients who showed at least one fracture on initial CXR, 26 were confirmed to have fractures on CT, with findings also confirmed by the reference standard. In the other 2 patients, CT demonstrated no fractures, which was consistent with the reference standard. Examples of the findings in CT and CXR images are shown in Figures 4.2, 4.3 and 4.4.

4.4.1.2 Diagnostic performance of chest CT in 46 patients who had CT within 7 days from initial chest radiographs

The diagnostic performance of chest CT for rib fractures on patient-, rib- and location-based analyses in 46 patients who had CT within 7 days of initial CXR (median: 1 day, IQR: 3 days, range 0 to 7 days) is detailed in Table 4.4. The sensitivity, specificity and accuracy of CT for detecting rib fractures for the following analyses were: per-patient, 91.54% (95% CI: 88.85–93.76), 81.29% (95% CI: 76.74–85.28) and 87.53% (95% CI: 85.15–89.65), respectively; per-rib, 81.22% (95% CI: 79.49–82.87), 93.67% (95% CI: 93.31–94.01) and 92.42% (95% CI: 92.05–92.77), respectively; and per-location, 75.85% (95% CI: 74.03–77.60), 96.51% (95% CI: 96.36–96.65) and 95.76% (95% CI: 95.60–95.92), respectively.

Table 4.4. Diagnostic performance of chest CT for the detection of rib fractures in 46 children who had CT with within 7 days from initial chest radiographs

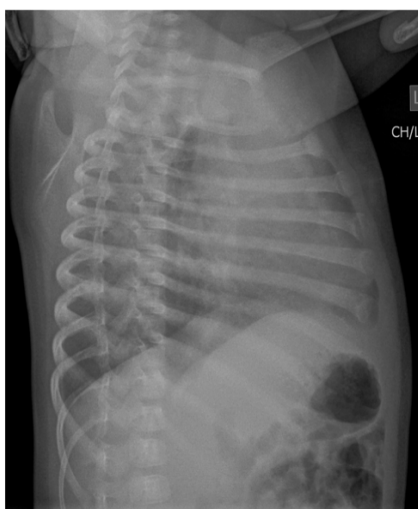
Analysis level	TP	TN	FP	FN	Sensitivity (95% CI)	Specificity (95% CI)	Accuracy (95% CI)
Per-patient (n=874)	487	278	64	45	91.54% (88.85–93.76)	81.29% (76.74–85.28)	87.53% (85.15–89.65)
Per-rib (n=20976)	1713	17673	1194	396	81.22% (79.49–82.87)	93.67% (93.31–94.01)	92.42% (92.05–92.77)
Per-location (n=62928)	1715	58547	2120	546	75.85% (74.03–77.60)	96.51% (96.36–96.65)	95.76% (95.60–95.92)

In these 46 children, the sensitivity, specificity, and accuracy of CT for detecting anterior rib fractures were 80.98% (95% CI: 78.15–83.59), 96.84% (95% CI: 96.59–97.07) and 96.21% (95% CI: 95.94–96.46), respectively; for lateral rib fractures, 55.39% (95% CI: 50.36–60.34), 98.84% (95% CI: 98.69–98.98) and 98.02% (95% CI: 97.82–98.20), respectively; and for posterior rib fractures, 79.63% (95% CI: 77.03–82.05), 93.76% (95% CI: 93.41–94.09) and 93.07% (95% CI: 92.72–93.41), respectively (Table 4.5).

Table 4.5. Diagnostic performance of chest CT by rib location (anterior, lateral and posterior) in 46 children who had CT with within 7 days from initial chest radiographs

	TP	TN	FP	FN	Sensitivity (95% CI)	Specificity (95% CI)	Accuracy (95% CI)
Anterior (n=20976)	677	19503	637	159	80.98% (78.15–83.59)	96.84% (96.59–97.07)	96.21% (95.94–96.46)
Lateral (n=20976)	221	20339	238	178	55.39% (50.36–60.34)	98.84% (98.69–98.98)	98.02% (97.82–98.20)
Posterior (n=20976)	817	18705	1245	209	79.63% (77.03–82.05)	93.76% (93.41–94.09)	93.07% (92.72–93.41)

A



B



C

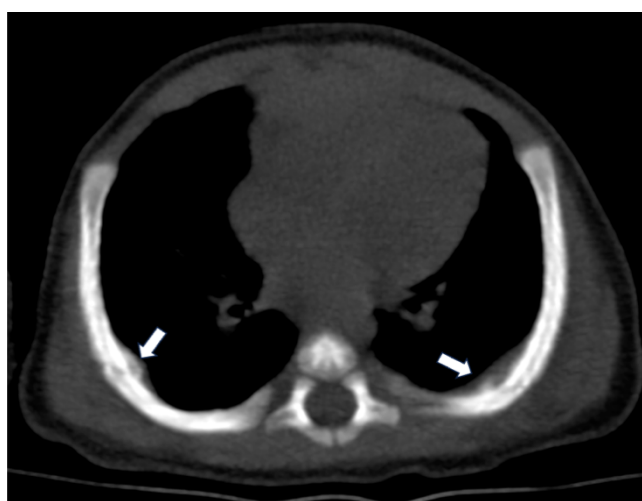


Figure 4.2 Example of true positive rib fracture (i.e. a fracture seen by CT and more than 50% of reporters on initial and follow-up chest radiographs).

Skeletal survey chest radiographs and CT imaging of a 6-week-old female patient. Anteroposterior and oblique chest radiographs of (A) the initial and (B) follow-up imaging performed within 13 days of each other. Reading the initial and follow-up chest radiographs showed multiple left acute fractures (arrows) at the 3rd posterior rib (19/19 reporters), 4th posterior rib (19/19 reporters), 5th posterior rib (19/19 reporters), 6th posterior rib (19/19 reporters) and 7th posterior rib (19/19 reporters), which were seen in the initial imaging by no or few readers as follows: 3rd posterior rib (0/19 reporters), 4th posterior rib (0/19 reporters), 5th posterior rib (0/19 reporters), 6th posterior rib (3/19 reporters) and 7th posterior rib (5/19 reporters). Additionally, there was a healing fracture of the right 6th rib (arrow). (C) Chest CT was performed on the same day as the initial chest radiographs and reporters identified all fractures that were seen in initial and follow-up chest radiographs as follows: left 3rd posterior rib (6/19 reporters), left 4th posterior rib (11/19 reporters), left 5th posterior rib (18/19 reporters), left 6th posterior rib (19/19 reporters, 4 o'clock, arrow), right 6th posterior rib (18/19 reporters, 8 o'clock, arrow), and left 7th posterior rib (19/19 reporters).

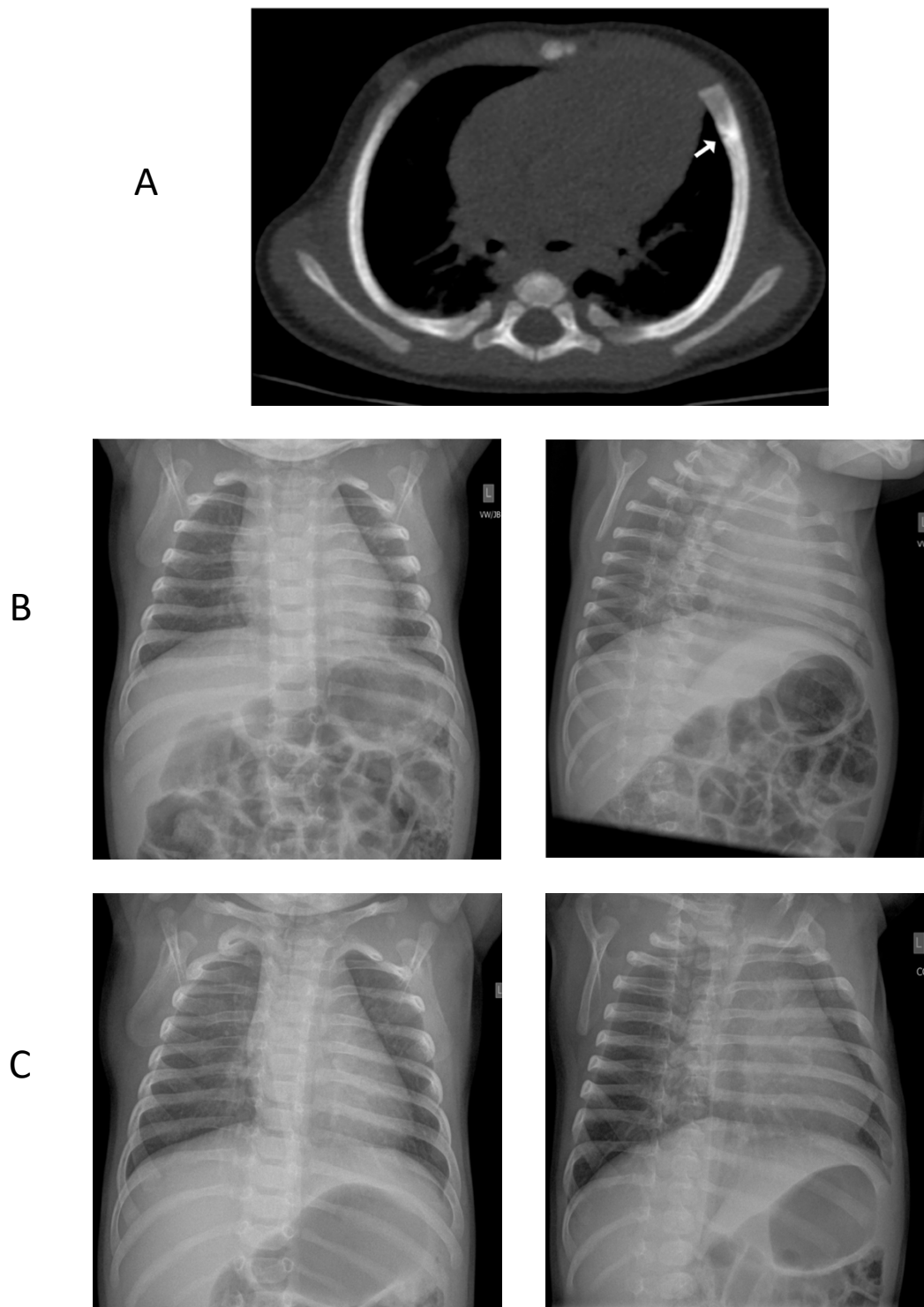
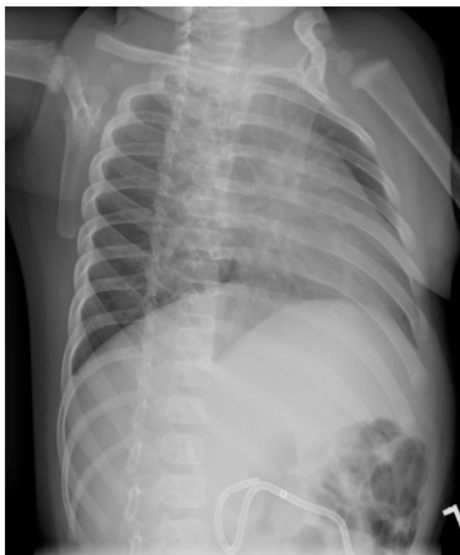
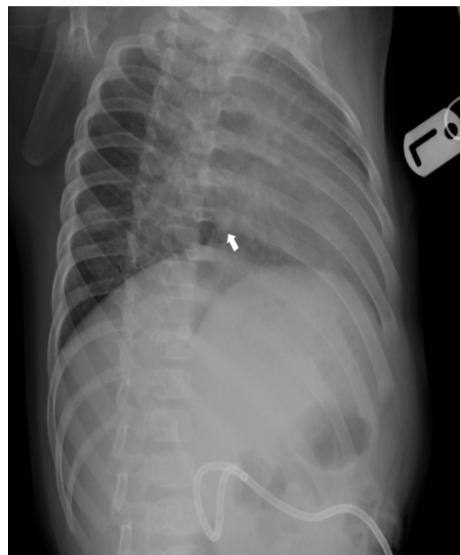


Figure 4.3 Example of false positive rib fracture (i.e. a fracture seen by CT but not on initial and follow-up chest radiographs by more than 50% of reporters).

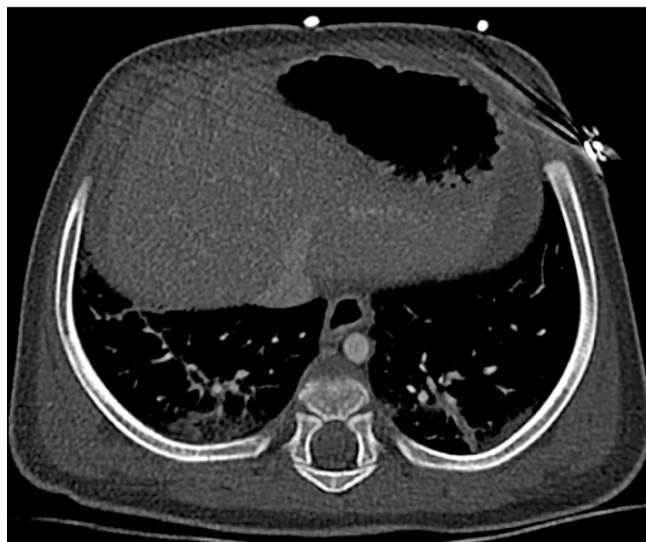
Chest radiographs and CT imaging of a 3-month-old male patient. Chest CT was performed on the same day as the initial chest radiograph. (A) chest CT showed a left 4th anterior rib fracture (2 o'clock, arrow) identified by 17/19 reporters, whereas 2/19 reporters identified this fracture when they read anteroposterior and left oblique chest radiographs of (B) the initial and (C) follow-up imaging performed within 11 days of each other.



A



B



C

Figure 4.4 Example of false negative rib fracture (i.e. a fracture seen on initial and follow-up chest radiographs by more than 50% of reporters but not on CT).

Chest radiographs and CT imaging of a 9-month-old female patient. An acute left 7th posterior fracture observed on (A) the left oblique radiograph of the initial imaging by 1/19 readers and by 16/19 reporters when reading left oblique chest radiographs of (A) the initial and (B) follow-up imaging (arrow), performed within 17 days of each other. This fracture was not identified by 18/19 reporters in (C) the chest CT performed 7 days before the initial skeletal survey.

4..4.2 Interpretation confidence and reporters' experience

A total of thirty-one consultant radiologists were recruited, but 12 (38.71%) withdrew from the study: of these, 10 (83.30%) did not complete or withdrew at the first round, and 2 (16.70%) withdrew after completing the first round. A total of 19 reporters completed all three rounds: 3 (15.8%) had 1 to 5 years of experience, 3 (15.8%) had 6 to 10 years of experience, and 13 (68.4%) had more than 11 years of experience.

The CT sensitivity and specificity for diagnosing rib fractures were comparable among the reporters' different level of clinical experience (Figure 4.5) which had no significant effect on the CT sensitivity and specificity for the different analyses (per-patient analysis: $P \geq 0.62$ and $P \geq 0.47$, respectively; per-rib analysis: $P \geq 0.97$ and $P \geq 0.23$, respectively; per-location analysis: $P \geq 0.95$ and $P \geq 0.19$, respectively).

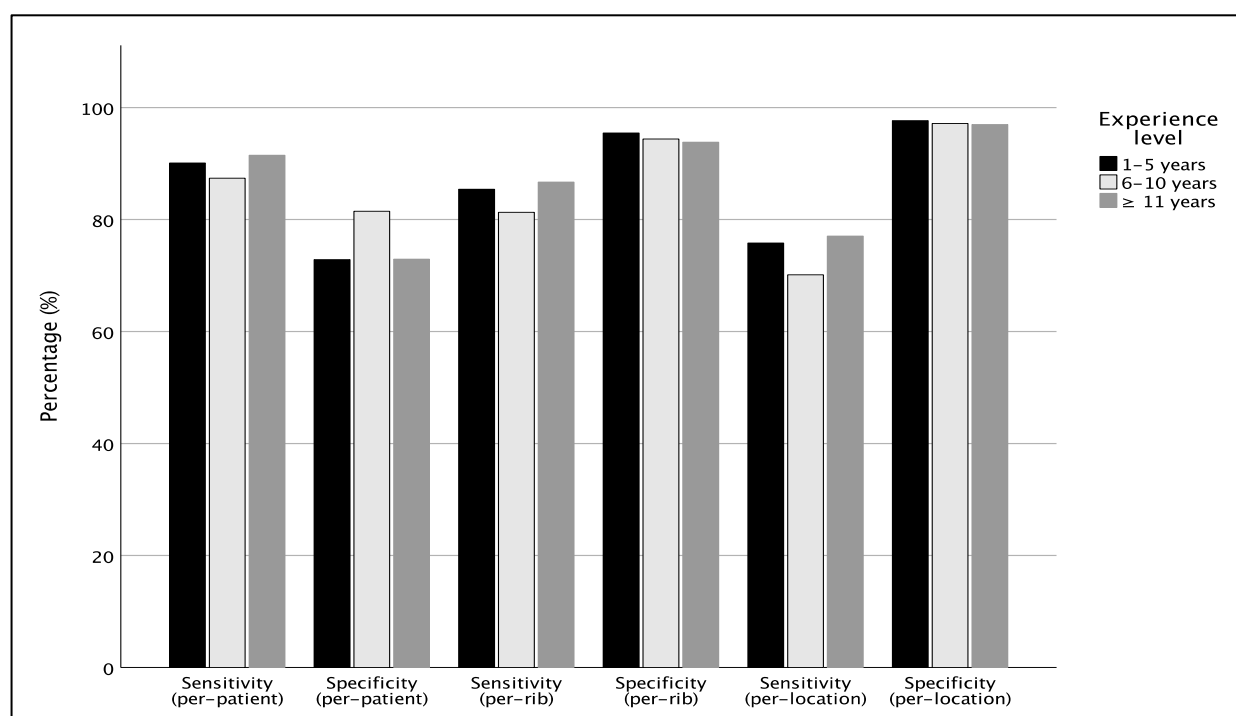


Figure 4.5. Comparison of sensitivity and specificity of chest computed tomography based on reporters' experience.

Readers recorded a total of 2,250 fractures on initial CXRs, of which 1,384 (61.5%) were reported with a confidence level of 3 (i.e., confident), 444 (19.73%) with a confidence level of 2 (i.e., equivocal) and 422 (18.76%) with a confidence level of 1 (i.e., not confident). There were 3,020 fractures recorded on the

initial and follow-up CXRs, of which 2,526 (83.6%) were reported with a confidence level of 3, 272 (9.01%) with a confidence level of 2 and 222 (7.35%) with a confidence level of 1. Regarding chest CT imaging, there were 4,533 fractures recorded, of which 3,524 (77.7%) were reported with a confidence level of 3, 591 (13.04%) with a confidence level of 2 and 418 (9.22%) with a confidence level of 1. Nineteen reporters reported 1,216 cases (64 cases each) in which 949 (78.0%) MPR and/or 3DVR were used and 63.2% (769/949) reported these as useful in assessing rib fractures.

4.5 Discussion

This study revealed that, overall, chest CT has a high diagnostic performance in the detection of rib fractures in live children with SPA using initial and follow-up CXRs as a reference standard. Furthermore, chest CT was more sensitive in identifying anterior and posterior rib fractures than lateral rib fractures. Importantly, years of reporter experience did not affect the diagnostic accuracy of CT in rib fracture detection. Our results support those of previous studies in that CT chest has a role in identifying rib fractures in children investigated for SPA.

Limited studies have assessed the role of CT in detecting rib fractures in children with SPA reporting that CT is more sensitive than CXRs in this regard for live [12-14, 22] and PM [15, 23] children. However, previous studies conducted on live children did not assess the diagnostic accuracy of CT against the current reference standard used in clinical practice of initial and follow-up CXRs. Ideally, the clinical effectiveness and diagnostic accuracy of a new diagnostic method must be assessed against the contemporaneous reference standard.

To the best of our knowledge, the current studies in the literature concerning the role of CT in detecting rib fractures in live children with SPA do not calculate the sensitivity but compare the frequency of the fracture detection between chest CT and CXR without using a reference standard [12-14, 22]. Although our study design is comparable to the study by Shelmerdine *et al.* [23] who investigated the accuracy of PMCT in detecting rib fractures in 25 children using autopsy as the reference standard, the reported sensitivity of CT in our study was higher than that reported by Shelmerdine *et al.* [23]. For example, our study showed a higher sensitivity (90.61%) of CT in detecting rib fractures on patient-based analysis than the reported sensitivity (44.9%) in the study by Shelmerdine *et al.* [23]. However, there are differences between our study and Shelmerdine *et al.* [23]. First, our study is based on live children, using initial and

follow-up CXRs as the reference standard, while the reference standard used on PM children was autopsy. Second, the sample size in the PM study ($n=25$) [23] was less than the sample size in our study ($n=64$), which may lead to underestimation of the sensitivity of CT in detecting rib fractures. Nevertheless, the increased sensitivity of CT in our study could result from potential reporting bias since the readers were asked to evaluate rib fractures in cases with SPA, where CT is usually used in cases when there is uncertainty as to the findings on CXR and the suspicion of abuse is high (which might increase the positive results).

It is reported that the location of a rib fracture in SPA has diagnostic and medicolegal importance [23, 24], and that posterior rib fractures are strongly associated with child abuse [1, 25-27]. This study indicates that 50% (68/136) of rib fractures identified at the reference standard were posteriorly located, with a CT sensitivity of 79.79%. Notably, chest CT has lower sensitivity (54.07%) in identifying lateral rib fractures, consistent with the results of previous studies. A systematic review and meta-analysis of two studies demonstrated that PMCT had the lowest sensitivity at lateral rib fracture locations at 21% (with 45% and 42% at anterior and posterior locations, respectively) using autopsy as the reference standard [28]; however, meta-analysis of PM CXR was not performed due to the different projections obtained in these two studies. Wootton-Gorges *et al.* [14] reported that the initial CXR detected more lateral rib fractures than CT in live children with SPA. By contrast, recent studies have reported that CT performed better than the initial CXRs in detecting rib fractures at all locations [12, 22]. As such, it would appear that the accuracy in detecting lateral rib fractures on chest CT is variable, which while still important in confirming multiplicity and varying age of fractures, may be of reduced medicolegal importance in the presence of confidently detected posterior rib fractures.

This study indicates that reporters' experience did not affect CT accuracy in detecting rib fractures. This aligns with the multiobserver diagnostic study conducted by Shelmerdine *et al.* [23] investigating the accuracy of PMCT and PM CXR in detecting rib fractures in 25 children using autopsy as the reference standard. There were 38 radiologist reporters (12 consultant radiologists and 26 specialist registrars: 3 of the 12 consultants withdrew at the CT reporting stage). They reported that PMCT offers greater accuracy than PM CXR in the detection of rib fractures, with no difference attributed to reporters' years of clinical experience. Therefore, regardless of the radiologist experience, chest CT examinations offer accurate rib fracture detection in children investigated for SPA.

In our study, radiologists were more confident using the initial and follow-up CXR images (83.64%) than CT images (77.74%) for diagnosing rib fractures, possibly due to a relative lack of experience in using CT for diagnosing rib fractures in children with SPA. However, radiologists' confidence when using CT is not significantly lower than for both initial and follow-up CXRs. Radiologists' confidence for diagnosing rib fractures, when using CT was greater than for initial CXRs (61.51%) alone, consistent with the findings from Shelmerdine *et al.* [23] where radiologists were more confident using PMCT (63.6%, 3317/5218) than PM CXR (46.6%, 1518/3303). This may be a result of improved image quality due to the higher radiation doses used, standardised CT techniques from a single institution and potentially, absence of motion artefact in the PM studied population. Another explanation could be that most fractures were acute – given the children had died thus for a single incident – which are often not visible or reduced confidence in diagnosis on CXR and being more easily identified on CT.

Chest CT has several advantages in diagnosing rib fractures in cases of SPA. The results of this and previous studies [12-15, 22, 23, 28] demonstrate that CT offers increased diagnostic accuracy in the identification of rib fractures in children with SPA, which is important from a safeguarding perspective, by allowing prompt initiation of child protection procedures. Another advantage of CT lies in the improved visibility of other injuries associated with physical abuse (e.g., scapular and thoracic vertebral body fractures, which was outside the scope of this study) [13, 20, 29]. Additionally, CT is able to provide 3DVR of the rib cage which could assist radiologists in confirming the presence of rib fracture(s), and as a visual aid for the clinicians in demonstrating the injuries to the parents and the court [26, 29, 30].

The higher radiation dose of chest CT compared to chest radiography is of importance [31-34], if CT is to be considered for routine clinical practice. Children are more vulnerable to the effects of ionising radiation than adults, since growing tissues and rapidly dividing cells are more sensitive to radiation effects than mature tissues and children also have a longer lifespan over which to develop any potential ill effects of radiation damage, such as radiation-induced cancers [35-38]. The risk of exposure to ionising radiation in chest CT should however be balanced against the risk of a missed diagnosis of physical abuse, given the reported increased sensitivity in the detection of rib fractures and the results of this study.

In the last decade, advancements in CT technology have allowed substantial reduction in radiation dose, whilst maintaining diagnostic image quality, using photon counting detector systems [39], iterative reconstruction and tube current modulation [40, 41], in addition to adjusting CT scanning parameters

(e.g. tube voltage [kV], tube current [mA] and pitch) [40, 41]. A low-dose CT (LDCT) protocol has been proposed for the detection of rib fractures in live children with SPA [30]. Sanchez *et al.* [42] reported an optimised chest CT protocol with an average effective dose of 0.56 millisieverts (mSv) in children up to 4 months of age, which is comparable to two times the dose of the American College of Radiologists recommended initial standard four view CXR (anteroposterior, lateral and two oblique projections). Recently, Karmazyn *et al.* [22] reported the development of a LDCT chest protocol with an effective dose of 0.17 mSv (which approach the average effective dose of the standard set of initial and follow-up skeletal survey CXRs (6 projections [anteroposterior and right and left oblique views], 0.1 mSv) [32, 33].

The Royal College of Radiologists (RCR) and Society of College of Radiographers (SCoR) guidelines, which are endorsed by the Royal College of Paediatrics and Child Health (RCPCH) [11], and recognised by the ESPR as the gold standard imaging investigating for SPA across Europe [43], state that 'CT has a greater sensitivity than radiography for the detection of rib, vertebral and scapular, fractures' [11]. However, the guidance currently recommends chest CT is performed only where there is doubt regarding the nature of rib abnormalities identified on chest radiograph(s).

The RCR-SCoR guidelines recommend that all children under the age of 1 year, and those children older than 1 year of age with signs of external evidence of head trauma and/or neurological symptoms or signs, should undergo head CT examination [11]. Given the superior diagnostic accuracy of CT in diagnosing skull fractures, it has recently been reported that skull radiographs can be safely omitted from the initial skeletal survey if head CT with 3DVR is performed in children investigated for SPA [44-46]. Our study demonstrates that chest CT has a high diagnostic performance for detecting rib fractures in live children with SPA, when compared to the initial and follow-up CXRs as a reference standard. Practically, chest CT could be performed during the same attendance for head CT, obviating the need for the six view CXRs as part of the skeletal survey examination, assisting clinicians, families and social care by allowing earlier decision making. Validation of a low dose CT protocol would however be required, before CT can be recommended to replace CXR for this indication.

This study has several limitations. First, some of the included cases had no left and right oblique projections on initial CXR ($n=3$), follow-up CXRs ($n=5$) or both initial and follow-up CXRs ($n=3$). Oblique projections improve the detection of rib fractures in SPA [47-49]. False positives reported in our study (i.e., fractures detected on CT but not radiography) could potentially have been actual fractures (i.e., true positives) not reported on chest radiography. Second, the sample size is small, however, to the best

of our knowledge, this study had a larger sample size than any recently published study investigating rib fracture detection in live children with SPA using chest CT [12-14, 22]. Our study was also the first to use the current recommended imaging of the 'six view' chest radiograph as a reference standard. Third, given the retrospective nature of this study, the radiation dose of the chest CT was not estimated due to the limited information available on different CT machines (vendors) and scanning protocols employed at participant centres (which is reflective of clinical practice). It is therefore unclear whether a LDCT chest protocol would affect the diagnostic accuracy of CT for detecting fractures. Fourth, although we asked all reporters to replicate their usual reading practice, this would be individual to each reporter, who also likely used different DICOM platforms, but with similar functionality (ability to adjust contrast, brightness and apply different windows). Fifth, 25% (16/64) of retrieved CT cases had no bone window reconstruction. Whilst reporters were asked to read the imaging on bone windows, by altering the window settings in their DICOM software, the image quality and sharpness of bony structures would be lower than that of images reconstructed using a bone kernel. This may have affected the diagnostic accuracy for detecting rib fractures for 25% of the studied cases but does mean that our results are the worst case scenario. Sixth, this is a potential selection bias in the patient population because chest CT is not usually performed to evaluate rib fractures in all children with SPA. However, this reflects the current use of chest CT in clinical practice where CT is performed when initial CXR is negative or equivocal but clinical suspicion of abuse is high. Seventh, 15% (10/64) of the retrieved CT cases were acquired at > 1 mm slice thickness, which could reduce the spatial resolution and thus affect the diagnostic accuracy of CT for detecting rib fractures. Eighth, in some cases (22%), the reporter did not use MPR and/or 3DVR when reading CT images; this may affect reporters' confidence and the accuracy of CT, since MPR/3DVR improve the detection of rib fractures [50, 51]. Ninth, the breadth of the time interval between initial CXR and CT in 64 children, ranging from 0 to 23 days (median: 2 days), may increase the detection of rib fractures on CT due to the progression of healing evidence. However, the reported diagnostic performance of CT in our study is less affected by the time interval between initial CXR and CT, because the diagnostic performance of CT for the 64 children, who had a time interval between CT and the initial CXR ranging from 0 to 23 days (median: 2 days), did not considerably differ from the patient cohort (n=46) who had the initial CXR and CT within 7 days (median: 1 day). Finally, the reporter attrition rate was high (38.7%), despite the details of the research protocol and requirements being fully outlined to all volunteers at the time of recruitment. The study involved a significant time commitment: 3 reads with a 1-month washout period in between each read, 64 CT scans analysing 12 ribs per case and

completion of a detailed data collection form for every case and read. The study design should therefore be considered when planning similar diagnostic accuracy studies to avoid response fatigue.

4.6 Conclusion

Chest CT offers accurate detection of rib fractures in live children investigated for SPA and has the potential to replace the current recommended imaging standard of six chest radiographs, optimising clinical and legal decision making in children being investigated for SPA.

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Chapter Five

Computed tomography-based rib fracture dating in children investigated for suspected physical abuse: a feasibility study

The paper is in preparation for publication

5. Computed tomography-based rib fracture dating in children investigated for suspected physical abuse: a feasibility study

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- Wrote the initial draft of the study protocol: **N.M.A.**
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5.1 Abstract

Background

Rib fractures are strongly associated with physical abuse in infants and young children. Chest computed tomography (CT) improves their detection. Dating fractures in suspected child abuse is important for forensic and legal proceedings.

Objective

To provide the CT-based healing pattern of rib fractures compared to the current clinical standard of chest radiography by assessing the agreement between the modalities in 1) identifying the parameters of rib fracture healing (fracture line and callus formation); and 2) estimating the broad timeframes for rib fracture dating (acute vs. healing). Furthermore, this study also aims to examine what healing parameters on CT could help to estimate the specific age range of rib fracture using radiography as the reference.

Methods

This multicentre retrospective study involved children less than two years of age investigated for suspected physical abuse (SPA), who had chest radiographs (CXR) as part of initial and follow-up skeletal surveys in addition to chest CT. Only children with ≤ 4 days interval between imaging modalities were included. The rib fractures were independently assessed by three paediatric radiologists for features of fracture healing (fracture line and callus formation) on chest CT. Blinded to the CT findings, two paediatric radiologists in consensus assessed the healing features and provided the specific age range of fracture from chest radiography to provide a reference. The radiologists also independently estimated the broad timeframes for fracture dating (acute vs healing) in chest radiography and CT.

Results

There were 40 fractures in 13 patients with a median age of two months. The median time between modalities was one day. Moderate agreement was found in the identification of healing features (fracture line: kappa (k)=0.42, 95% confidence interval [CI]: 0.21–0.63, $P<0.001$; callus formation: $k=0.49$, 95% CI: 0.28–0.70, $P<0.001$) with substantial agreement in estimating the timeframe ($k=0.76$, 95% CI: 0.55–0.97, $P<0.001$). Callus formation feature on CT scans showed a discriminative pattern for estimating the specific age range of rib fractures.

Conclusion

Dating rib fractures using chest CT in children with SPA is feasible and demonstrates moderate and substantial agreement with chest radiography in assessing healing features and broad timeframes of rib fractures, respectively. Callus formation may serve as a guide for radiologists to estimate the specific age range of rib fractures from CT scans.

5.2 Introduction

Fractures are the second most common injuries observed in physically abused children after soft tissue injuries, such as bruises and contusions [1-3]. Certain fractures and fracture patterns are highly specific for physical abuse, e.g., rib fractures, classic metaphyseal lesions and multiple fractures at different stages of healing, in the absence of an alternative explanation [4-6]. In the absence of a confirmed traumatic cause, the probability of physical abuse for rib fractures is 71% [7].

Radiologists play an important role in recognising the radiological manifestations of physical abuse [1, 8]. In addition, radiologists are often expected to provide opinion on whether any proposed mechanism provided by carers is consistent with an identified fracture [1, 8, 9]. Clinical histories may be inaccurate or absent and injuries are often reported to be unwitnessed, yet from a legal perspective, the timing of any injury may be key to the case, influencing decision-making regarding the potential pool of perpetrators and optimum placement of the child [8, 10]. Radiologists are therefore often asked to date fractures, to assist in confirming or refuting the accounts of when any injury occurred [1, 11, 12].

The radiographic skeletal survey is the current imaging examination of choice in children being investigated for suspected physical abuse (SPA) and comprises an initial survey followed by a (limited) follow-up survey performed 11 to 14 days later [13, 14]. Anteroposterior and right and left oblique chest radiographs (CXR) are the current imaging standard to assess for rib fractures (detection and dating) [13, 14]. However, acute rib fractures are often radiologically occult on initial CXR because they are either minimally displaced, incomplete or obscured by overlying structures [15-18]. The onset of fracture healing (i.e. callus formation) increases the conspicuity and detection of rib fractures, this being the rationale for the follow-up skeletal survey [19, 20].

Chest computed tomography (CT) has shown promising results in improving rib fracture detection in children investigated for SPA [15-17, 21-24], which may become the clinical standard imaging for rib fracture identification in cases of SPA in children. In this context, there will be no chest radiography with which to compare or determine fracture age. From a medicolegal perspective, expert radiologists appointed by the court would then be expected to date any rib fractures from CT alone. To the authors' knowledge, the possibility of dating rib fractures using CT in live children has not been previously assessed. Given that CT is more sensitive than radiography, there is the potential that fractures might appear to heal faster when assessed by CT compared to radiographs. This study aimed to provide the CT-based healing pattern of rib compared to the current clinical standard of chest radiography by assessing the agreement between the modalities in 1) identifying the parameters of rib fracture healing; and 2) estimating the broad timeframes for rib fracture dating (acute vs. healing). Furthermore, this study also aimed to examine what healing parameters on CT could help to estimate the specific age range of rib fracture using chest radiography as the reference.

5.3 Methods

This is a sub-study of RECEPTOR (Rib fracturE diagnosis in suspecTed abuse: comPUted Tomography Or Radiographs); a multicentre retrospective study assessing the diagnostic accuracy of CT in detecting rib fractures in live children less than two years of age investigated for SPA, using the current practice of initial and follow-up CXRs as the reference standard. The study was approved by United Kingdom Health Research Authority (UK HRA; 21/HRA/2368) (Appendix 2) and the research ethics committee of each participating centre. The research ethics board waived the need for informed consent due to the retrospective nature of the study and the use of anonymised patient data. Radiologists at thirteen European hospitals searched their picture archiving and communication systems (PACS) over a 10-year period (September 2011 to 2021) for children under the age of 2 years, who had both CXRs and chest CT as part of their imaging investigations for SPA. Radiologists independently read the images in three separate reads: Read 1 (initial CXRs only), Read 2 (CTs only) and Read 3 (initial and follow-up CXRs) performed at least one month apart. The order of Reads 1 and 2 were varied between reporters but no reporter performed Read 3 before Read 1 or 2. Radiologists independently reported fracture presence, estimated broad timeframes of fracture dating (acute vs healing) and fracture location (rib number, side, and location on the rib) for each read phase. Acute fractures were defined as those with sharp margins

and no evidence of healing, while healing fractures were those with periosteal reaction (even if subtle), and/or callus (soft or hard), and/or remodelling. The anonymised CXRs and CT data sets were provided to readers in the form of Digital Imaging and Communications Medicine (DICOM) files via a password protected file sharing website (Google Drive). Reporters were advised to replicate their usual practice when reporting cases i.e., using diagnostic quality imaging displays, appropriate dim lighting, etc.

CXR, including anteroposterior and right and left oblique projections, were extracted from the skeletal survey. The thinnest available axial CT slices on bone and soft tissue windows were provided to the reporters. Where chest CT images were only available in soft tissue and/or lung windows, reporters were asked to read the images on bone windows (by manually selecting this window in their imaging software). The CXRs from the skeletal survey and chest CT examinations were performed in different centres on machines from multiple vendors with different protocols. For the chest CT examinations, the reporting clockface method utilised by Shelmerdine *et al.* [21] was used to standardise reporting of rib locations along the rib arc. This method allows reporters to record the rib fracture location around an imaginary clockface when the chest is viewed in an axial section. The rib fracture location is divided into three categories: anterior, lateral and posterior. At any given level, the 12 o'clock position is the sternum (not scorable), the 1 to 5 o'clock positions are located along the left rib, the 6 o'clock position is the vertebral column (not scorable), and the 7 to 11 o'clock positions are located along the right rib. The 1 and 11 o'clock positions refer to costosternal junction locations, and the 5 and 7 o'clock positions refer to costovertebral junction locations. Therefore, anterior fractures include the 1, 2, 10, and 11 o'clock positions; lateral fractures include the 3 and 9 o'clock positions; and posterior fractures include the 4, 5, 7, and 8 o'clock positions.

For this sub-study, three paediatric radiologists (A.C.O, A.M.J and M.P with 20, 20 and 5 years of experience, respectively) performed:

- A. An assessment of the features of fracture healing (fracture line and callus) in Read 1 - consensus (Readers 1 and 2); Read 2 - independently, all three radiologists.
- B. An assessment of the broad timeframes for fracture dating (acute vs healing) in Read 1 and Read 2 – independently, all three radiologists, as part of the parent study.
- C. An assessment of the specific age range of rib fractures in Read 1- consensus (Readers 1 and 2 who act as expert witnesses in suspected child abuse cases).

Only children with ≤ 4 days interval between imaging modalities were included to reduce the chance of healing progression between modalities; and fractures that were identified on both Read 1 (by the two radiologists) and by at least 2 of 3 radiologists in Read 2 (Figure 5.1). The criteria for identification of healing features of rib fractures (fracture line and callus formation) were modified and adopted from Sanchez *et al.* [25] (Table 5.1). The criteria for determination of the specific age range of rib fractures on chest radiography were modified and adopted from Offiah and Hall [26] (Table 5.2) and the dating of fractures (in weeks) was based on initial and (when available) follow-up CXR to reflect standard practice.

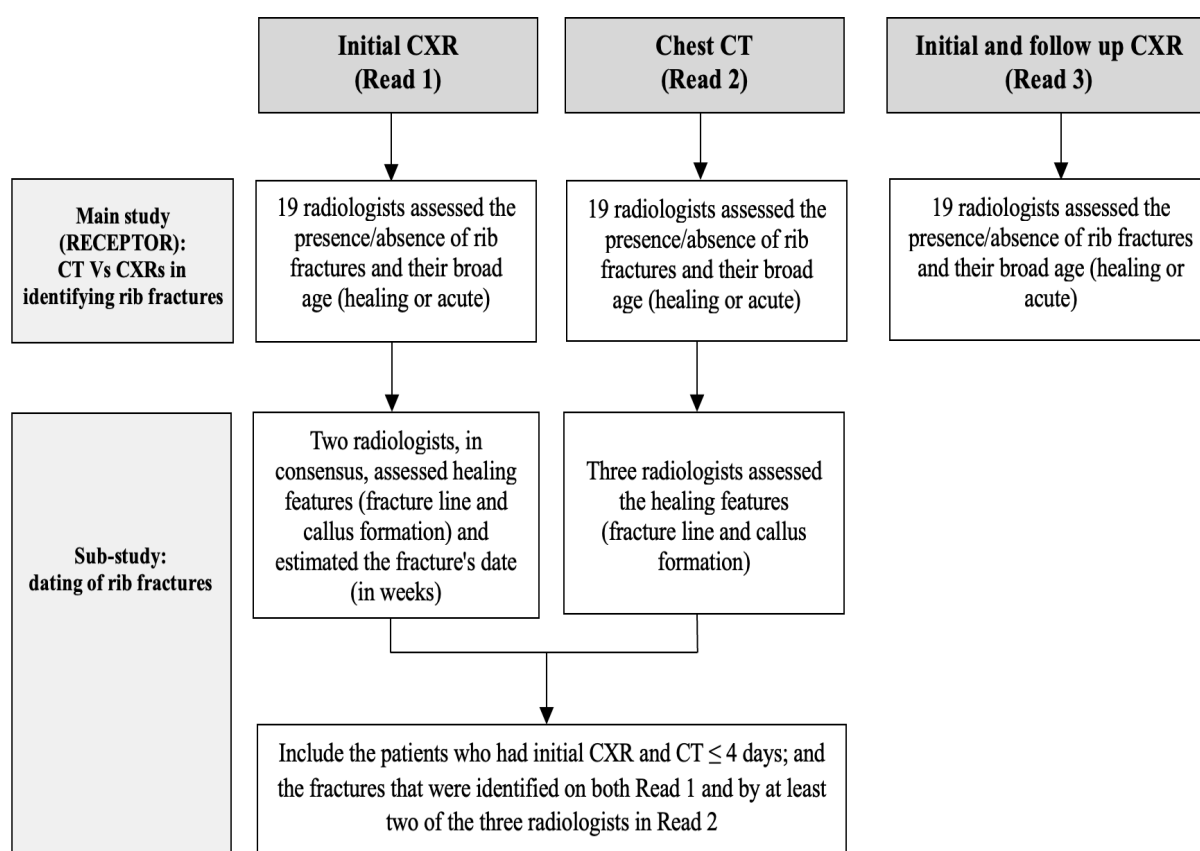


Figure 5.1. The flow chart shows the method used for recruitment to this sub-study.

Table 5.1. The healing features of rib fractures

Healing features	Radiologic appearance
Fracture line	Barely visible fracture line or step-off Thin fracture line with some resorption Fracture line is clearly visible Near-complete bridging of the fracture line
Callus formation	No periosteal reaction Periosteal reaction <2 mm in thickness (thin periosteal reaction) Callus formation presence Focal sclerosis or cortical thickening

(Adopted and modified from Sanchez et al. [25], with permission)

Table 5.2. Radiological dating of fractures

Radiological feature	Fracture age
No periosteal reaction, sharp/clearly visible fracture line	< 2 weeks
Thin periosteal reaction (<2mm), soft callus	2–4 weeks
Hard callus, blurring of fracture line	4–6 weeks
Remodelling, near complete bridging of the fracture line	6–8 weeks
Remodelling, no fracture line	>8 weeks

(Adopted and modified from Offiah and Hall [26], with permission)

To assess the overall agreement between the modalities in identifying the healing features (objective 1), we compared the consensus score of CT healing features (scores assigned by at least two readers) to the radiography reference standard. To assess the overall agreement between the modalities in estimating the broad timeframes for fracture dating (acute vs healing) (objective 2), we compared the consensus score for each modality. To examine which CT healing parameters could help to estimate the specific age range (in weeks) of rib fractures (objective 3), we assessed the relationship between consensus CT healing parameters and the estimated specific age range of rib fractures (in weeks) derived from chest radiography.

Kappa statistics (k) with 95% confidence intervals (CIs) assessed the agreement between modalities. The interobserver agreement between a pair of readers (i.e. Reader 1 vs Reader 2, Reader 1 vs Reader 3 and Reader 2 vs Reader 3) and between all readers were assessed using Cohen's and Fleiss' kappa statistics with 95% CIs, respectively. The kappa value was interpreted as slight agreement (0.00–0.20), fair

agreement (0.21–0.40), moderate agreement (0.41–0.60), substantial agreement (0.61–0.80) and almost perfect agreement (0.81–1.00) [27]. Statistical significance was defined as a $P < 0.05$. Statistical analysis was performed using SPSS (version 27, IBM, Armonk, NY).

5.4 Results

Of the total images of 68 patients retrieved, 13 were eligible for inclusion in this fracture dating sub-study. The median patient age was 2 months (range 1–5.6 months): seven patients (54%) were female. The median time between initial CXR and chest CT was 1 day (range 0–4 days; Table 5.3). There were 40 rib fractures identified, of which 13 (32.5%) were anterior, 16 (40.0%) were lateral and 11 (27.5%) were posterior in location.

Table 5.3. Summary of patient demographics

Patient number	Sex	Age (months)	Time between initial chest radiographs and CT (days)	Total number of rib fractures	Fracture location
1	Male	1.0	2	7	2 anterior fractures 5 posterior fractures
2	Male	1.4	1	1	Posterior
3	Female	3.2	0	1	Posterior
4	Female	5.6	2	5	Lateral
5	Female	3.2	1	1	Anterior
6	Male	1.6	2	1	Posterior
7	Female	1.0	2	1	Lateral
8	Male	2.5	4	5	Lateral
9	Male	1.4	0	1	Posterior
10	Female	2.0	0	11	6 anterior fractures 5 lateral fractures
11	Male	1.4	1	1	Posterior
12	Female	2.0	1	4	Anterior
13	Female	2.0	4	1	Posterior

5.4.1 Agreement in identifying healing features

There was moderate agreement between chest radiography and CT in identifying the radiological features of fracture healing (fracture line: $k=0.42$, 95% CI: 0.21–0.63, $P<0.001$; callus formation: $k=0.49$, 95% CI: 0.28–0.70, $P<0.001$; Table 5.4; Figure 5.2). The interobserver agreement between all readers in identifying fracture healing on chest CT was moderate with respect to fracture line ($k=0.49$, 95% CI: 0.34–0.63, $P<0.001$) and substantial for callus formation ($k=0.65$, 95% CI: 0.53–0.77, $P<0.001$; Table 5.4). The agreement between any pair of readers ranged from fair ($k=0.35$) to substantial ($k=0.67$) for fracture line and from moderate ($k=0.48$) to almost perfect ($k=0.82$) for callus formation (Table 5.4).

Table 5.4. Intermodality and interobserver agreement in identifying healing features

Healing feature ^a		Kappa value (95% CI) ^b	
		Fracture line	Callus formation
Overall intermodality agreement (chest CT vs chest radiography)		0.42 (0.21 – 0.63)	0.49 (0.28 – 0.70)
Interobserver agreement on chest CT	Reader 1 vs Reader 2	0.67 (0.45 – 0.87)	0.82 (0.66 – 0.96)
	Reader 1 vs Reader 3	0.52 (0.31 – 0.74)	0.48 (0.27 – 0.69)
	Reader 2 vs Reader 3	0.35 (0.15 – 0.54)	0.69 (0.51 – 0.87)
	Reader 1 vs Reader 2 vs Reader 3	0.49 (0.34 – 0.63)	0.65 (0.53 – 0.77)

^aFracture line and callus formation

^bAll kappa values were statistically significant with P -values being <0.001

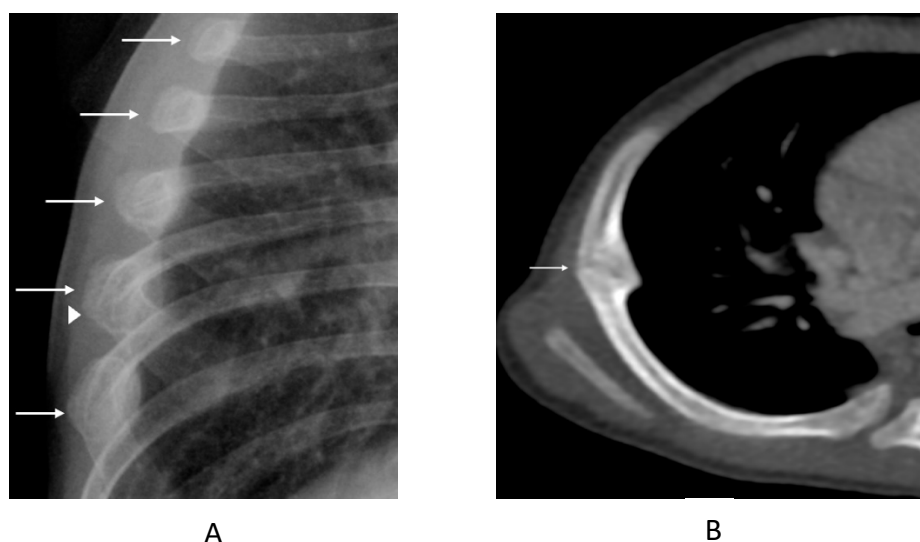


Figure 5.2. Features of healing rib fractures in a 6-month-old girl.

(A) Cropped anteroposterior chest radiograph shows several healing right-sided lateral rib fractures with callus formation (arrows) and a barely visible fracture line of the lateral arc of the right 6th rib (arrowhead). **(B)** Cropped axial chest computed tomography image (bone window) better illustrates the fracture of the lateral arc of the right 6th rib (9 o'clock, arrow) with surrounding callus.

5.4.2 Agreement in estimating the broad timeframes of rib fractures

The comparison of chest radiography versus chest CT in estimating the broad timeframes for rib fractures (acute vs healing; Table 5.5) showed substantial agreement ($k=0.76$, 95% CI: 0.55–0.97, $P<0.001$; Table 5.5; Figure 5.3). The intermodality agreement within the same reader was almost perfect for reader 1 ($k=0.87$, 95% CI: 0.70–1.00, $P<0.001$), and substantial for readers 2 and 3 ($k=0.75$, 95% CI: 0.63–0.95, $P<0.001$), ($k=0.65$, 95% CI: 0.41–0.90, $P<0.001$), respectively; Table 5.5). The interobserver agreement between all readers was almost perfect for chest radiography ($k=0.84$, 95% CI: 0.66–1.00, $P<0.001$) and substantial for chest CT ($k=0.71$, 95% CI: 0.52–0.90, $P<0.001$; Table 5.5). The agreement between any pair of readers for chest radiography ranged from substantial ($k=0.78$) to almost perfect ($k=0.89$) and from substantial ($k=0.61$) to almost perfect ($k=0.87$) for chest CT (Table 5.5).

Table 5.5. Intermodality and interobserver agreement in estimating the broad timeframes of rib fractures

Broad timeframe of rib fracture dating ^a		Kappa value (95% CI) ^b
Overall intermodality agreement (chest CT vs chest radiography)		0.76 (0.55 – 0.97)
Intermodality agreement within the same reader (chest CT vs chest radiography)	Reader 1 vs Reader 1	0.87 (0.70–1.00)
	Reader 2 vs Reader 2	0.75 (0.63–0.95)
	Reader 3 vs Reader 3	0.65 (0.41–0.90)
Interobserver agreement on chest radiography	Reader 1 vs Reader 2	0.78 (0.58 – 0.98)
	Reader 1 vs Reader 3	0.88 (0.72 – 1.00)
	Reader 2 vs Reader 3	0.89 (0.74 – 1.00)
	Reader 1 vs Reader 2 vs Reader 3	0.84 (0.66 – 1.00)
Interobserver agreement on chest CT	Reader 1 vs Reader 2	0.70 (0.47 – 0.93)
	Reader 1 vs Reader 3	0.87 (0.69 – 1.00)
	Reader 2 vs Reader 3	0.61 (0.33 – 0.86)
	Reader 1 vs Reader 2 vs Reader 3	0.71 (0.52 – 0.90)

^aAcute versus healing

^bAll kappa values were statistically significant with *P*-values being <0.001

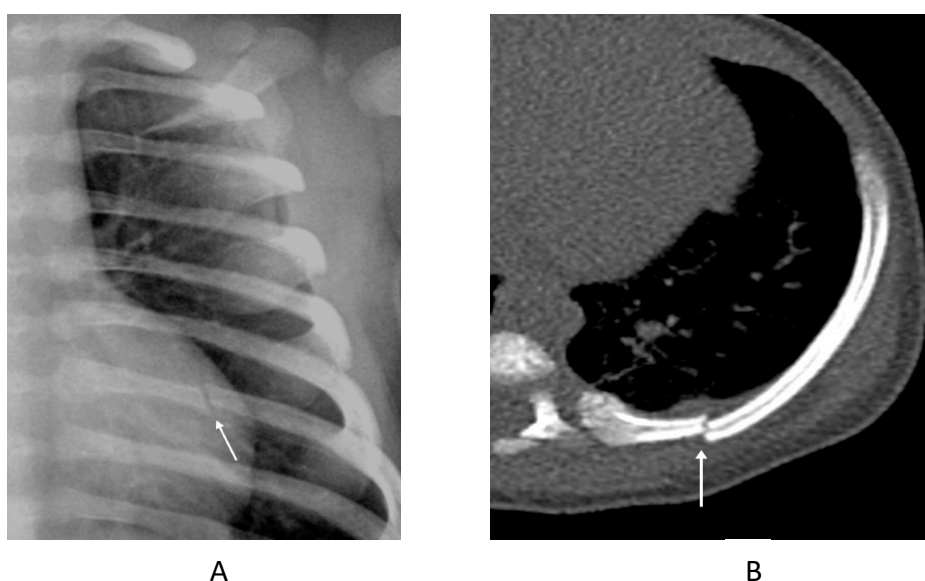


Figure 5.3. Dating of a rib fracture in a 1-month-old boy.

(A) Cropped anteroposterior chest radiograph demonstrates a displaced acute posterior fracture of the left 7th rib (arrow). **(B)** Cropped axial chest computed tomography image (bone window) demonstrates the fracture (5 o'clock, arrow) also dated as acute.

5.4.3 Estimating specific age range of rib fractures from computed tomography

The distribution of the presence of CT healing features by the estimated fracture age range obtained from chest radiography is shown in Figures 5.4 and 5.5. CT fracture line did not show a discriminative pattern for estimating the specific age range of rib fractures (Figure 5.4).

On the other hand, callus formation on CT showed a discriminative pattern for estimating specific age range of rib fractures (Figure 5.5). A rib fracture on CT with no periosteal reaction was more likely to have age of < 2 weeks; thin periosteal reaction was more likely to have age of 2–4 weeks; callus formation presence was more likely to have age of > 2 weeks; and focal sclerosis or cortical thickening was more likely to have age of 4–6 weeks.

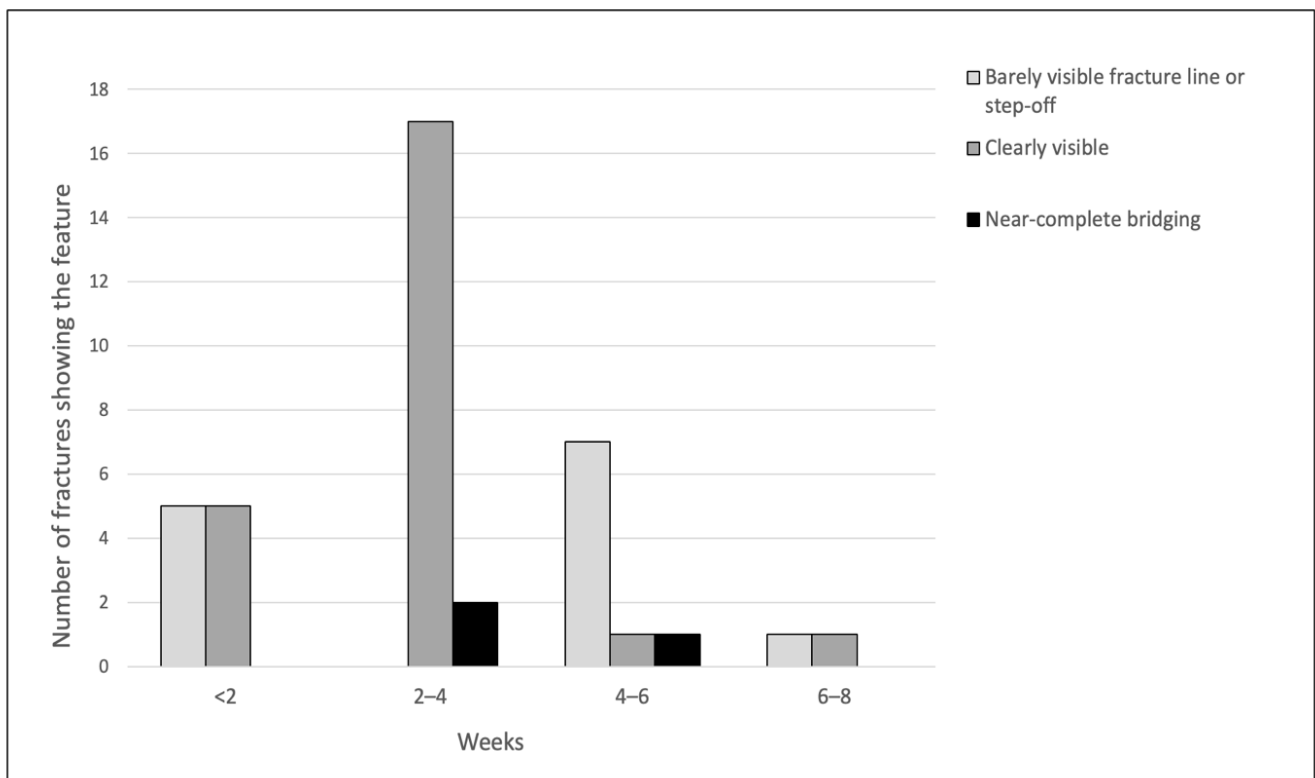


Figure 5.4. The bar graph shows the number of fractures showing the computed tomography healing features of the fracture line over the fracture age estimated from chest radiographs

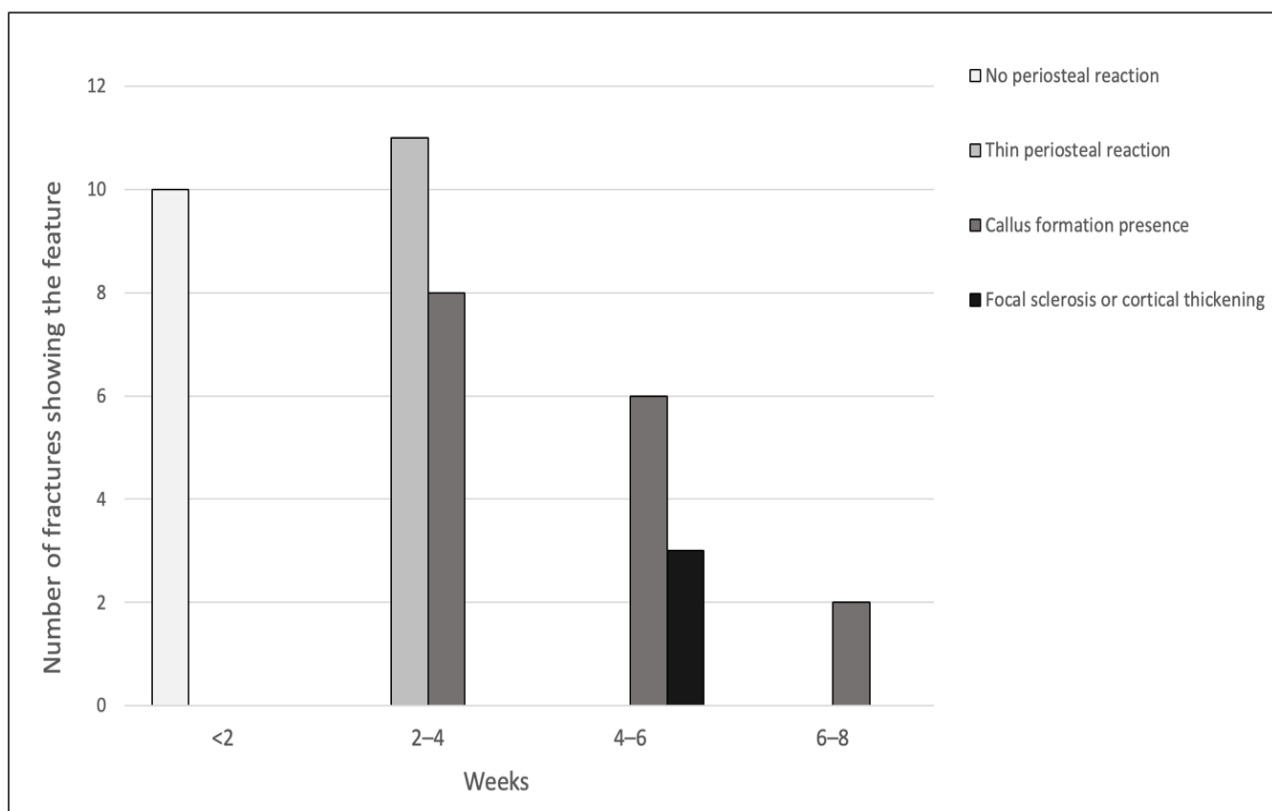


Figure 5.5. The bar graph shows the number of fractures showing the computed tomography healing features of the callus formation over the fracture age estimated from chest radiographs.

5.5 Discussion

In cases of SPA, radiologists are often asked to date fractures (i.e. to provide a timeline for the age of fractures based on the presence or absence of the radiological features of healing) [12, 28]. Fracture dating is often key to decision making in care proceedings, by assisting the courts to narrow down the potential pool of perpetrators and ensuring optimum safe placement of the child [8, 12, 28].

Radiologists should be aware of the limitations of the current literature with respect to fracture dating when reporting radiological imaging in cases of SPA. A recent systematic review [11] found that most studies assessing fracture healing referred to the chapter on “Dating Fractures” in *Diagnostic Imaging of Child Abuse* [29] which is based on the authors’ clinical experiences of radiological reporting as opposed to empirical data. Most general [non-expert] paediatric radiologists may not have a comprehensive and up to date knowledge of the current literature regarding fracture dating and healing [8, 11]. As such, when asked to ‘date’ fractures in cases SPA, it is recommended that radiologists provide

a broad timeframe for rib fracture dating (i.e., acute or healing) rather than stating specific timescales (unless providing an expert opinion to the Court where dating would usually be expected to be based on published scientific literature as well as on the clinical experience of the expert).

Recent studies have demonstrated that chest CT has greater sensitivity than initial CXR for detecting rib fractures in live children with SPA [22-24]. Our results reveal moderate agreement between chest radiography and CT in identifying the radiological features of fracture healing regarding fracture line ($k=0.42$) and callus formation ($k=0.49$). Substantial agreement ($k=0.76$) was found between modalities in the estimation of the broad timeframes for rib fracture dating (i.e., acute vs healing) with almost perfect interobserver agreement on chest radiography ($k=0.84$) and substantial on chest CT ($k=0.71$). The difference in interobserver agreement between chest radiography and CT could be due to a lack of radiologists' experience in dating fractures from CT (which would be the case for most practicing radiologists), because the fracture dating is traditionally assessed on radiographs, which are the current imaging standard used in clinical practice [13, 14], with CT being reserved as a problem solving tool for indeterminate radiographic appearances. However, our results suggest the callus formation parameters may help in estimating the specific age of rib fractures in infants from CT scans.

To the authors' knowledge, this is the first study attempting to assess the comparability of dating rib fractures from chest CT and radiography in live children investigated for SPA. However, this study has several limitations. First, only a small number of fractures were included (40 fractures in 13 patients) and so the results should be interpreted with caution. Second, the criteria for the healing features identification of rib fractures were limited only to fracture line and callus formation (we did not assess for pleural thickening/pleural effusion or characterise callus into "soft" or "hard"), however, these are the most common features that are manifest radiologically during bone healing [8] and authors have shown poor observer reliability for the characterisation of callus [30].

Further studies that provide a more detailed assessment of the correlation of CT-based features of fracture healing with known fracture age are required to support legal investigations if chest CT is to become the clinical standard for rib fracture identification in cases of SPA in children.

5.6 Conclusion

Fracture dating in cases of SPA in children has clinical, forensic and medicolegal implications. Features and broad timeframes of rib fracture healing by chest CT show moderate and substantial agreement, respectively, with chest radiography, the current standard used in clinical and medicolegal practice. Further CT analysis of the evolution of callus with healing could serve as a guide for radiologists in estimating the specific age range of rib fractures identified on CT.

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Chapter Six

Computed tomography radiation dose optimisation for the diagnosis of rib fractures in infants investigated for suspected physical abuse: an experimental animal study

The paper is in preparation for publication

6. Computed tomography radiation dose optimisation for the diagnosis of rib fractures in infants investigated for suspected physical abuse: an experimental animal study

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- Study conception and design: **N.M.A.**, A.C.O., A.J. and M.P.
- Wrote the initial draft of the study protocol: **N.M.A.**
- Review of study protocol: A.C.O., A.J. and M.P.
- Sought approval from Sheffield and Leeds Hospitals: **N.M.A.**
- Searched for best deceased animal model for the study and sourced them: **N.M.A.**
- Induced rib fractures in the deceased animal model: **N.M.A.**
- Participated in performing the CT scanning of animals by preparing CT parameters and positioning the rabbits at both centres (Leeds and Sheffield): **N.M.A.**
- Anonymised the images: **N.M.A.**
- Data collection: **N.M.A.**
- Designed the report proforma: **N.M.A.**
- Statistical analysis
 - Cleaned and tabulated the data for analysis: **N.M.A.**
 - Chose the appropriate tests: **N.M.A.** and A.R.
 - Performed the statistical analysis: **N.M.A.**
 - Supervised the statistical analysis: A.R.
- Wrote the initial draft of the manuscript: **N.M.A.**
- Reviewed and approved the final draft of the manuscript: **N.M.A.**, A.C.O., A.J. and M.P.

6.1 Abstract

Background

Computed tomography (CT) of the chest has proven promising in improving rib fracture detection in children with suspected physical abuse (SPA). However, concerns regarding relatively higher radiation exposure make it less desirable in routine clinical practice.

Objective

To investigate the effect of varying CT scanning parameters (tube voltage and current) on radiation dose, image quality and sensitivity, and to optimise chest CT scanning parameters for the detection of rib fractures in infants with SPA.

Methods

Following traumatic induction of rib fractures, five rabbits underwent post-mortem CT scanning at two centres using combinations of tube voltage (80 kV and 100 kV) with a progressive 10% reduction in tube current (mA) until 10 mA was reached. Two paediatric radiologists, blinded to the scan parameters, independently assessed subjective image quality with respect to noise and sharpness using a 5-point Likert scales and recorded presence of undisplaced rib fractures. A consensus read formed the reference standard. Interobserver agreement (kappa) and sensitivity were calculated. Linear regression between the readers' scores for image quality and effective dose was used to determine the imaging parameters providing the lowest effective dose with acceptable diagnostic image quality (≥ 3 out of 5).

Results

There was moderate agreement between readers' subjective assessment of image noise (Centre 1, kappa (k)=0.5, P =0.001; Centre 2, k =0.45, P =0.001) and sharpness (Centre 1, k =0.59, P =0.001; Centre 2, k =0.55, P =0.001). The lowest dose with acceptable diagnostic image quality at Centre 1 was 80 kV/30 mA with an effective dose of 0.32 mSv and sensitivity of 93.5%, and 80 kV/40 mA with an effective dose of 0.2 mSv and sensitivity of 84.3% at Centre 2, approaching the combined effective dose (mSv) for initial and follow-up skeletal survey chest radiographs performed for SPA (0.1 mSv).

Conclusion

Low-dose CT (with an effective dose which approaches the average dose for chest radiographs performed for SPA) may provide images of sufficient diagnostic quality to confidently diagnose rib fractures. Studies in children with SPA are required.

6.2 Introduction

In the absence of an alternative plausible accidental explanation, rib fractures are highly specific for physical abuse in infants and young children [1-4]. International guidelines currently recommend chest radiography (anteroposterior and right and left oblique views) as part of the skeletal survey when evaluating children suspected of having been physically abused [5, 6]. However, chest radiography has a low sensitivity in the detection of acute rib fractures given that they are often minimally displaced/incomplete [7, 8] and may be obscured by overlying structures [9, 10]. As such, follow-up chest radiographs (anteroposterior and right and left oblique projections) are performed as part of the follow-up skeletal survey 11 to 14 days after the initial skeletal survey. The rationale behind this is to improve the identification of any rib fractures not previously visualised on initial chest radiographs [11, 12] due to interval fracture healing (callus development), increasing fracture conspicuity [13, 14].

In recent years, it has been demonstrated that chest computed tomography (CT) is more sensitive than chest radiography in detecting rib fractures in abused children [9, 10, 15-18]. However, the dose associated with chest CT is generally greater than chest radiography [19-22] which makes CT a less favourable option in routine clinical practice when evaluating live children for suspected physical abused (SPA). In the last decade, advancements in CT technology have improved its clinical utility with the introduction of various methods for CT dose optimisation in routine clinical practice, including adjusting CT scanning parameters (e.g., tube voltage [kV], tube current [mA] and pitch), iterative reconstruction and tube current modulation [23-25]. Several studies have reported significantly reduced radiation dose for CT examinations in paediatric patients while maintaining diagnostic image quality [26-30]. This study used an animal model to investigate the effect of varying scan parameters (tube voltage and current) on radiation dose and image quality and sensitivity in an attempt to derive chest CT scan parameters for evaluating rib fractures at the lowest possible radiation dose without compromising the diagnostic image quality in children being investigated for SPA.

6.3 Material and methods

6.3.1 Material

The frozen bodies of 5 rabbits were sourced from a company (Kiezebrink UK Ltd, Suffolk, United Kingdom) who provides a range of deceased prey for feeding other wild animals; therefore, no rabbits

were killed specifically for the purposes of this study (as such, ethical approval was not required, Appendix 3). The average weight of the rabbits ranged from approximately 2.0 kg to 5.6 kg, comparable to the average weight of human infants up to the age of 3 months [31, 32]. Local institutional approval was obtained to perform CT imaging on the deceased rabbits.

6.3.2 Methods

6.3.2.1 Trauma

The deceased rabbits were thawed by extracting them from the refrigeration unit three hours before inducing fractures and subsequent scanning. To induce rib fractures, the thoracic regions of all rabbits were squeezed in the front-to-back and side-to-side directions and subjected to blunt force trauma with a hammer in dorsal and the left and right lateral locations (to simulate blunt trauma from a fist). Both methods reflect the mechanisms thought to be involved in the infliction of rib fractures in abused children [33, 34].

6.3.2.2 CT examinations

The rabbits were placed in sealed protective bags to prevent fluid leakage. The CT examinations were performed at two paediatric hospitals using a VCT 64 CT Lightspeed scanner (GE Healthcare, Waukesha, WI; Centre 1) and a dual-source CT scanner SOMATOM Force (Siemens Healthcare, Forchheim, Germany; Centre 2). Each rabbit was scanned at both centres pre- and post-fracture induction using identical CT parameters, varying tube voltages (80 kV and 100 kV) and a progressive reduction of tube current (mA) by 10% from the standard chest CT protocol at each site until 10 mA was reached. At both centres, the automatic tube current modulation was deactivated to adjust the current value manually.

At Centre 1, the standard protocol is 100 kV, Smart mA (automatic exposure control, ranging from 40 to 60), 0.6 s rotation time, 0.984 pitch factor, 1.25 mm slice thickness, using 50% Adaptive Statistical Iterative Reconstruction (ASIR) for soft tissue and bone algorithm reconstruction with 1.2 mm and 0.625 mm slice thickness, respectively. At Centre 2, the standard protocol is Sn100 kV, 200 effective mA, 0.25 s rotation time, 2 pitch factor, 0.6 mm slice thickness, using Advanced Modelled Iterative Reconstruction 3 (ADMIRE 3) for soft (B40) and sharp bone (B69) algorithms and image reconstruction with 1.5 mm and 0.6 mm slice thickness, retrospectively. At Centre 1, we aimed to reduce the tube current value by 6,

representing 10% of the maximum value of the smart current range (60 mA); however, the CT scanner did not allow for such a reduction and so the tube current was reduced by 5 mA for each scan.

6.3.2.3 Image quality evaluation

Two paediatric radiologists (A.C.O and A.M.J, each with 20 years of experience) independently assessed the subjective image quality for each parameter set using a Digital Imaging and Communications Medicine (DICOM) reader on diagnostic monitors to simulate clinical practice. Image sets were assigned random numbers and all scan parameters (tube voltage and current) were removed from the images so that readers were unaware of which settings were used. Subjective evaluation of image quality (image noise and sharpness) was performed using the scoring systems described by Jin *et al.* [35] and Patro *et al.* [36], respectively. Subjective image noise was rated using a 5-point Likert scale: 1=noisy image, 2=higher than acceptable noise level, 3=acceptable noise level, 4=less than average noise level and 5=very minor noise level. An acceptable noise level was defined as an image that satisfactorily reveals cortical bone, vertebral trabecular bone and subtle fracture lesions and displays clear boundaries for nearby tissues. Image sharpness was also rated using a 5-point Likert scale: 1=structures cannot be identified or defined, 2=structures can be visualised but are insufficient for diagnostic reporting with blurred contours, 3=structures can be seen, contours are sufficiently sharp and diagnostic information can be retrieved (below average sharpness), 4=structures are seen, but contours are not fully sharp (average sharpness) and 5=structures are well defined with sharp contours (above average sharpness). Image sharpness was assessed by evaluating the sharpness of the cortical/trabecular bones of the ribs and vertebrae and the adjacent soft tissues.

All image sets provided to the readers were in the axial plane with slice thickness 0.6 mm and were reconstructed using the bone window algorithm (width [W]:2000 Hounsfield Unit [HU], level [L]:350 HU at Centre 1; and W:1500 HU, L:450 HU at Centre 2). Readers were able to adjust window and level settings on their DICOM readers, as required, reflecting clinical practice.

6.3.2.4 Fracture diagnosis

After completing the assessment of subjective image quality, the two paediatric radiologists independently identified the presence/absence of undisplaced rib fractures, describing rib number, side, and fracture location along the rib (anterior, anterolateral, lateral, posterolateral or posterior). The reference standard was established by the paediatric radiologists in consensus using the image sets with the highest radiation dose (i.e. that had the most appropriate image quality). Radiologists had the ability

to adjust window and level settings and perform multiplanar reconstructions (MPR) on their own imaging software as they would as part of their routine clinical practice. Radiologists reviewed the images three weeks after setting the reference standard and each rabbit was assigned a unique code different from the original code to minimise recall bias. A handful of pre-fracture image sets were included to reduce confirmation bias.

6.3.2.5 Radiation dose

For each combination of scan parameters (tube voltage and current), the volume CT dose indices (vol [mGy]) and the dose length product (DLP [mGy·cm]) were recorded from the CT scanner output reports (Tables 6.1 and 6.2). The size-specific dose estimate (SSDE [mGy]), a recently recommended dose index that estimates radiation dose taking into account the patient's size, has been shown to improve the precision of dose estimation in paediatric CT imaging [19, 21, 22]. Therefore, effective doses (ED [mSv]) in this study were calculated based on SSDE, as described in Brady *et al.* [22].

6.3.2.6 Statistical analysis

Continuous variables were expressed as the mean $\pm$ standard deviation (SD). Scores for subjective image noise and sharpness, and sensitivity were calculated for each reader and averaged across both readers. To determine the optimal parameter set, the combined Likert scores for subjective image quality (i.e., image noise and sharpness) for each parameter set were calculated for each reader and averaged across both readers. Linear regression was used to analyse the relationship between the effective dose and the average combined Likert score of the subjective image quality for each parameter set. Those with low effective doses and acceptable subjective image quality (Likert score ≥ 3) were considered the optimal parameter set. The analysis of variance (ANOVA) with a *post hoc* test and an unpaired Student's *t*-test were used to assess the differences in image noise, sharpness and radiation dose at the various tube voltage and current values. Kappa statistics assessed the interobserver agreement of the subjective image quality scores. The kappa (k) value was interpreted as slight agreement (0.0–0.2), fair agreement (0.21–0.40), moderate agreement (0.41–0.60), substantial agreement (0.61–0.80) and almost perfect agreement (0.81–1.0) [37]. Statistical significance was defined as a *p*-value < 0.05 . Statistical analyses were performed using SPSS Statistics (v.27; IBM, Armonk, NY).

6.4 Results

6.4.1 Trauma

All five rabbits had at least one rib fracture. After excluding displaced rib fractures, the total number of undisplaced rib fractures identified by the radiologists in consensus was 16. These were identified at different locations along the rib arc (anterolateral=1, lateral=3, posterolateral=8 and posterior=4).

6.4.2 CT examinations

A total of 44 different dose levels (22 scans at each centre) resulted from varying the tube voltage and current settings (Tables 6.1 and 6.2).

6.4.3 Image quality evaluation

The qualitative scoring for the CT image noise and sharpness of each reader is presented in Tables 6.1 and 6.2 for Centre 1 and Centre 2, respectively. At Centre 1, the subjective image noise score (out of 5) ranged from 1.0 ± 0.0 (mean $\pm$ SD) to 4.8 ± 0.5 and from 1.2 ± 0.5 to 4.8 ± 0.5 for Readers 1 and 2, respectively. The combined score of the subjective image noise for the readers ranged from 1.1 ± 0.22 to 4.6 ± 0.7 . The subjective image sharpness score (out of 5), ranged from 2.0 ± 0 to 5.0 ± 0.0 for both readers, whereas the combined scores ranged from 2.0 ± 0.0 to 4.9 ± 0.2 . At Centre 2, the subjective image noise score ranged from 1.0 ± 0.0 to 4.8 ± 0.5 and from 1.8 ± 0.5 to 5.0 ± 0.0 for Readers 1 and 2, respectively. The combined score for subjective image noise for the readers ranged from 1.5 ± 0.4 to 4.8 ± 0.5 . The subjective image sharpness score ranged from 2.6 ± 0.6 to 5.0 ± 0.0 for Reader 1, from 2.0 ± 0.0 to 4.8 ± 0.5 for Reader 2 and from 2.3 ± 0.5 to 4.8 ± 0.5 for the combined sharpness score.

When varying the tube voltage values (80 and 100 kV only, i.e., other parameters were constant), there was no statistically significant change in the subjective noise score ($P=0.62$ at Centre 1, $P=0.67$ at Centre 2) and subjective sharpness score ($P=0.06$ at Centre 1, $P=0.08$ at Centre 2). In contrast, there were significant differences in the subjective noise score ($P=0.001$ at Centres 1 and 2) and subjective sharpness score ($P=0.001$ at Centres 1 and 2) by varying the tube current values only (i.e. other parameters were unchanged).

Interobserver agreement for subjective image noise was moderate at Centre 1 ($k=0.5$, $P=0.001$) and Centre 2 ($k=0.45$, $P=0.001$). A moderate degree of agreement was also found between readers regarding subjective image sharpness at Centre 1 ($k=0.59$, $P=0.001$) and Centre 2 ($k=0.55$, $P=0.001$).

Table 6.1. CT imaging parameters, image assessment and calculated radiation dose for Centre 1

Protocol	Parameter set		Reader	Subjective image quality (5-point Likert scale ±SD)		CT dose			
	kV	mA		Noise	Sharpness	CTDIvol (mGy)	SSDE (mGy) ±SD	DLP (mGy·cm) ±SD	Effective dose (mSv) ±SD
1	100	60	R1	4.8 ± 0.5	4.8 ± 0.5	1.63	2.23 ± 0.11	34.58 ± 3.50	1.26 ± 0.06
			R2	4.4 ± 0.9	4.6 ± 0.65				
			Combined	4.6 ± 0.7	4.7 ± 0.5				
2		55	R1	4.4 ± 0.9	4.6 ± 0.9	1.49	2.04 ± 0.10	31.70 ± 3.21	1.16 ± 0.06
			R2	4.8 ± 0.5	5.0				
			Combined	4.6 ± 0.7	4.8 ± 0.5				
3		50	R1	4.4 ± 0.6	4.6 ± 0.6	1.35	1.84 ± 0.09	28.82 ± 2.91	1.04 ± 0.06
			R2	4.6 ± 0.6	4.6 ± 0.6				
			Combined	4.5 ± 0.6	4.6 ± 0.6				
4		45	R1	4.0 ± 0.7	4.4 ± 0.6	1.22	1.67 ± 0.08	25.85 ± 2.63	0.94 ± 0.06
			R2	3.8 ± 0.5	4.2 ± 0.5				
			Combined	3.9 ± 0.6	4.3 ± 0.5				
5		40	R1	3.4 ± 0.9	3.8 ± 0.5	1.08	1.47 ± 0.07	23.9 ± 3.58	0.83 ± 0.04
			R2	4.8 ± 0.5	4.8 ± 0.5				
			Combined	4.1 ± 0.7	4.3 ± 0.5				
6		35	R1	3.8 ± 0.5	4.0	0.95	1.30 ± 0.06	20.39 ± 2.20	0.73 ± 0.05
			R2	3.4 ± 0.6	4.0				
			Combined	3.6 ± 0.5	4.0				
7		30	R1	3.0	3.4 ± 0.6	0.81	1.10 ± 0.05	17.47 ± 1.89	0.62 ± 0.03
			R2	3.0	4.2 ± 0.8				
			Combined	3.0	3.8 ± 0.7				
8		25	R1	2.6 ± 0.6	3.2 ± 0.5	0.68	0.93 ± 0.04	14.56 ± 1.57	0.51 ± 0.02
			R2	2.8 ± 0.5	3.6 ± 0.9				
			Combined	2.7 ± 0.5	3.4 ± 0.7				
9		20	R1	2.8 ± 0.8	3.4 ± 0.6	0.54	0.73 ± 0.04	11.65 ± 1.26	0.40 ± 0.03
			R2	3.0 ± 0.7	3.4 ± 0.9				
			Combined	2.9 ± 0.8	3.4 ± 0.7				
10		15	R1	2.4 ± 0.6	3.0	0.41	0.56 ± 0.03	8.74 ± 0.95	0.29 ± 0.01
			R2	2.2 ± 0.5	3.4 ± 1.1				
			Combined	2.3 ± 0.5	3.2 ± 0.6				
11		10	R1	1.8 ± 0.5	2.4 ± 0.6	0.27	0.36 ± 0.02	5.82 ± 0.63	0.18 ± 0.02
			R2	2.0	2.4 ± 0.6				
			Combined	1.9 ± 0.2	2.4 ± 0.6				
12	60	R1	4.6 ± 0.6	4.8 ± 0.5	0.88	1.20 ± 0.06	18.83 ± 2.03	0.67 ± 0.04	
		R2	4.4 ± 0.6	4.6 ± 0.6					
		Combined	4.5 ± 0.6	4.7 ± 0.5					
13	55	R1	4.2 ± 0.8	5.0	0.80	1.09 ± 0.05	17.26 ± 1.87	0.62 ± 0.04	
		R2	4.6 ± 0.6	4.8 ± 0.5					
		Combined	4.4 ± 0.7	4.9 ± 0.2					
14	50	R1	4.4 ± 0.9	4.8 ± 0.5	0.73	1.00 ± 0.05	15.69 ± 1.69	0.54 ± 0.03	
		R2	4.2 ± 0.8	4.8 ± 0.5					
		Combined	4.3 ± 0.9	4.8 ± 0.5					
15	45	R1	3.8 ± 0.8	4.8 ± 0.5			14.12 ± 1.53		

Protocol	Parameter set		Reader	Subjective image quality (5-point Likert scale ±SD)		CT dose			
	kV	mA		Noise	Sharpness	CTDIvol (mGy)	SSDE (mGy) ±SD	DLP (mGy·cm) ±SD	Effective dose (mSv) ±SD
	80		R2	3.0	4.4 ± 0.6	0.66	0.90 ± 0.05		0.50 ± 0.02
			Combined	3.4 ± 0.4	4.6 ± 0.5				
16	40		R1	3.8 ± 1.1	3.8 ± 1.1	0.58	0.79 ± 0.04	12.55 ± 1.36	0.44 ± 0.04
			R2	4.0 ± 0.7	4.6 ± 0.65				
			Combined	3.9 ± 0.9	4.2 ± 0.8				
17	35		R1	3.0 ± 0.7	3.6 ± 0.9	0.51	0.69 ± 0.04	10.99 ± 1.18	0.37 ± 0.02
			R2	3.2 ± 0.5	4.0				
			Combined	3.1 ± 0.6	3.8 ± 0.5				
18	30		R1	2.6 ± 0.9	3.0 ± 0.7	0.44	0.60 ± 0.03	9.41 ± 1.01	0.32 ± 0.02
			R2	3.0	3.6 ± 0.6				
			Combined	2.8 ± 0.5	3.3 ± 0.6				
19	25		R1	2.4 ± 0.9	3.0 ± 0.7	0.36	0.49 ± 0.02	7.84 ± 0.85	0.25 ± 0.01
			R2	2.8 ± 0.5	3.0 ± 0.7				
			Combined	2.6 ± 0.7	3.0 ± 0.7				
20	20		R1	2.0	2.8 ± 0.5	0.29	0.39 ± 0.02	6.28 ± 0.67	0.20 ± 0.02
			R2	2.4 ± 0.9	2.8 ± 0.5				
			Combined	2.2 ± 0.5	2.8 ± 0.5				
21	15		R1	2.0	2.0	0.22	0.30 ± 0.01	4.71 ± 0.51	0.14 ± 0.02
			R2	2.0	2.0				
			Combined	2.0	2.0				
22	10		R1	1.0	2.0	0.15	0.20 ± 0.01	3.09 ± 0.28	0.07 ± 0.01
			R2	1.2 ± 0.5	2.0				
			Combined	1.1 ± 0.2	2.0				

R1 Reader 1, R2 Reader 2

Table 6. 2. CT imaging parameters, image assessment and calculated radiation dose for Centre 2

Protocol	Parameter set		Reader	Subjective image quality (5-point Likert scale ±SD)		CT dose			
	kV	mA		Noise	Sharpness	CTDIvol (mGy)	SSDE (mGy) ±SD	DLP (mGy·cm) ±SD	Effective dose (mSv) ±SD
1	100	200	R1	4.6 ± 0.6	4.8 ± 0.5	3.15	4.31 ± 0.21	69.76 ± 5.56	2.49 ± 0.12
			R2	4.8 ± 0.5	4.8 ± 0.5				
			Combined	4.7 ± 0.5	4.8 ± 0.5				
2		180	R1	4.6 ± 0.9	4.2 ± 0.5	2.84	3.88 ± 0.19	62.74 ± 4.97	2.25 ± 0.10
			R2	4.6 ± 0.9	4.6 ± 0.6				
			Combined	4.6 ± 0.9	4.4 ± 0.5				
3		160	R1	4.4 ± 0.9	4.2 ± 0.8	2.52	3.45 ± 0.17	55.76 ± 4.40	1.98 ± 0.10
			R2	5.0	4.4 ± 0.9				
			Combined	4.7 ± 0.5	4.3 ± 0.9				
4		140	R1	4.0 ± 1.0	4.6 ± 0.6	2.21	3.03 ± 0.15	48.84 ± 3.81	1.74 ± 0.09
			R2	4.2 ± 0.8	4.4 ± 0.6				
			Combined	4.1 ± 0.9	4.5 ± 0.6				
5		120	R1	2.8 ± 1.1	4.0 ± 1.0	1.88	2.57 ± 0.13	41.64 ± 3.3	1.47 ± 0.06
			R2	4.8 ± 0.5	4.0 ± 1.0				
			Combined	3.8 ± 0.8	4.0 ± 1.0				
6	100	R1	3.4 ± 0.6	4.4 ± 0.6	1.57	2.15 ± 0.11	34.72 ± 2.77	1.22 ± 0.06	
		R2	3.4 ± 0.9	4.4 ± 0.6					
		Combined	3.4 ± 0.7	4.4 ± 0.6					
7	80	R1	3.2 ± 0.8	3.6 ± 0.6	1.25	1.71 ± 0.09	27.60 ± 2.09	0.97 ± 0.05	
		R2	3.8 ± 0.5	3.6 ± 0.6					
		Combined	3.5 ± 0.7	3.6 ± 0.6					
8	60	R1	2.4 ± 0.6	2.8 ± 0.8	0.93	1.27 ± 0.06	20.64 ± 1.64	0.70 ± 0.04	
		R2	3.2 ± 0.8	3.8 ± 0.8					
		Combined	2.8 ± 0.7	3.3 ± 0.8					
9	40	R1	3.0	3.4 ± 0.6	0.62	0.85 ± 0.04	13.62 ± 1.10	0.45 ± 0.03	
		R2	3.2 ± 0.5	3.4 ± 0.6					
		Combined	3.1 ± 0.2	3.4 ± 0.6					
10	20	R1	2.6 ± 0.65	2.8 ± 0.5	0.30	0.41 ± 0.02	6.60 ± 0.51	0.21 ± 0.01	
		R2	2.2 ± 0.5	3.2 ± 0.5					
		Combined	2.4 ± 0.5	3.0 ± 0.5					
11	10	R1	2.0	2.6 ± 0.9	0.17	0.23 ± 0.01	3.80 ± 0.32	0.10 ± 0.01	
		R2	1.8 ± 0.5	2.0					
		Combined	1.9 ± 0.2	2.3 ± 0.5					
12	80	200	R1	4.4 ± 0.6	5.0	1.46	2.00 ± 0.10	32.12 ± 3.72	1.12 ± 0.06
			R2	4.4 ± 0.6	4.4 ± 0.6				
			Combined	4.4 ± 0.6	4.7 ± 0.3				
13		180	R1	4.6 ± 0.9	4.6 ± 0.6	1.32	1.80 ± 0.09	28.92 ± 3.37	1.03 ± 0.06
			R2	4.6 ± 0.9	4.8 ± 0.5				
			Combined	4.6 ± 0.9	4.7 ± 0.5				
14		160	R1	4.8 ± 0.5	4.2 ± 0.5	1.17	1.60 ± 0.08	25.62 ± 2.99	0.90 ± 0.05
			R2	4.8 ± 0.5	4.8 ± 0.5				
			Combined	4.8 ± 0.5	4.5 ± 0.5				

Protocol	Parameter set		Reader	Subjective image quality (5-point Likert scale ±SD)		CT dose			
	kV	mA		Noise	Sharpness	CTDIvol (mGy)	SSDE (mGy) ±SD	DLP (mGy·cm) ±SD	Effective dose (mSv) ±SD
15		140	R1	1.8 ± 0.8	3.2 ± 0.5	1.02	1.39 ± 0.07	22.46 ± 2.62	0.79 ± 0.04
			R2	3.4 ± 0.6	4.4 ± 0.6				
			Combined	2.6 ± 0.7	3.8 ± 0.5				
16		120	R1	2.0	3.6 ± 0.9	0.88	1.20 ± 0.06	19.26 ± 2.20	0.67 ± 0.04
			R2	4.2 ± 1.3	3.6 ± 0.9				
			Combined	3.1 ± 0.7	3.6 ± 0.9				
17		100	R1	2.6 ± 0.6	3.4 ± 0.6	0.73	1.00 ± 0.05	15.94 ± 1.88	0.54 ± 0.03
			R2	3.2 ± 0.5	3.4 ± 0.6				
			Combined	2.9 ± 0.5	3.4 ± 0.6				
18		80	R1	1.8 ± 0.8	3.4 ± 0.6	0.58	0.79 ± 0.04	12.70 ± 1.48	0.44 ± 0.04
			R2	3.8 ± 0.8	3.2 ± 0.5				
			Combined	2.8 ± 0.8	3.3 ± 0.5				
19		60	R1	2.4 ± 0.6	3.0	0.43	0.58 ± 0.03	9.50 ± 1.12	0.31 ± 0.02
			R2	3.2 ± 0.5	3.0				
			Combined	2.8 ± 0.5	3.0				
20		40	R1	3.0	3.2 ± 0.5	0.29	0.39 ± 0.02	6.26 ± 0.72	0.2 ± 0.02
			R2	2.6 ± 0.6	3.2 ± 0.5				
			Combined	2.8 ± 0.3	3.2 ± 0.5				
21		20	R1	2.2 ± 0.8	2.6 ± 0.6	0.14	0.19 ± 0.01	3.02 ± 0.34	0.07 ± 0
			R2	2.0	2.6 ± 0.6				
			Combined	2.1 ± 0.4	2.6 ± 0.6				
22		10	R1	1.0	2.6 ± 0.6	0.08	0.10 ± 0.01	1.74 ± 0.21	0.04 ± 0
			R2	2.0 ± 0.7	2.4 ± 0.9				
			Combined	1.5 ± 0.4	2.5 ± 0.7				

R1 Reader 1, R2 Reader 2

The Likert score for subjective image quality versus the effective dose revealed several sets of parameters with a low dose and acceptable diagnostic quality (Likert score ≥ 3). There was a significant positive correlation between the radiation dose and subjective image quality scores: $r=0.83$, $P=0.001$ at Centre 1; and $r=0.84$, $P=0.001$ at Centre 2. Figure 6.1 and Figure 6.2 illustrate the best-fit line for the relationship between the rating values of the subjective image quality and effective dose at Centres 1 and 2, respectively. At Centre 1, the linear regression analysis resulted in $R^2=0.70$ with a significance level of $P=0.001$ and a parameter set with a combination of the lowest radiation dose and acceptable diagnostic image quality at 80 kV/30 mA. The image quality score was 3.05, and the effective dose was 0.32 mSv and SSDE was 0.6 mGy (Figure 6.1). At Centre 2, the linear regression analysis resulted in $R^2=0.72$ with a significance level of $P=0.001$ and a parameter set with a combination of the lowest

radiation dose and acceptable diagnostic quality at 80 kV/40 mA. The image quality score was 3.0, and the effective dose was 0.2 mSv and SSDE was 0.39 mGy (Figure 6.2). Figure 6.3 illustrates selected axial chest CT images of the chosen parameter sets (80 kV/30 mA for Centre 1 and 80 kV/40 mA for Centre 2).

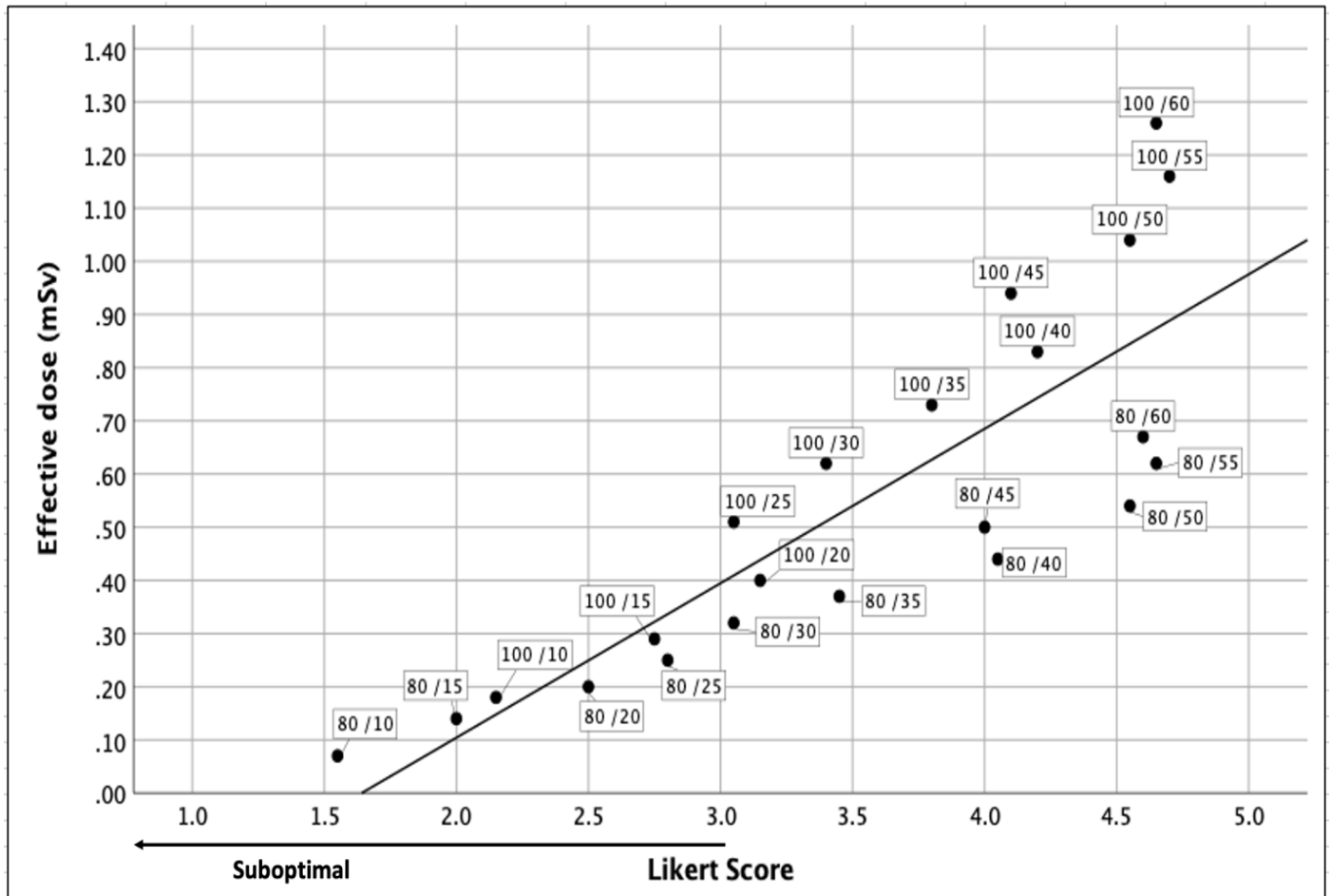


Figure 6.1. Scatter plot with best fit line demonstrating linear regression analysis between the average combined scores of image quality for both readers and the effective dose at Centre 1. A/B (e.g., 100/60) =kV/mA setting.

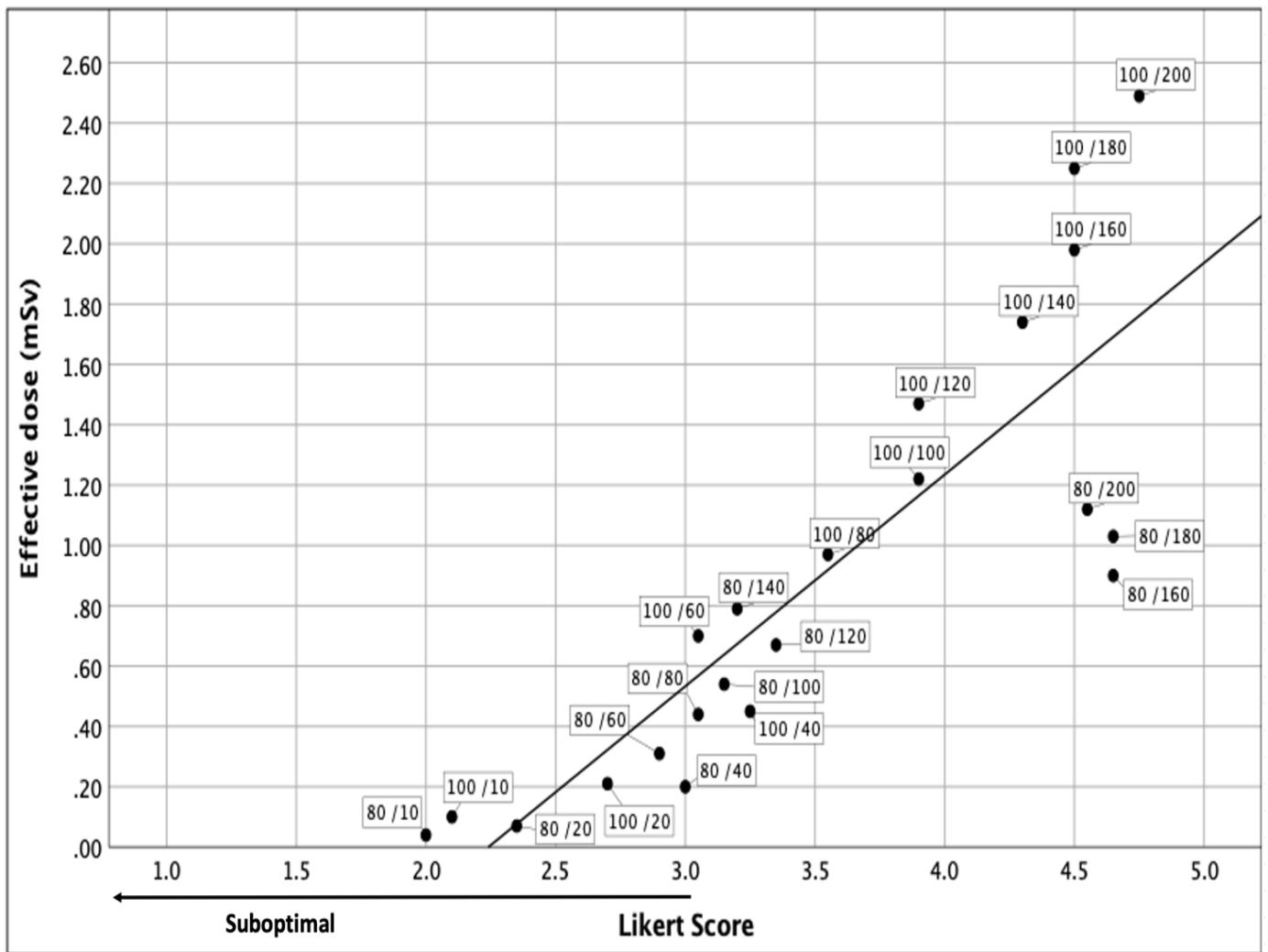


Figure 6.2. Scatter plot with best fit line demonstrating linear regression analysis between the average combined scores of image quality for both readers and the effective dose at Centre 2. A/B (e.g., 100/200) =kV/mA setting

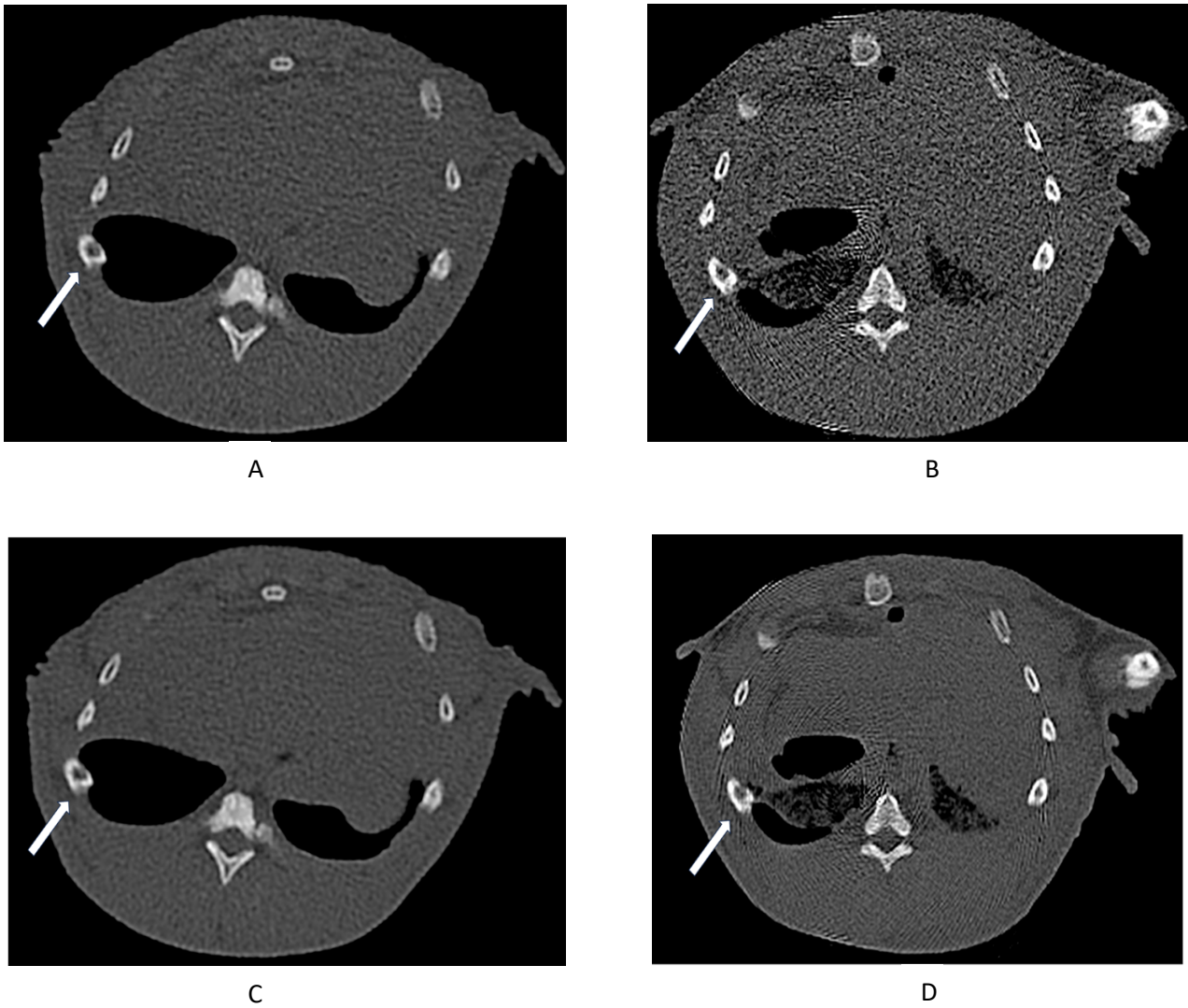


Figure 6.3. Axial computed tomography images of the chest (bone windows) for an animal subject (rabbit of weight= 4 Kg).

They demonstrate a right posterolateral 8th rib fracture (arrows) at chosen parameter set **(A)** 80 kV/30 mA at Centre 1 (W:350, L: 2000) and **(B)** 80 kV/40 mA at Centre 2 (W:450, L: 1500). The reference standard images were at **(C)** 100 kV/60 mA at Centre 1 (W:350, L: 2000) and **(D)** 100 kV/200 mA at Centre 2 (W:450, L: 1500).

6.4.4 Fracture diagnosis

Tables 6.3 and 6.4 present sensitivities of detecting undisplaced rib fractures at each parameter set for each reader at Centres 1 and 2, respectively. At Centre 1, sensitivity remained constant at 87% and

100% for readers 1 and reader 2, respectively, with combined score of 93.5%, except for the following parameter sets: 100 kV/15 mA (13.3% and 46.6% for readers 1 and 2, respectively), 100 kV/10 mA (0% for readers 1 and 2), 80 kV/15 mA (6.6% and 13.3% for readers 1 and 2, respectively), and 80 kV/10 mA (0% for readers 1 and 2; Table 6.3). At Centre 2, sensitivity remained constant at 87.5% and 100% for readers 1 and 2, respectively, with a combined score of 93.7%, except for the following parameter sets: 100 kV/20 mA (18.7% and 50% for readers 1 and 2, respectively), 100 kV/10 mA (0% for readers 1 and 2), 80 kV/60 mA (93.7% for reader 2), 80 kV/40 mA (75% and 93.7% for readers 1 and 2, respectively), 80 kV/15 mA (0% for readers 1 and 2) and 80 kV/10 mA (0% for readers 1 and 2; Table 6.4).

Table 6.3. Sensitivity for Centre 1

Protocol	Parameter set		Reader	Sensitivity
	kV	mA		
1	100	60	R1	87.0
			R2	100.0
			Combined	93.5
2		55	R1	87.0
			R2	100.0
			Combined	93.5
3		50	R1	87.0
			R2	100.0
			Combined	93.5
4		45	R1	87.0
			R2	100.0
			Combined	93.5
5		40	R1	87.0
			R2	100.0
			Combined	93.5
6		35	R1	87.0
			R2	100.0
			Combined	93.5
7		30	R1	87.0
			R2	100.0
			Combined	93.5
8		25	R1	87.0
			R2	100.0
			Combined	93.5
9		20	R1	87.0
			R2	100.0
			Combined	93.5

Protocol	Parameter set		Reader	Sensitivity
	kV	mA		
10	80	15	R1	13.3
			R2	46.6
			Combined	29.9
11		10	R1	0
			R2	0
			Combined	0
12		60	R1	87.0
			R2	100.0
			Combined	93.5
13		55	R1	87.0
			R2	100.0
			Combined	93.5
14		50	R1	87.0
			R2	100.0
			Combined	93.5
15		45	R1	87.0
			R2	100.0
			Combined	93.5
16		40	R1	87.0
			R2	100.0
			Combined	93.5
17	35	R1	87.0	
		R2	100.0	
		Combined	93.5	
18	30	R1	87.0	
		R2	100.0	
		Combined	93.5	
19	25	R1	87.0	
		R2	100.0	
		Combined	93.5	
20	20	R1	87.0	
		R2	100.0	
		Combined	93.5	
21	15	R1	6.6	
		R2	13.3	
		Combined	9.9	
22	10	R1	0	
		R2	0	
		Combined	0	

R1 Reader 1, R2 Reader 2

Table 6.4. Sensitivity for Centre 2

Protocol	Parameter set		Reader	Sensitivity
	kV	mA		
1	100	200	R1	87.5
			R2	100.0
			Combined	93.7
2		180	R1	87.5
			R2	100.0
			Combined	93.7
3		160	R1	87.5
			R2	100.0
			Combined	93.7
4		140	R1	87.5
			R2	100.0
			Combined	93.7
5		120	R1	87.5
			R2	100.0
			Combined	93.7
6		100	R1	87.5
			R2	100.0
			Combined	93.7
7		80	R1	87.5
			R2	100.0
			Combined	93.7
8		60	R1	87.5
			R2	100.0
			Combined	93.7
9		40	R1	87.5
			R2	100.0
			Combined	93.7
10		20	R1	18.7
			R2	50.0
			Combined	34.3
11		10	R1	0
			R2	0
			Combined	0
12	80	200	R1	87.5
			R2	100.0
			Combined	93.7
13		180	R1	87.5
			R2	100.0
			Combined	93.7
14		160	R1	87.5
			R2	100.0

Protocol	Parameter set		Reader	Sensitivity
	kV	mA		
15		140	Combined	93.7
			R1	87.5
			R2	100.0
16		120	Combined	93.7
			R1	87.5
			R2	100.0
17		100	Combined	93.7
			R1	87.5
			R2	100.0
18		80	Combined	93.7
			R1	87.5
			R2	100.0
19		60	Combined	93.7
			R1	87.5
			R2	93.7
20		40	Combined	90.6
			R1	75.0
			R2	93.7
21		20	Combined	84.3
			R1	0
			R2	0
22		10	Combined	0
			R1	0
			R2	0

R1 Reader 1, R2 Reader 2

6.4.5 Radiation dose

The radiation doses from modifying the CT parameters at Centres 1 and 2 are summarised in Tables 6.1 and 6.2, respectively. At Centre 1, the highest radiation dose with a SSDE of 2.23 ± 0.11 mGy (mean $\pm$ SD) and an effective dose of 1.26 ± 0.06 mSv were achieved using the 100 kV/60 mA parameter set, whereas the lowest radiation dose with a SSDE of 0.20 ± 0.01 mGy and an effective dose of 0.07 ± 0.01 mSv were achieved using the 80 kV/10 mA parameter set. At Centre 2, the highest radiation dose with a SSDE of 4.31 ± 0.21 mGy and an effective dose of 2.49 ± 0.12 mSv were achieved using the 100 kV/200 mA parameter set, whereas the lowest radiation dose with a SSDE of 0.10 ± 0.01 mGy and an effective dose of 0.04 ± 0 mSv were achieved using the 80 kV/10 mA parameter set. The radiation dose was

statistically significant ($P=0.001$) in the developed protocols at both centres when varying the tube voltage with a constant tube current and when varying the tube current with a constant tube voltage.

6.5 Discussion

Accurately diagnosing injuries in children presenting with SPA is crucial to implement the appropriate protective interventions. Evidence suggests that CT is more accurate than chest radiographs in detecting rib fractures in abused children [9, 10, 15-18]. However, the high radiation burden of CT compared to chest radiography makes it less favourable given that children are more radiosensitive than adults and increasing evidence indicates the potential long-term risks associated with childhood radiation exposure [38-40]. Therefore, optimising CT protocols to achieve the lowest possible radiation dose while maintaining acceptable diagnostic image quality is paramount.

We varied the parameters (tube voltage and current) of the standard chest CT protocol at two paediatric hospitals and have demonstrated that it is possible to achieve a low radiation dose in rib fracture evaluation while maintaining acceptable diagnostic image quality. At Centre 1, the 80 kV/30 mA parameter set achieved acceptable diagnostic image quality (3.05 on a 5-point Likert scale) with the lowest radiation dose (SSDE of 0.6 mGy, effective dose of 0.32 mSv) and demonstrated sensitivity of 93.5%. At Centre 2, the 80 kV/40 mA parameter set achieved a combination of acceptable diagnostic image quality (3.0 on a 5-point Likert scale) with the lowest radiation dose (SSDE of 0.39 mGy, effective dose of 0.2 mSv) and demonstrated sensitivity of 84.3%. The dose of these optimised chest CT protocols at both centres was well below the mean radiation dose of a standard chest CT in children with average weight up to 8 kg (equivalent to infant up to 6 months of age), which are approximately 2.3–4.9 mGy (SSDE) [19] and 1.2 mSv [22]. The effective dose of the optimised chest CT protocol at Centre 2 approaches to the average effective dose of the standard set of initial and follow-up skeletal survey chest radiographs (6 projections [anteroposterior and right and left oblique views], 0.1 mSv) [20, 21].

Various studies have reported that dose reduction can be achieved in paediatric CT without compromising diagnostic image quality [41-44]. It has also been previously reported that a low-dose CT (LDCT) chest protocol could achieve radiation doses which approach that of chest radiographs without compromising diagnostic image quality [45, 46]. Furthermore, an optimised chest CT protocol has been proposed to evaluate rib fractures in live children with SPA [47]. A recent study by Karmazyn *et al.* [16]

developed a LDCT chest protocol with an effective dose of 0.17 mSv. Sanchez *et al.* [48] reported an optimised chest CT protocol by adjusting CT parameters to 100 kV/15 mA with 0.5 s rotation time, 0.98 pitch and 20% ASIR, with an average effective dose of 0.56 mSv in children aged up to 4 months.

Our results reveal a positive correlation between subjective image quality (i.e. the overall combined reader score) and effective dose, validating the scoring system. Generally, altering the tube voltage and current is one of the most common methods to optimise CT by impacting radiation dose and image quality [23, 25]. Lowering the tube voltage or current (assuming all other parameters are constant) reduces the radiation dose [23, 25, 39, 49]. In this study, adjustments in tube voltage (when the tube current was constant) or the tube current (when the tube voltage was constant) displayed a statistically significant reduction in the radiation dose ($P=0.001$) at both centres.

Although lowering the tube current reduces the radiation dose, the image noise increases which decreases image quality [23, 25, 39, 49]. Our results reveal a statistically significant difference in the scores for subjective image noise ($p=0.001$) at both centres when the adjustments were to tube current only (with constant tube voltage). In general, the relationship between tube voltage and image quality is not straightforward. Although decreased voltage yields a reduction in radiation dose and improved image contrast, the image noise increased due to decreased photon penetration [39, 50, 51]. Interestingly, the results demonstrate that the tube voltage adjustments (constant tube current) displayed no statistically significant difference in the scores for subjective image noise ($P=0.62$ at Centre 1 and $P=0.67$ at Centre 2) and sharpness ($P=0.06$ at Centre 1 and $P=0.08$ at Centre 2). However, the range of tube voltage values in this study were limited (100 and 80 kV) which may have led to an unnoticeable effect of voltage on image noise and sharpness. It is worth mentioning that the relationships between voltage, image quality and radiation dose are complex and influenced by many factors, such as the combination of several energy dependent X-ray interactions and body size [51, 52]. Arguably, low voltage is more suitable and applicable for paediatric CT scans than adult scans [39, 53] because children have smaller bodies, requiring less energy for photon transmission through the body, thus reducing the radiation dose while maintaining diagnostic image quality [39, 53]. Increased noise is tolerable for high-contrast diagnostic tasks, such as assessing bone structure, because a high intrinsic contrast exists between the surrounding soft tissue and bone structure [39]. Given that the effect of altering one or both CT parameters on radiation dose and image quality is not straightforward, they

must be appropriately selected to achieve radiation dose reduction while preserving diagnostic image quality.

In the last decade, various CT dose reduction strategies have been introduced into clinical practice [24, 25]. Iterative reconstruction is an image reconstruction method which has been reported to significantly reduce CT radiation dose while maintaining diagnostic image quality [43, 54, 55]. A study by Singh *et al.* [55] reported that the use of iterative reconstruction reduced the radiation dose of chest CT by 46.4% without compromising diagnostic image quality. A photon-counting detector CT is an emerging technology with a promising role in CT dose reduction [56-58]. A recent study by Tsiflikas *et al.* [59] reported that chest CT-based photon-counting detector has achieved an effective dose of 0.19 mSv in 20 paediatric patients with an average age of 2.6 years. Recently introduced, artificial intelligence (AI) has been used in radiology for several purposes including improving diagnostic accuracy, optimising radiation doses and reducing cost and examination time [60, 61]. Implementing CT deep learning reconstruction algorithms has resulted in dose reduction by more than half (52%) for chest-abdomen-pelvis CT examinations in paediatric patients with an average age of 11 years [62].

Justification is a fundamental concept in medical imaging and radiation protection. The potential risk for cancer induction from radiation exposure during CT is of concern [50, 53, 63] in children given that they are more radiosensitive and have a longer life expectancy [39, 53, 63] over which any ill effect may manifest. In imaging children with SPA, the risk of a missed diagnosis of abuse exceeds the risk of radiation exposure: this is reinforced by cases that use CT to diagnose rib fractures when initial chest radiography is inconclusive or suspicious [6]. Follow-up imaging is not guaranteed (given that this relies on parents or caregivers to return the child to the imaging department) and children may be exposed to further injury if residing with their abuser. Improving rib fracture detection using a LDCT chest protocol would facilitate child protection management.

This study has several limitations. Firstly, although autopsy is a gold standard reference in post-mortem evaluation, this study used a radiological consensus as the reference standard to identify undisplaced rib fractures to assess sensitivity of different dose level scans. This is because: first, we tried to simulate real clinical practice in which the final radiological evaluation of fractures in live children with SPA relies on a consensus report by radiologists. The second reason was that it has been reported that autopsy does not serve as a 'perfect reference standard' in detecting subtle acute rib fractures, with CT being superior in detecting such fractures [18, 64, 65]. Furthermore, some of the rabbits were disposed of

before the autopsy while the histological assessment of the ribs of the other rabbits was not accurate/valid due to deterioration of the ribs (i.e., ribs were in the formalin for a long time). Secondly this study focuses on acute rib fractures and does not assess healing fractures, which are often found in abused children [66]. However, detecting acute, especially undisplaced rib fractures is challenging and often missed in initial chest radiographs as part of skeletal surveys [7, 8]. Arguably, healing rib fractures are more likely to be identified in chest LDCT than acute fractures due to associated callus formation. Thirdly, the number of undisplaced rib fractures (n=16) included in this study is small. Fourthly, the body size of the patient is an important factor when assessing image quality and radiation dose [53]. We only performed CT examinations on rabbits with an average weight comparable to infants up to 3 months old (2 kg to 5.6 kg); thus, our results may only be transferable to infants with such a comparable average weight (it is known that the highest incidence of abusive fractures is those infants under 4 months of age). As such, these results may not extrapolated to the older age range of infants known to be at risk of physical abuse (up to 24 months, with half of all fractures under the age of 12 months being attributable to abuse) [67]. Lastly, this was an animal study using rabbits and so the findings may not be directly transferrable to human infants. There is a dearth of research in the development of LDCT chest protocols to assess rib fractures in live children with SPA which may be, in part, due to the ethical aspects of prospectively irradiating children for research purposes. As such, establishing the lowest possible radiation dose without compromising the diagnostic image quality in children is challenging. We have used a deceased animal model and experimentation to show that reducing radiation dose in paediatric rib fracture diagnosis is possible. Future research to develop a LDCT protocol for detecting rib fractures in children with SPA could be performed on post-mortem children with rib fractures for which ethical approval is less challenging. An alternative model could be an infant anthropomorphic phantom with simulated acute and healing rib fractures created in collaboration with commercial anthropomorphic CT phantom providers.

Further studies should be performed which evaluate the feasibility and applicability of proposed CT protocols in rib fracture diagnosis in live children suspected of having been physically abused. Implementing photon-counting CT technology [57, 59] and deep learning reconstruction algorithms [62] in assessing rib fractures in live children with SPA may help to further reduce the radiation dose while maintaining diagnostic image quality. Proving the effectiveness, feasibility and validation of LDCT in diagnosing rib fractures would enable future research on the diagnostic accuracy of LDCT versus the current initial and follow-up chest radiographs performed as part of skeletal surveys investigating SPA.

6.6 Conclusion

This study evaluated the subjective image quality and sensitivity of varying CT tube currents and voltages. We have demonstrated that a LDCT chest protocol is technically feasible with acceptable diagnostic image quality and high sensitivity for assessing undisplaced acute rib fractures and approaches a radiation dose close to the average dose of standard chest radiographs performed in skeletal surveys for SPA.

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Chapter Seven

Professional practice and awareness of child abuse among radiologists and radiologic technologists: Results from Saudi Arabia

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7. Professional practice and awareness of child abuse among radiologists and radiologic technologists: Results from Saudi Arabia

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7.1 Abstract

Objective

To assess the current practice, knowledge and awareness of child abuse among radiologic technologists and radiologists in Saudi Arabia.

Methods

An internet-based questionnaire was distributed to radiologic technologists and radiologists working in Saudi Arabia via national radiology societies and social media channels over a six-week period (27 October to 8 December 2021). Survey questions covered knowledge regarding child abuse, professional practice in radiology departments in Saudi Arabia in cases of suspected physical abuse (SPA), and knowledge of the national legislation and reporting and acting procedures in child abuse.

Results

A total of 315 respondents (224 radiologic technologists and 91 radiologists) participated in this study. The median score for knowledge of abuse was higher amongst radiologists (4.80) than radiologic technologists (4.00), $P < 0.001$. In total, 210 (93.8%) radiologic technologists and 61 (67.0%) radiologists reported that there was no protocol (i.e., skeletal survey) in their hospital for imaging children with SPA. Most radiologic technologists (165/224, 73.7%) had no training in paediatric radiology and most radiologists (73/91, 80.2%) had received no training in evaluating imaging performed for SPA. Over half of respondents, 131 (58.5%) radiologic technologists and 44 (48.4%) radiologists, were not familiar with the reporting and acting procedures in their hospitals in cases of child abuse.

Conclusions

Although radiologic technologists and radiologists in Saudi Arabia have good knowledge and awareness of child abuse in general, they lack specific knowledge of the reporting and acting procedures in their hospitals in cases of suspected child abuse. National imaging guidelines and training courses are needed to develop appropriate skills in the recognition, imaging and reporting of SPA in infants and young children in Saudi Arabia.

7.2 Introduction

Child abuse, a significant worldwide problem with serious long-term consequences, has been defined by the World Health Organization as “every kind of physical, sexual, emotional abuse, neglect or negligent treatment, commercial or other exploitation resulting in actual or potential harm to the child’s health, survival, development or dignity in the context of a relationship of responsibility, trust or power” [1]. Globally, it has been estimated that 1 billion children experienced abuse over the course of one year [2], which may be underestimated given that abuse may go unreported or incorrectly reported as other causes of death, such as falls and drowning.

Child abuse recognition is challenging and complex, more so in developing countries due to the perceived lack of awareness of child abuse and lack of institutional legislation on child protection, in addition to societal influences and cultural contexts. In Saudi Arabia, child abuse was not well reported until 1990, due to lack of awareness amongst healthcare professionals alongside the belief that reporting may affect reporter job security [3, 4]. In recent decades, Saudi Arabia has worked to improve child welfare by ratifying the United Nations Convention on the Rights of the Child [5] and, in 2004, by establishing the National Family Safety Program (NFSP) which is concerned with the prevention of child abuse, neglect and domestic violence [3, 5] and which elaborates on the role of the healthcare system and the regulations around cases of child abuse. At the time of writing, the National Health Council, the highest health services authority in Saudi Arabia, had accredited 62 major hospitals as hospital-based child protection centres – hospitals with child protection units which deal with issues relating to safeguarding children and young people [6]. Moreover, healthcare professionals are now legally obliged to report child abuse [3, 7].

Although paediatricians and general practitioners play a vital role in identifying suspected child abuse, the diagnosis is not straightforward and requires a multidisciplinary team approach. Diagnostic medical imaging is instrumental in the diagnosis of suspected physical abuse (SPA) in infants and young children. As the first healthcare professionals to view any radiographic imaging obtained, radiologic technologists (healthcare professionals who are trained and qualified to perform diagnostic imaging examinations using different imaging modalities, also known as radiographers or technicians) play a crucial role in raising the suspicion of SPA to colleagues and radiologists through the identification of the suspicious radiographic findings, such as, rib and metaphyseal fractures, multiple fractures at different stages of healing [8], and potentially inappropriate interactions between caregivers and the child [9]. Clinical

radiologists (specialist medical doctors who are trained and qualified to interpret and report upon medical imaging to diagnose injuries and diseases) play a pivotal role in SPA through the identification and reporting of acute and/or healing fractures when physical abuse may not be suspected or when injuries are not clinically apparent (occult) or disclosed (e.g., intracranial haemorrhage) [10, 11].

Knowledge, awareness, and adequate training of all healthcare professionals regarding child abuse is key to the identification and reporting of suspected cases. Whilst there are a few studies in the published literature that have assessed the knowledge and awareness of interns, medical students, paediatricians and general practitioners in suspected child abuse in Saudi Arabia [4, 7, 12-14], they report that paediatricians [7, 12] and general practitioners [13] have a “satisfactory” knowledge of child abuse. To the best of the authors’ knowledge, a study assessing current practice, knowledge and awareness of radiologists and radiologic technologists in relation to child abuse in Saudi Arabia has not been performed.

7.3 Methods

We obtained ethical approval from the University of Sheffield Research Ethics Committee (Ethics approval number: 043217, Appendix 4) before data collection commenced.

7.3.1 Survey development

We created an online survey using the Google Forms web-based platform (Mountain View, CA). There were two groups of study participants: radiologic technologists and radiologists. The survey included 22 open and 26 closed questions for radiologic technologists (Appendix 5) and radiologists (Appendix 6), respectively. All responses were anonymised. No personal identifiable information was collected.

Prior to conducting the survey, we undertook a pilot study with seven radiologic technologists and five radiologists with minor changes made based on this initial participant feedback (regarding question wording). The survey was comprised of four sections. The first section related to demographic and job information. The second assessed child abuse knowledge, including the recognition of abusive acts toward children, risk factors for child abuse [15, 16] and comprehension of the different terms used when describing physical child abuse. The third section of the survey investigated professional practice in dealing with SPA in radiology departments in Saudi Arabia. The final section assessed knowledge regarding national legislation and reporting procedures and actions in child abuse.

7.3.2 Survey distribution

We distributed the survey to the membership of national radiology societies in Saudi Arabia, including the Saudi Society of Medical Radiological Technology (SSMRT) and the Radiological Society of Saudi Arabia (RSSA), via email and social media channels. Additionally, the Saudi Commission for Health Specialties (SCFHS), a national official scientific commission that regulates healthcare-related practices in Saudi Arabia, sent a participation email invitation to all radiologic technologists and radiologists registered on the SCFHS database. Furthermore, the survey was circulated via the professional network of the first author (snowball sampling) and social media channels (Twitter and established WhatsApp and Telegram groups of radiologic technologists and radiologists working in Saudi Arabia). Responses were collected over a six-week period (27 October to 8 December 2021) with two reminder emails/messages sent at fortnightly intervals to maximise the response rate.

7.3.3 Statistical analysis

Statistical analyses were conducted using IBM SPSS Statistics (v. 27, Chicago, IL) and R software (v. 4.1.3) to visualise the data for the 5-point questions. Categorical variables were expressed as counts and percentages. For between comparisons (i.e., radiologic technologists versus radiologists), we used the Mann–Whitney U test for ordinal variables and the chi-square test for percentages. $P < 0.05$ was significant.

7.4 Results

7.4.1 Respondent demographics

Of the 315 respondents, 224 (71.1%) were radiologic technologists and 91 (28.9%) were radiologists: those from Saudi Arabia (radiologic technologists, 193/224, 86.2%; radiologists 56/91, 61.5%) were represented more than other nationalities. Most participants worked at the Ministry of Health (radiologic technologists, 109/224, 48.7%; radiologists, 51/91, 56.0%; Online Supplementary Material 3). More than half of the radiologic technologists (142/224, 63.5%) and radiologists (56/91, 61.5%) worked at general hospitals. Most respondents were from the Western province (radiologic technologists, 37.9%, 85/224; radiologists, 48.4%, 44/91) followed by the central province of Saudi Arabia (radiologic technologists, 28.1%, 63/224; radiologists, 18.7%, 17/91).

Most radiologic technologists had completed an undergraduate bachelor's degree as their highest level of educational attainment (142/224, 63.4%) with 34.4% (77/224) reporting less than 5 years of clinical experience, and 38.4% (86/224) with 5 to 10 years of experience. Most radiologic technologists worked in a general department (133/224, 59.4%) followed by: computed tomography (CT; 34/224, 15.2%); ultrasound (21/224, 9.45%); magnetic resonance imaging (MRI; 19/224, 8.5%); and nuclear medicine (7/224, 3.1%).

Consultant radiologists, medical doctors who have completed all of a postgraduate specialist radiology training programme (which may also include subsequent further specialist clinical training in the form of a postgraduate fellowship) allowing them to be registered as a specialist medical practitioner in their home country [and at least 3–5 years post completion of a specialist training programme] represented more than half of the radiologist respondents (52/91, 57.1%), followed by specialist radiologists (medical doctors who have completed a specialist radiology training programme but have not yet completed the required 3–5 years of experience post specialist training and thus are not yet consultants) (35/91, 38.5%) and residents (4/91, 4.4%). Reported years of radiologists' experience were less than 5 years (5/91, 5.5%), 5 to 10 years (33/91, 36.3%), 11 to 15 years (32/91, 35.2%) and more than 15 years (21/91, 23.1%). Consultant paediatric radiologists (consultant radiologists with a special interest/fellowship in paediatric radiology) comprised 17.6% (16/91) of the sample, of whom 62.5% (10/16) had 5 to 10 years of experience. Respondent demographic characteristics and job information are presented in Table 7.1. Unlike the United Kingdom (UK) and the United States (US), radiologists in Saudi Arabia need to work for 3–5 years after completion of their specialist training/fellowship to become registered as a consultant on the national register. Radiologists can complete the specialist training either overseas or locally (i.e., Saudi Board of Radiology for 4 years).

Table 7.1. Demographic and professional characteristics of participants (n=315)

	Radiologic technologists (n=224)		Radiologists (n=91)	
Nationality	n (%)		n (%)	
Saudi	193 (86.2)		56 (61.5)	
Non-Saudi	31 (13.8)		35 (38.5)	
Type of hospital	n (%)		n (%)	
Medical city / Speciality hospital	60 (26.8)		34 (37.4)	
General hospital	142 (63.4)		56 (61.5)	
Primary health care centres	22 (9.8)		1 (1.1)	
Region of work	n (%)		n (%)	
Central province	63 (28.1)		17 (18.7)	
Western province	85 (37.9)		44 (48.4)	
Eastern province	21 (9.4)		10 (11.0)	
Southern province	40 (17.9)		14 (15.4)	
Northern province	15 (6.7)		6 (6.6)	
	Qualification	n (%)	Job Title	n (%)
	Diploma	55 (24.6)	Resident radiologist	4 (4.4)
	Bachelor	142 (63.4)	Specialist radiologist	35 (38.5)
	Master	18 (8.0)	Consultant radiologist	52 (57.1)
	PhD or other training certificates (i.e., Board)	9 (4.0)		
	Imaging unit mostly covered	n (%)	Specialisation	n (%)
	General radiography	133 (59.4)	Paediatric radiologist	16 (17.6)
	MRI	19 (8.5)	Non-paediatric radiologist	75 (82.4)
	Fluoroscopy	0		
	Dental radiography	2 (0.9)		
	CT	34 (15.2)		
	Mammography	2 (0.9)		
	Nuclear Medicine	7 (3.1)		
	Ultrasound	21 (9.4)		
	DEXA	1 (0.4)		
	Interventional radiology	5 (2.2)		
Years of experience	n (%)		n (%)	
Less than 5	77 (34.4)		5 (5.5)	
5–10	86 (38.4)		33 (36.3)	
11–15	40 (17.9)		32 (35.2)	
More than 15	21 (9.4)		21 (23.1)	
			Years of experience as paediatric radiologist	n=16 (%)
			Less than 5	2 (12.5)
			5–10	10 (62.5)
			11–15	2 (12.5)
			More than 15	2 (12.5)

CT computed tomography, DEXA dual-energy X-ray absorptiometry, MRI magnetic resonance imaging

7.4.2 Knowledge regarding child abuse

We assessed several aspects of knowledge regarding child abuse: recognition of abusive acts towards children; recognition of risk factors for child abuse, and understanding of the various terms relating to

physical child abuse. The survey asked participants their thoughts about five abusive acts toward children with their responses presented in Figure 7.1. Although both groups had good knowledge regarding the acts of child abuse, radiologists tended to demonstrate a higher score in all five items compared to radiologic technologists, with a median score of 4.80 and 4.00, respectively ($P<0.001$).

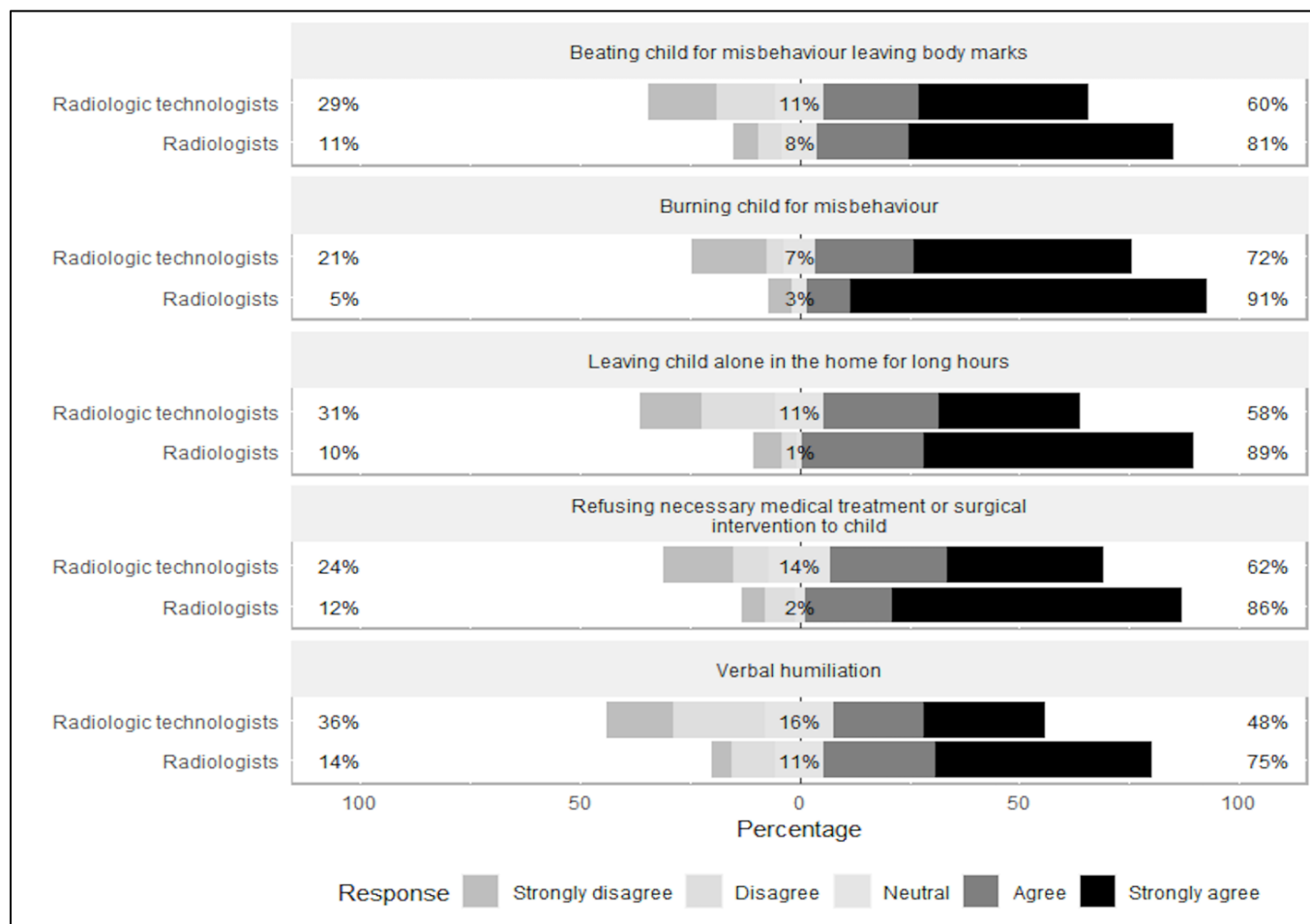


Figure 7.1. Level of agreement regarding five proposed forms of child abuse. The percentage of neutral responses is indicated on each bar with the total percentage of disagreement (strongly disagree or disagree) noted at left and the total percentage of agreement (strongly agree or agree) noted at right.

When asked about risk factors for child abuse, the responses varied among radiologic technologists and radiologists (Figure. 7.2). More than half of radiologists believed that low socioeconomic status is a risk factor for child abuse (48/91, 53.0%) compared to 34.0% (77/224) of radiologic technologists. Similarly, 65.0% (59/91) of radiologists compared to 46.0% (102/224) of radiologic technologists believed that having a parent or caregiver younger than 16 years is a risk factor for child abuse. Radiologists had a

greater knowledge of these risk factors compared to radiologic technologists with a median score of 4.00 and 3.50, respectively ($P<0.001$).

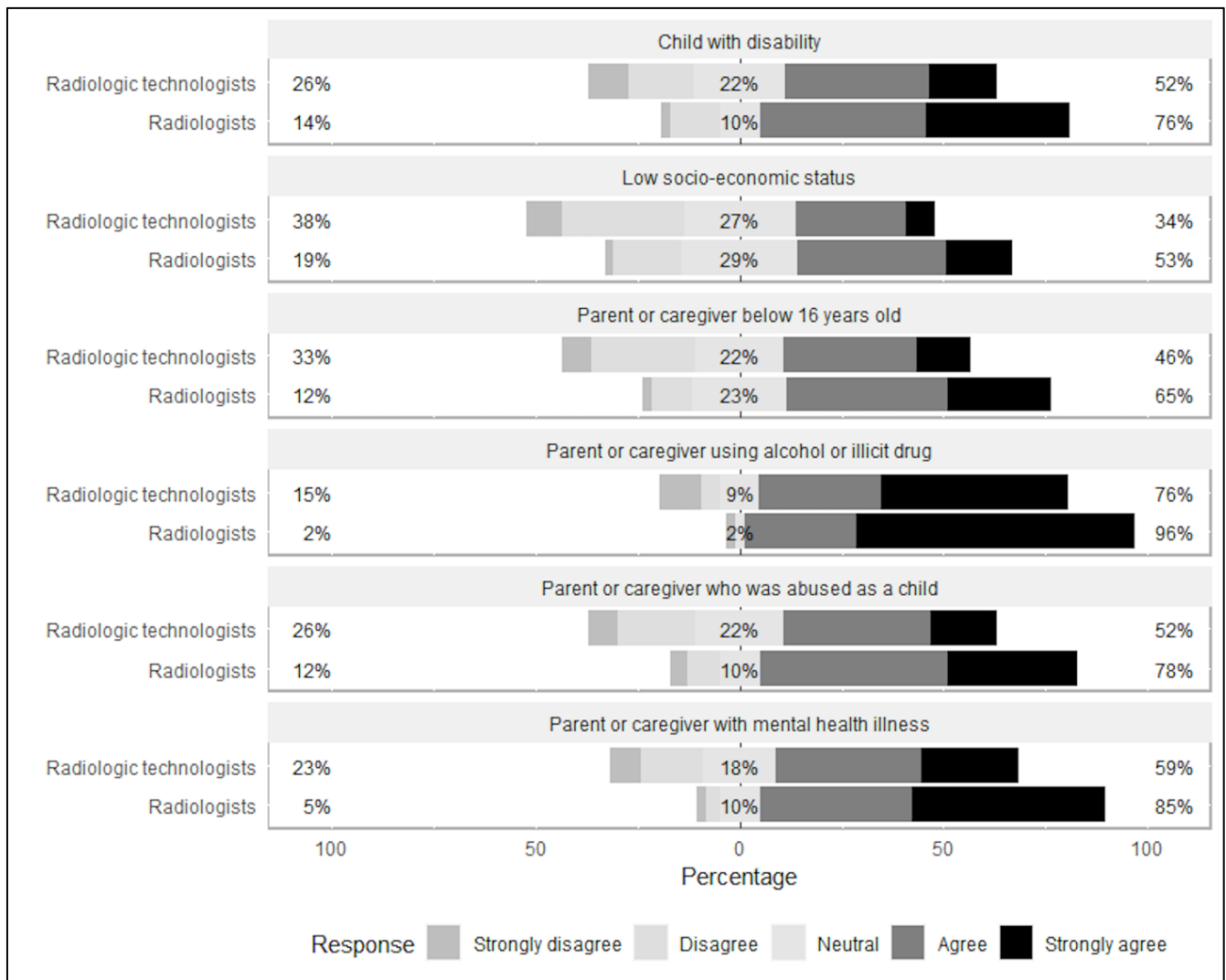


Figure 7.2. Level of agreement regarding six proposed risk factors for child abuse. The percentage of neutral responses is indicated on each bar with the total percentage of disagreement (strongly disagree or disagree) noted at left and the total percentage of agreement (strongly agree or agree) noted at right.

With regard to the understanding of the term *child physical abuse* and its synonyms (inflicted injury and non-accidental injury), radiologic technologists and radiologists demonstrated good and excellent understanding of the term, respectively (154/224, 68.8% for technologists and 85/91, 93.4% for radiologists), with radiologists having a higher median score compared to radiologic technologists (5.00 and 4.00, respectively; $P<0.001$; Appendix 7).

7.4.3 The radiologic practice of imaging children with suspected physical abuse

Of the 335 participants, 92.0% (206/224) of radiologic technologists and 83.5% (76/91) of radiologists reported that their practice covered paediatric patients (Appendix 7). Of those, 66.9% (138/206) of radiologic technologists and 56.5% (43/76) of radiologists estimated that they image/report on 1–10 cases of SPA annually (Appendix 7). With regard to protocols, 93.8% (210/224) of radiologic technologists and 67.0% (61/91) of radiologists reported that no skeletal survey (SkS) protocol existed in their hospital for imaging children for SPA (Table 7.2). We found great variation in the protocols for imaging children for SPA in Saudi Arabia (Appendix 7). Most radiologic technologists (193/224, 86.2%) and more than half of radiologists (55/91, 60.4%) had no awareness of the published international guidelines for imaging children with SPA (Table 7.2).

Availability of paediatric radiologists was lacking in many hospitals: more than half of radiologists (51/91, 56.0%) reported no paediatric radiologist at their workplace. Most radiologists said that no radiologist was assigned to report radiologic imaging performed for SPA (79/91, 86.8%) that there was no double reporting (by at least two radiologists) of such imaging studies at their hospitals (80/91, 87.9%) (Table 7.2).

Table 7.2. Participants' responses to professional practice regarding imaging children with suspected physical abuse.

Questions	Radiologic technologists (n=224)		Radiologists (n=91)	
	Yes	No	Yes	No
	n (%)	n (%)	n (%)	n (%)
Is there an imaging protocol (i.e., skeletal survey) at your hospital for children below 2 years old with suspected physical abuse?	14 (6.3)	210 (93.8)	30 (33.0)	61 (67.0)
Are you aware of the international guidelines for imaging children with suspected physical abuse?	31 (13.8)	193 (86.2)	36 (39.6)	55 (60.4)
Have you received training (i.e., courses, workshops, workplace mentoring, etc) in paediatric radiology?	59 (26.3)	165 (73.7)	N/A	
Have you received training (i.e., courses, workshops, etc) in evaluating injury in children related to suspected physical abuse?	N/A		18 (19.8)	73 (80.2)
Is there a paediatric radiologist at your hospital?			40 (44.0)	51 (56.0)
Is there a named radiologist at your hospital to report cases with suspected abuse?			12 (13.2)	79 (86.8)
Are the radiological images of suspected child abuse reported by at least 2 radiologists at your hospital?			11 (12.1)	80 (87.9)

N/A not applicable

On the question of training, most radiologic technologists (165/224, 73.7%) had no training in paediatric radiology (Table 7.2). Of those radiologic technologists who had received training in paediatric radiology, only 32.2% (19/59) stated that their training discussed injuries relating to SPA (Appendix 7). Furthermore, it was more common for radiologic technologists to attend the national training format in Saudi Arabia (i.e., courses, workshops or conferences) related to paediatric radiology (37/59, 62.7%) as opposed to the international training format (4/59, 6.8%; Appendix 7). Finally, 33.5% (75/224) of radiologic technologists responded that they thought they were not competent to be involved with cases of SPA, with most indicating that they required training for such cases (179/224, 80.0%) (Figure 7.3).

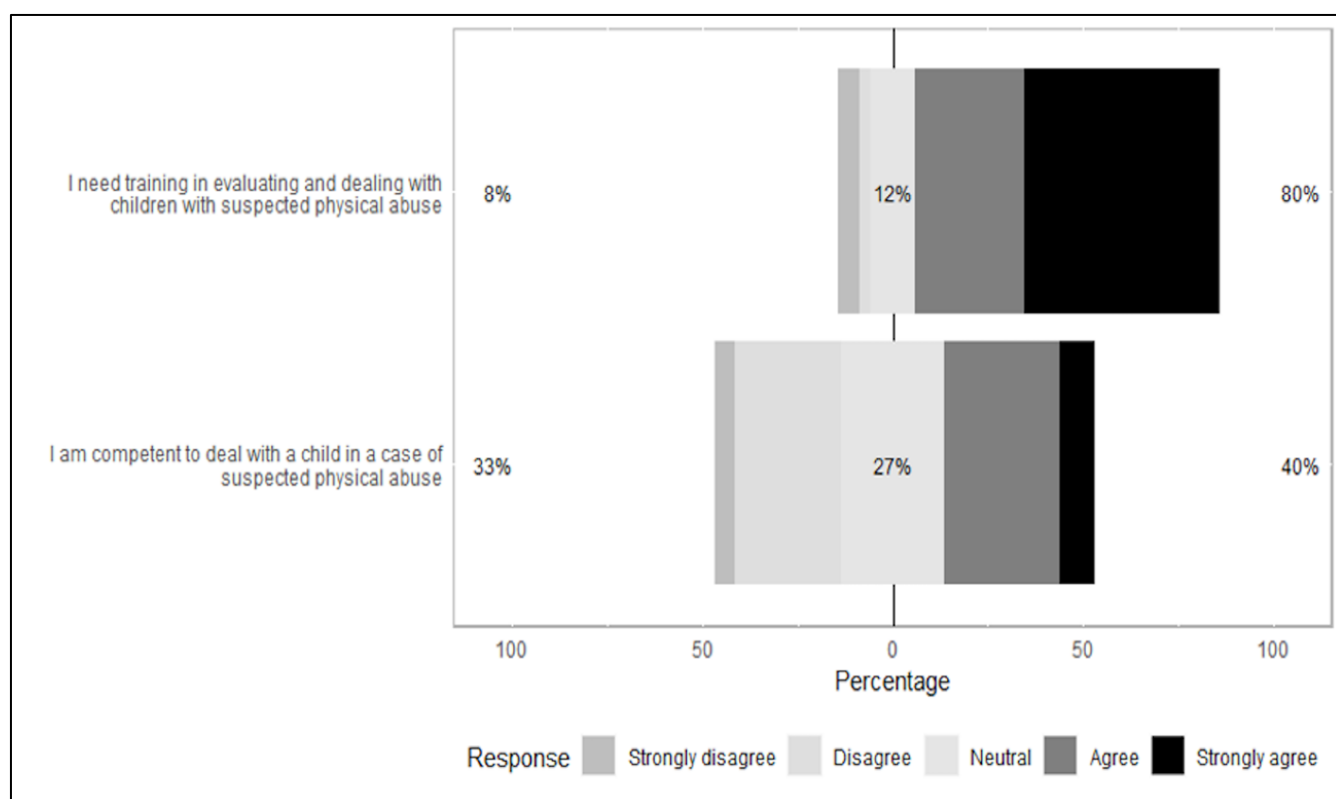


Figure 7.3. Radiologic technologists' opinions regarding their training needs and confidence in evaluating and dealing with cases of suspected physical abuse. The percentage of neutral responses is indicated on each bar with the total percentage of disagreement (strongly disagree or disagree) noted at left and the total percentage of agreement (strongly agree or agree) noted at right.

Among radiologists, most had received no training in evaluating radiological imaging in children performed for SPA (73/91, 80.2%). Of those radiologists who had received such training, it was slightly more common that they had undertaken the international training format (i.e., courses, workshops or conferences; 8/18, 44.4%) as opposed to the national training format (6/18, 33.3%; Appendix 7). Most

radiologists were aware of the radiological patterns of fracture in children with SPA (71/91, 78.0%) and more than half of radiologists stated that they were confident to report radiological imaging performed for SPA (49/91, 54.0%). However, most radiologists indicated that they required (further) training (67/91, 74.0%) (Figure 7.4).

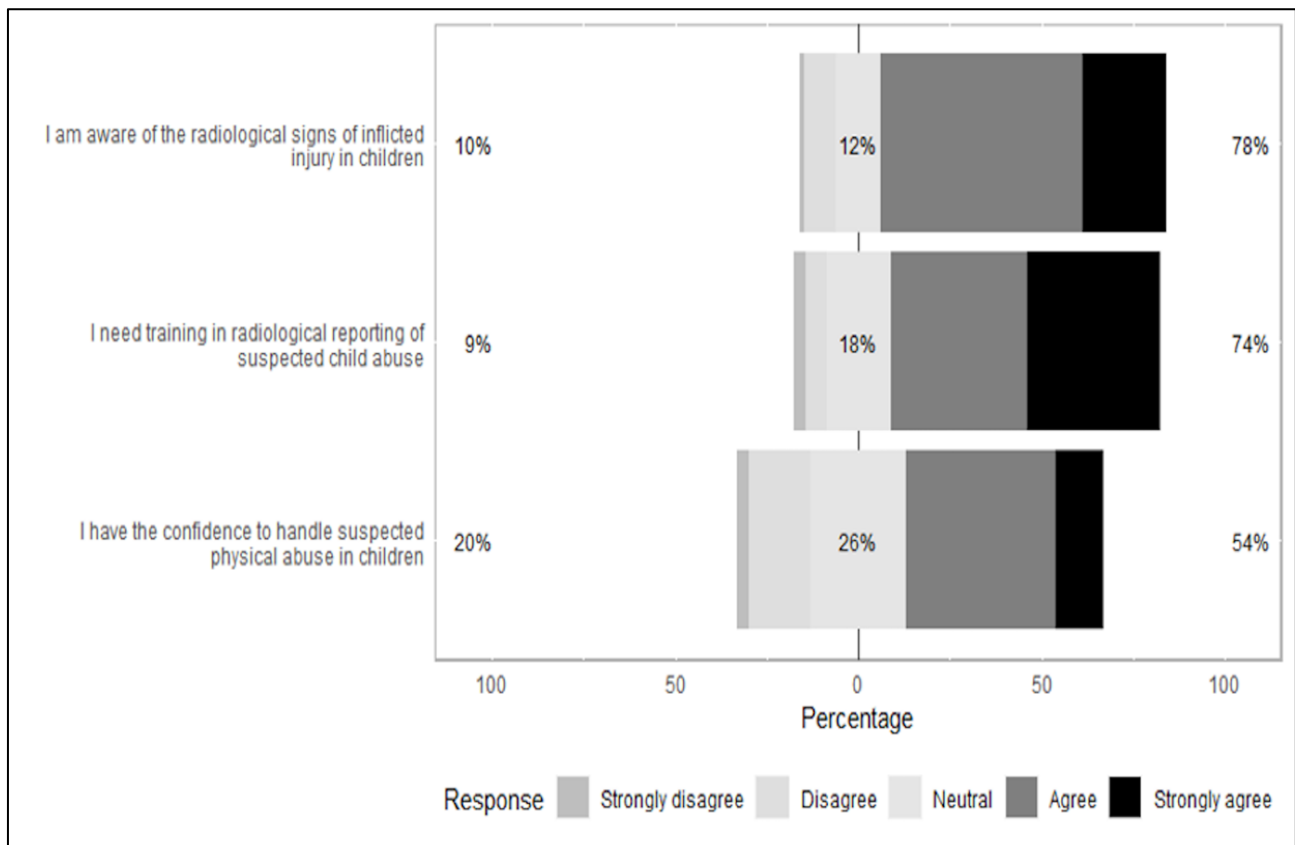


Figure 7.4. Radiologists' opinions regarding recognising the radiological signs, their training needs and confidence in the radiological reporting cases of suspected physical abuse. The percentage of neutral responses is indicated on each bar with the total percentage of disagreement (strongly disagree or disagree) noted at left and the total percentage of agreement (strongly agree or agree) noted at right.

7.4.4 Knowledge of national legislation and reporting and acting procedures in child abuse

The survey asked participants about the NFSP and the local reporting procedure at their hospitals in cases of SPA in children. More than half of radiologic technologists and radiologists were unfamiliar with the NFSP (134/224, 60.0%, and 55/91, 60.0%, respectively), and 58.5% (131/224) of radiologic technologists and 48.4% (44/91) of radiologists were also unfamiliar with the reporting and action procedures at their hospitals in cases of SPA (Figure 7.5). Radiologists were more familiar with the legal

mandate to report child abuse in Saudi Arabia (69/91, 76.0%) than radiologic technologists (105/224, 47.0%). Both groups had little knowledge regarding the reporting procedures and actions in cases of child abuse (all forms); however, radiologists demonstrated a slightly higher score than radiologic technologists regarding reporting procedures in cases of SPA than radiologic technologists (median score 3.0 compared to 2.7, respectively; $P < 0.002$).

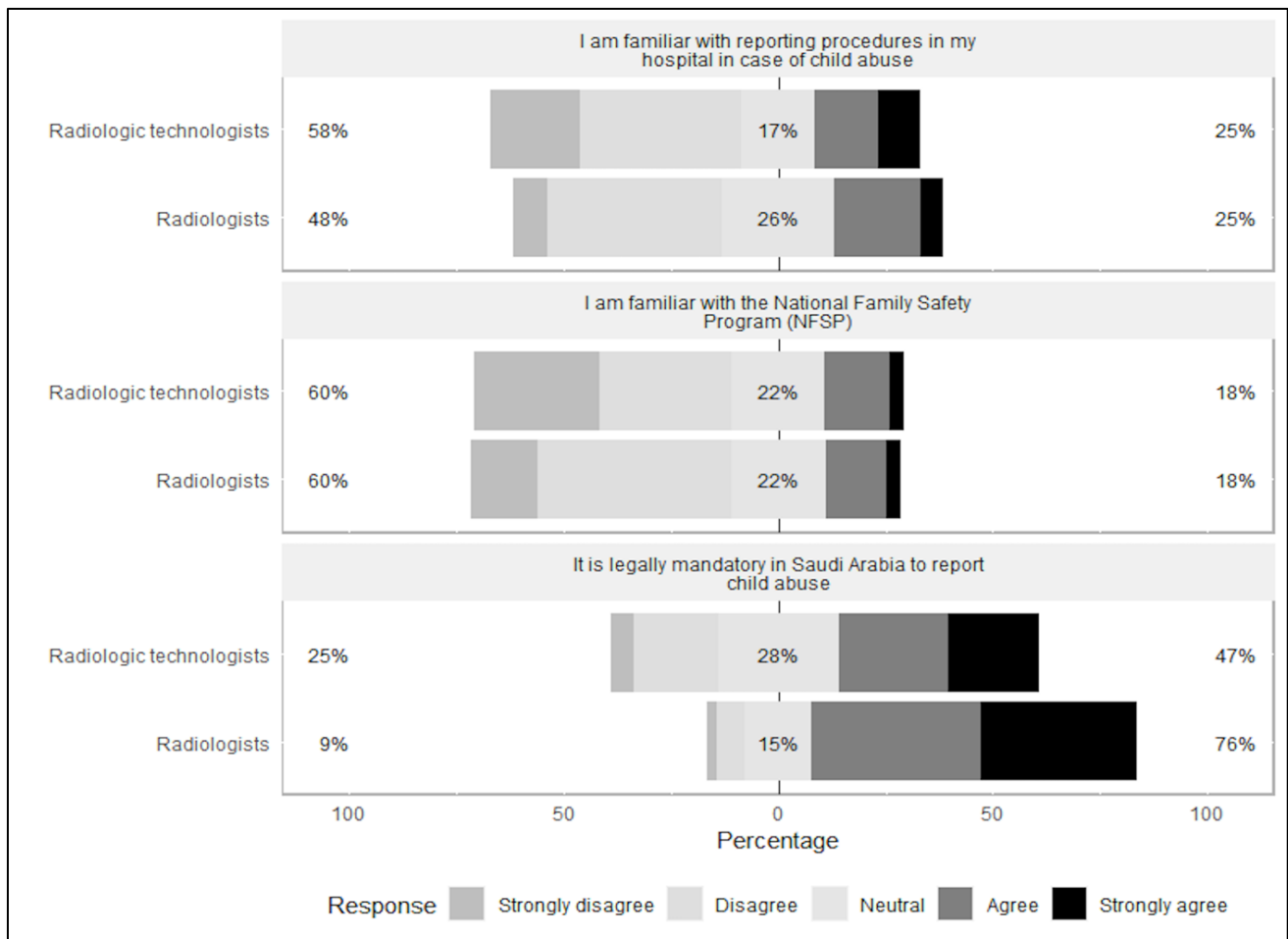


Figure 7.5. Level of agreement among responders regarding their knowledge of the national law and programs for child abuse and reporting procedures and actions in their hospitals in suspected child abuse cases. The percentage of neutral responses is indicated on each bar with the total percentage of disagreement (strongly disagree or disagree) noted at left and the total percentage of agreement (strongly agree or agree) noted at right.

7.5 Discussion

This cross-sectional survey assessed the current practice, knowledge and awareness of child abuse amongst radiologists and radiologic technologists in Saudi Arabia. Overall, most survey respondents had a good knowledge of the various forms and risk factors for child abuse. However, 48.4% of radiologists and more than half of radiologic technologists (58.5%) lacked knowledge regarding the reporting procedures in cases of child abuse. Moreover, most radiologic technologists (93.8%) and many radiologists (67.0%) reported no imaging protocol (i.e., SkS) at their hospital for imaging children with SPA.

Child abuse is a serious global problem with severe consequences for victims, their families and society. In Saudi Arabia, the number of child abuse cases is reported to be increasing annually [6, 17]. The NFSP's national record for child abuse and neglect reported that 428 and 1,253 children were physically abused in 2020 and 2021, respectively [6, 18]. A comprehensive understanding of the various forms and the factors that increase the risk of child abuse is vital for healthcare professionals to facilitate increased detection and reporting of suspected cases.

The definition of abuse (in general) varies between societies. For example, in the Arab culture, corporal punishment and verbal discipline are likely to be considered societal norms [14]. Several risk factors have been established for child abuse and maltreatment, including but not limited to low socioeconomic status/economic disadvantage, caregivers with mental health or drug issues, young parents and children with disabilities [15, 19, 20]. Although it is well reported that socioeconomic status is an important risk factor for child abuse in the literature [15], more than one-third (36.0%) of radiologic technologists in this study did not recognise this as a risk factor.

Although child abuse can take various forms (emotional abuse, sexual abuse and neglect), physical abuse may be more well-known due to the media attention surrounding high-profile cases. However, the diagnosis of physical child abuse is challenging; children require a thorough physical examination, radiological imaging, laboratory tests and a social evaluation [20, 21]. Given that children who are physically abused are more likely to have negative lifelong consequences such as behavioural problems and neurological disabilities [22], an early and accurate diagnosis of physical child abuse is paramount to improving child health outcomes and preventing potential future harm.

Medical imaging is a crucial tool in the diagnosis and management of children with SPA. Published guidelines for imaging SPA in children include those from the American College of Radiology and the Society of Pediatric Radiology (ACR-SPR) [23], the Royal College of Radiologists (RCR) and the Society of College of Radiographers (SCoR). The last has been endorsed by the Royal College of Paediatrics and Child Health (RCPCH) in the UK [24] and recognised by the European Society of Paediatric Radiology (ESPR) as the gold standard guidance for imaging children with SPA across Europe [25].

The radiographic SkS, which comprises of a series of radiographic images of the entire skeleton [23, 24], is a well-established radiological examination in the investigation of SPA in children. In our study, 93.8% of radiologic technologists and 67.0% of radiologists reported having no SPA SkS protocol at their place of work. Additionally, 86.2% of radiologic technologists and 60.4% of radiologists were unfamiliar with any published guidelines for SPA imaging. It is important that radiology departments have a clear imaging protocol in place for imaging children with SPA; the previously mentioned guidelines [23, 24] serve as exemplar practice and it is recommended that radiology departments in Saudi Arabia endorse and utilise one of these imaging guidelines as evidenced-based best practice.

Radiologists have a pivotal role in the assessment of children investigated for SPA by differentiating traumatic injuries from normal variants or other pathologies, recognising features that may indicate underlying metabolic and inherited conditions, and suggesting the most likely time frame and mechanisms for injuries; further, radiologists sometimes play a key role in subsequent legal proceedings [10, 11, 26]. The role of radiologists in SPA is rendered less effective if suspicions regarding physical abuse are not promptly and appropriately communicated to the relevant clinical team. In Saudi Arabia, the child protection team includes a paediatric physician, psychologist, and professionals from social services and the legal department [3]. We recommend that a radiologist also be considered as a key member of the child protection team to facilitate communication of important radiological findings to aid clinical and child-protection decision-making.

In the context of evaluating children with SPA, radiology departments should have at least one dedicated paediatric radiologist (or radiologist trained in paediatric imaging) who is designated (and trained) to report SkS imaging; ideally two experienced reporters are required to facilitate independent double reporting [24]. Paediatric-trained radiologists could support and train colleagues in their department to increase the number of available radiologists to double-report such examinations. In the UK, 61.0% of radiology departments have a designated radiologist to report the SkS, and 62.0% of radiology

departments reported that the SkS is double-reported by radiologists [26]. In this study, 51.0%, 79.0% and 80.0% of radiologists reported no paediatric radiologist, no designated radiologist to report the SkS, and no double reporting of SkS, respectively, at their centres.

Unlike general radiologists, paediatric radiologists have more experience and a greater familiarity with normal paediatric bone development, normal variants in children and the radiographic appearance of fracture patterns in children with SPA. However, paediatric radiology is a relatively small radiological subspeciality, there is an international shortage of paediatric radiologists [27-29]. As a consequence, not all hospitals will have direct access to a trained paediatric radiologist. We advise that such centres forge links/networks with paediatric radiologists to facilitate access to timely reports on such imaging, which in turn could facilitate quicker decision-making. Such a system would also promote continuing professional development in paediatric radiology and SPA imaging. We also recommend involving experienced musculoskeletal radiologists and neuroradiologists to report brain and spine imaging performed for SPA.

In Saudi Arabia, it is a necessity to improve not only the practice of paediatric radiography and radiology, particularly in the evaluation of SPA in children, but also the education of relevant professionals on this topic. In Saudi Arabia, the clinical radiology speciality training curriculum includes only a 4-month rotation in paediatric radiology out of the 4-year training program with a single lecture on fracture patterns in abused children [30]. Trainees enrolled in a UK clinical radiology speciality program usually complete at least a 3-month rotation in paediatric radiology during their 5-year training program [31]. The RCR speciality training curriculum states that trainees are expected to have appropriate skills in interpreting images of children with SPA: *"... examples of imaging procedures in which all radiology trainees will develop skills to Level 4 (fully independent practice)... include accidental and non-accidental injury in children"*. Although didactic lectures are important in training programs, the practice of interpreting cases at the workstation with an experienced paediatric radiologist is essential to training. Additionally, discussion with the clinical teams regarding the proffered history and mechanism of injury is of critical importance to contextualising any radiological findings.

In clinical practice, double reporting is recommended for radiological studies with elevated risk [32, 33] with the second read improving confidence for less experienced radiologists and offering an improvement in diagnostic accuracy and consistency [32, 34]. Arguably, the SkS performed in cases of SPA could be considered one of the highest-risk examinations performed given the impact of any

positive (or negative) findings on the accurate and timely diagnosis of SPA. Moreover, the radiologic report may be critical to legal proceedings, further signifying not only its clinical importance but its utility in the forensic and medicolegal arena.

As healthcare professionals in Saudi Arabia, radiologic technologists are mandated to alert the relevant authorities to cases of SPA whilst maintaining patient confidentiality and professionalism. In cases of SPA, the role of the radiologic technologists is to produce high-quality diagnostic images using an evidence-based (and reproducible) SkS protocol with careful documentation of the examination, including the time; who was present; and the type, number and dose of projections obtained [24, 35]. The aforementioned guidelines [23, 24] for imaging children with SPA recommend that radiologic technologists trained in paediatric imaging perform the SkS. In our study, fewer than half of radiologic technologists (40.0%) reported that they were competent in dealing with imaging children in cases of SPA which may reflect a lack of education and training.

There is a national reporting centre in Saudi Arabia [6] and healthcare professionals are mandated by law to report suspected abuse to child protective services [3]. In this study, 76.0% of radiologists and 47.0% of radiologic technologists were aware of the existing law in Saudi Arabia relating to the mandated reporting of all types of child abuse. However, few participants (25.0% in each group) were familiar with their workplace's reporting procedures for suspected child abuse. This result is consistent with the results of other surveys conducted among health professionals in Saudi Arabia concerning suspected child abuse [12, 13]. The reason for the lack of knowledge regarding reporting procedures, which we found in up to 60.0% of both radiologists and radiologic technologists in our study, could result from a lack of training and awareness of the NFSP. We hope the survey increased knowledge of the NFSP among radiologic technologists and radiologist who participated and that any lack of knowledge could be further remedied with ongoing promotion of the program on a national scale.

Training healthcare professionals in recognising, evaluating and reporting child abuse is central for improving and promoting the health and welfare of children. In this study, most participants had not received training to deal with or evaluate cases of SPA, with many respondents reporting the need for (further) training in such cases. About 73.3% of radiologic technologists in this study had not received training in paediatric radiology and 64.4% of radiologic technologists had not received training related to imaging children with SPA. The results of our study correlate with a study conducted in Nigeria [9], which demonstrated that 49.0% and 65.3% of radiologic technologists had not received training in

paediatric radiology and imaging children with SPA, respectively. Improving the education system and establishing training courses in paediatric radiology, with specific reference to SPA, is necessary to enable radiologic technologists and radiologists to engage in this important facet of their practice whilst working alongside other healthcare professionals to protect vulnerable children. Furthermore, a dedicated training program for healthcare professionals in Saudi Arabia is needed to help them recognise cases of SPA and to outline the steps of reporting to the appropriate authorities within the workplace.

This study has several limitations. Firstly, although we distributed via various channels, and included reminders, the findings must be interpreted with caution due to the small number of responders (the overall number of members in the national radiology/radiography societies was not known at the time of the study). The small number of participants could be due to a lack of interest in research in general, or more specifically in paediatric radiology where it is well recognised that there is a significant clinical workforce shortage [27, 29, 36]. In addition, email-based contact may have been labelled “junk” by mail servers, increasing the possibility that intended emails were not received or read by recipients. The number of radiologic technologists and radiologists in Saudi Arabia is not small but unfortunately, we are not able to ascertain the exact number due to the lack of statistical data provided by the Ministry of Health in Saudi Arabia. Secondly, there is sampling bias due to the online design of the survey whereby access might have been restricted to only those with email or social media accounts (i.e., Twitter, WhatsApp and Telegram) and those working in Saudi Arabia radiology departments. Furthermore, there may be a response bias, with responses potentially being biased by personal experience or opinions regarding child abuse, or by cultural background/understanding of child abuse from the non-Saudi radiologic technologists and radiologists, who represented 13.8% and 38.5% of respondents, respectively. Additionally, although most of participating radiologic technologists were primarily working with modalities commonly used for imaging children with SPA, such as general radiography (59.4%), CT (15.2%) and MRI (8.5%), a few radiologic technologists were more involved with other modalities that are far less likely (ultrasound, 9.4%; nuclear medicine, 3.1%; and dental radiography, 0.9%) or never (e.g., interventional radiology, 2.2%; and mammography, 0.9% of respondents), used imaging children with SPA. However, the results of this study still provide a valuable insight into the current practice, knowledge and awareness of child abuse amongst radiologists and radiologic technologists in Saudi Arabia. The final limitation is that the study is restricted to Saudi Arabia and may therefore be of limited relevance to readers from other countries. However, it may represent a similar

lack of awareness of child physical abuse in other lower income countries in Africa and the Middle East. Our results will serve as a baseline to which other countries can compare their findings, and with which Saudi Arabia can compare itself in future studies. The ESPR and SPR are significantly involved in outreach work through the World Federation of Pediatric Imaging, and perhaps through them future international studies can be conducted. Importantly, child abuse is a worldwide problem and therefore dissemination of a such study in internationally recognised journals should lead to the sharing of knowledge on a wider international scale, increasing the awareness of healthcare professionals of child protection and reminding them of the role of medical imaging in diagnosing SPA.

7.6 Conclusion

Radiologic technologists and radiologists, alongside all healthcare professionals who work with or alongside children, play an integral role in the diagnosis and management of children suspected of having been physically abused. This study has demonstrated that overall knowledge and awareness of child abuse amongst radiologists and radiologic technologists in Saudi Arabia is good; however, they lack specific knowledge regarding the reporting and acting procedures at their hospitals in cases of suspected child abuse. Moreover, there is a lack of standardised protocols, radiological reporting expertise for cases of suspected child abuse. This study highlights that there is a clear need for national imaging guidelines and training programs relating to the imaging and radiological reporting of SPA in infants and young children in Saudi Arabia.

7.7 References

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Chapter Eight

Overall summary and discussion

Contribution Statement:

- Writing: **N.M.A.**
- Supervision and review: A.C.O. and A.J.

8. Overall summary and discussion

8.1 Overall summary

Rib fractures are highly specific for physical abuse in infants and young children. Chest radiography as part of the skeletal survey (SkS) is currently the recommended standard imaging method for detecting rib fractures in children investigated for suspected physical abuse (SPA). However, acute rib fractures are often undetected in initial chest radiographs (CXRs). Therefore, follow-up CXR SkS performed 11 to 14 days after initial CXR SkS are recommended because callus formation associated with fracture healing increases the visibility and improves the detection of rib fractures. As a result, the presence or absence of abusive rib fractures cannot always be confirmed until at least 11 days after initial CXR SkS have been performed. The time interval between initial and follow-up SkS imaging is challenging for the safeguarding team and police because the child needs to be moved to a suitable place of safety and investigations need to be conducted to quickly identify the possible perpetrators. Moreover, there is also no guarantee that the child will be returned for follow-up imaging, and thus physical abuse could be missed, and the child placed at risk of further potential harm. Computed tomography (CT) has been suggested/proposed to improve the detection of rib fractures in children with SPA.

Therefore, one of the aims of this thesis was to review the literature regarding the accuracy of chest CT in detecting rib fractures in children with suspected or confirmed physical abuse (Chapter Three, page 62). The systematic review and meta-analysis included four eligible studies: two in live children, and two in post-mortem (PM) children. The systematic review and meta-analysis showed that chest PMCT had an overall sensitivity of 34% and specificity of 99% using autopsy as a reference standard. In live children with SPA, chest CT detected more rib fractures than initial CXR SkS. However, two included studies on live children had several limitations including small sample size, few reporters and inappropriate reference standards (initial CXR only). To better elucidate the diagnostic accuracy of chest CT in detecting rib fractures in live children with SPA, chest CT needs to be assessed against the current recommended standard used in routine clinical practice (initial and follow-up CXRs) as the reference.

The initial systematic review was updated to include studies from April 2020 to June 2024 (previously from January 1980 to April 2020). Two further papers were identified that met the inclusion criteria as defined in Chapter Three (page 82). The results of these studies did not change the key conclusion of the systematic review, which was that chest CT is superior to initial CXR in detecting rib fractures in live children investigated for SPA.

The aim of Chapter Four (page 84) was to assess the diagnostic performance of CT in detecting rib fractures compared with the current recommended standard used in routine clinical practice (initial and follow-up CXRs). We recruited the images of 64 children under 2 years of age who underwent CXRs as part of initial and follow-up SkS and chest CT for SPA. Overall, the sensitivity, specificity, and accuracy of CT for detecting rib fractures for per-patient analysis were 90.61%, 74.26% and 83.72%, respectively; for per-rib analysis, they were 85.63%, 94.16% and 93.46%, respectively; and for per-location analysis, they were 75.75%, 97.10% and 96.47%, respectively. Moreover, chest CT had a sensitivity of 79.79% in detecting posterior rib fractures, which is widely reported to be strongly associated with child physical abuse. Additionally, the level of experience of the 19 reporting radiologists did not affect the diagnostic accuracy of CT in rib fracture detection. The results of this study confirm the findings of the previous chapter (Chapter Three, page 62), that chest CT has a promising role in identifying rib fractures in live children investigated for SPA. Because chest CT shows a high overall diagnostic performance when compared to the current recommended standard used in routine clinical practice (initial and follow-up CXRs), chest CT has the potential to replace six CXRs undertaken as part of the SkS, facilitating prompt clinical and legal decision-making in children being evaluated for SPA.

If chest CT has a potential to become the clinical standard for rib fracture identification in cases of SPA in children, the feasibility of dating rib fractures using chest CT needs to be investigated. Dating fractures in suspected child abuse has clinical, forensic and medicolegal implications. The aim of Chapter Five (page 111) was to provide the CT-based healing pattern of rib fractures compared to the current clinical standard of chest radiography by assessing the agreement between the modalities in identifying the parameters of rib fracture healing (fracture line and callus formation) (page 118) and estimating the broad timeframes for rib fracture dating (acute vs. healing). An additional aim was to examine what healing parameters seen on CT could be used to estimate the specific age range of rib fractures, using CXR as the reference. The results showed a moderate agreement between chest CT and radiography in the identification of the features of fracture healing (fracture line: $k=0.42$; callus formation: $k=0.49$). Moreover, there was substantial agreement in estimating the timeframe of rib fractures (acute vs. healing) ($k=0.76$); this often being requested from the non-expert radiologists to provide fracture dating in suspected child abuse cases. However, expert paediatric radiologists are expected to provide specific timescales (in weeks) for dating rib fractures to assist the courts in narrowing the pool of potential perpetrators and to ensure optimum safe placement of the child. The results also showed how healing

features could serve as a guide for radiologists in estimating the specific age range of rib fractures identified on CT as follows: a rib fracture on CT with no periosteal reaction was more likely to be < 2 weeks old; thin periosteal reaction was more likely to be 2–4 weeks old; presence of callus formation was more likely to be > 2 weeks old; and focal sclerosis or cortical thickening was more likely to be 4–6 weeks old. These findings illustrate that dating rib fractures from CT is feasible, if chest CT becomes the clinical standard for rib fracture detection in children with SPA.

The higher radiation dose of chest CT compared to chest radiography makes CT less desirable in routine clinical practice for assessing rib fractures in children investigated for SPA. The aim of Chapter Six (page 130) was to investigate the effect of varying CT scanning parameters (KV and mA) on radiation dose, image quality and sensitivity, and to optimise chest CT scanning parameters for the detection of rib fractures in infants with SPA in two paediatric centres using an animal model (rabbits). There was moderate agreement between readers' subjective assessment of image noise (Centre 1, $k=0.5$; Centre 2, $k=0.45$) and sharpness (Centre 1, $k=0.59$; Centre 2, $k=0.55$). The parameter sets with a combination of the lowest radiation dose and acceptable diagnostic image quality were at 80 kV/30 mA with an effective dose of 0.32 millisievert (mSv) and sensitivity of 93.5% at Centre 1, and 80 kV/40 mA with an effective dose of 0.2 mSv and sensitivity of 84.3% at Centre 2. This study showed that a LDCT chest protocol is technically feasible, with acceptable diagnostic image quality and high sensitivity for assessing undisplaced acute rib fractures; the effective dose approaches the average effective dose of standard chest radiographs performed in skeletal surveys for SPA (0.1 mSv). However, this result is based on an animal model and cannot be directly transferred to human children. Importantly, the risk of exposure to ionising radiation in chest CT should be balanced against the risk of a missed diagnosis of physical abuse, especially when initial chest radiography is inconclusive or suspicious.

The identification and early reporting of child abuse cases are crucial for both their timely management and ultimately, safeguarding of the child. In the last decade, the healthcare system in Saudi Arabia has paid great attention to improving early detection and reporting of child abuse cases. Among other healthcare professionals, radiologic technologists and radiologists play a key role in diagnosing SPA in children. Chapter Seven (page 159) was a cross-sectional survey to assess current practice, knowledge and awareness of radiologists and radiologic technologists in relation to child abuse in Saudi Arabia. The results showed that participants (224 radiologic technologists and 91 radiologists) had a good knowledge of the various forms of and risk factors for child abuse, with radiologists having higher average

knowledge of child abuse (4.8) than radiologic technologists (4.0). However, 58.5% (131/224) of radiologic technologists and 48.4% (44/91) of radiologists lacked knowledge of the reporting procedures in cases of child abuse. Most survey respondents (93.8% of radiologic technologists and 67.0% of radiologists) reported no imaging protocols (e.g., SkS) at their hospital for imaging children with SPA. Moreover, 73.7% (165/224) of radiologic technologists had no training in paediatric radiology and 80.2% (73/91) of radiologists had received no training in evaluation of imaging performed for children with SPA. These results confirm the need for national imaging guidelines and comprehensive training programs focused on imaging and radiologic reporting for SPA cases in children in Saudi Arabia.

In conclusion, the findings reported in this thesis have demonstrated that chest CT provides accurate detection of rib fractures in live children investigated for SPA and may have the potential to replace the current recommended imaging standard used in routine clinical practice (6 CXRs as part of initial and follow-up SkS), improving both the clinical and safeguarding procedures for children being investigated for SPA. Furthermore, the preliminary study showed the feasibility of dating rib fractures using chest CT. Moreover, the experimental study showed that optimising the radiation dose of CT is technically feasible, with acceptable diagnostic image quality and high sensitivity for diagnosing undisplaced acute rib fractures, with a radiation dose approaching near the average dose of standard 6 CXRs performed in SkS for SPA. Finally, there is a need to establish national imaging guidelines and implement training programs in Saudi Arabia to improve the imaging and radiologic reporting of SPA in infants and young children.

8.2 Overall discussion and future direction

The current studies in the literature [1-4] have suggested that chest CT can be used in detecting rib fractures in live children with SPA when the initial CXR is negative or equivocal but suspicion of abuse is high. This is because CT is more sensitive than initial CXR in detecting rib fractures [1-4], as demonstrated by comparisons of CT with initial CXR using initial and follow-up CXRs as the reference standard (Chapter Four) (sensitivity of initial CXR vs. chest CT was 63.58% vs. 90.61% at per-patient analysis level, 49.71% vs. 85.63% at per-rib analysis level and 35.77% vs. 75.75% at per-rib analysis level, respectively). In light of the results of Chapter Four that show a high diagnostic performance of chest CT for detecting rib fractures in live children with SPA when compared to the recommended standard imaging methods of initial and follow-up CXRs, suggest implementation of chest CT as a standard tool in routine clinical

practice, instead of the 6-view CXRs as part of initial and follow-up SkS. Employing chest CT as a standard tool in routine clinical practice in children investigated for SPA will improve the detection of rib fractures and ultimately facilitate the timely safeguarding and management of children. Practically speaking, chest CT can be performed during the same session as a head CT scan examination, which is recommended by guidelines of the Royal College of Radiologists and the Society and College of Radiographers (RCR-SCoR) [5] for children under the age of 1 year and children older than 1 year of age with external evidence of head trauma and/or neurological symptoms.

It could be argued the collected cases did not reach the powered sample size (108) to provide definitive diagnostic accuracy of chest CT compared to initial and follow-up CXRs for detecting rib fractures in live children with SPA. Therefore, a multicentre study with powered sample size is needed to demonstrate definitive diagnostic accuracy of chest CT for detecting rib fractures in live children with SPA against the current reference standard of initial and follow-up CXRs used in clinical practice. The study design of such future diagnostic accuracy studies should be considered to avoid response fatigue. Future studies could adopt a blinded randomised cross-over study design where reporters are randomly assigned to two groups, each comprising half of the CXRs and chest CT cases from the total study population. The period allocated for reading images for each read (i.e., CXRs or CT) should be sufficient, around 2–3 months, to encourage radiologists to participate in such studies. Reaching that number of 108 is challenging because chest CT is not the clinical norm (i.e., not used as a standard imaging tool in clinical practice) in detecting rib fractures in children with SPA and the incidence of SPA in children per centre is relatively low. The thesis (Chapter Four) retrospectively collected a total of 64 cases from 13 European centres over a period of 10 years. However, to the best of my knowledge, the study of diagnostic accuracy of CT in detecting of rib fractures in children with SPA (presented in Chapter Four) had the largest sample size to date and it is the first study that uses current clinical practice as the reference standard (i.e., initial and follow-up CXRs) to assess the diagnostic accuracy of chest CT in detecting rib fractures in live children with SPA.

It could be argued that employing chest CT as a standard tool in the routine clinical practice for the evaluation of rib fractures in children investigated for SPA should be reviewed on a case-by-case basis. For example, when initial SkS shows metaphyseal fractures (also known as classic metaphyseal lesions) in an infant without plausible accidental causality, it could be argued that chest CT should not be used instead of CXRs to evaluate the ribs due to the concern of radiation dose associated with CT and the

feasibility of a decision-making regarding child protection on the basis of metaphyseal fractures which are considered highly specific for abuse [6]. In contrast, the use of CT could be supported in this case scenario for the evaluation of possible rib fractures because of CT has greater sensitivity than initial CXR in the detection of rib fractures [1-4]. The presence of the rib fracture can lead to a prompt and appropriate intervention with clinical and social management for children. Documentation of the number of fractures in children investigated for SPA is important in legal proceedings and the court often requires that every single fracture be confidently identified. It should be noted that some rib fractures such as costochondral junction (CCJ) fractures and posterior costovertebral fractures can be missed on both initial and follow-up CXRs due to their location near the spine and the tendency of CCJ to heal without callus or subperiosteal new bone formation (SPNBF) [7-9].

In the last few years, artificial intelligence (AI) applications have earned attention in the medical field and are expected to play an important role in the future of diagnostic imaging. However, less research has been done on performances of AI-based applications in paediatric imaging than in adult imaging [10]. A recent study by Ghosh *et al.* [11] develops an AI-based algorithm for detecting rib fractures on frontal CXR in children under 2 years of age. This study reported that AI-based algorithms have diagnostic performance (sensitivity and specificity of 72%–81% and 70%–79%, respectively) comparable to attending paediatric radiologists in detecting rib fractures on frontal CXR [11]. A recent systematic review and meta-analysis of accuracy of AI-based algorithms for detecting rib fractures on CT scans in the adult population reported pooled sensitivity and specificity of 85% and specificity 96%, respectively [12]. More studies are needed to evaluate the diagnostic performance of the currently available AI-based algorithms in detecting rib fractures in children with SPA. It is also recommended that the automated rib fracture AI-based algorithms be improved to be able to characterise a broad timeframe of rib fractures (acute and healing), calculate the total number of fractured ribs and locate them precisely.

Recent advancements in CT technology have improved the evaluation of rib fractures on chest CT. Defining rib fractures on CT datasets may be challenging for radiologists secondary to the complexity of rib shape with a diagonal trajectory along their longitudinal axes across CT sections; and assessment of ribs in CT datasets is often performed sequentially one-by-one from the axial (cross-sectional) images followed by post-processing in coronal or sagittal multiplanar reconstructions (MPRs), which can be a

time-consuming process [13]. Rib reformatting software has been developed recently to improve rib fracture detection with a reduction in evaluation time [14-17]. Simply, this rib reformatting software is a post-processing tool that flattens and unfolds the thoracic cage to display all the ribs in a single plane with automatic labelling of ribs and vertebral bodies [15]. The software has different commercial names based on the CT vendors (i.e., CT bone reading software, Siemens Healthcare, Forchheim, Germany; Open Rib software, Canon Medical Systems, Otawara, Japan). Several studies have shown that using unfolded CT rib reformation software shortens the reading time and improves the diagnostic accuracy in the detection of rib fractures in adults in trauma settings [14-17]. To the best of my knowledge, the diagnostic accuracy of rib reformatting software in detecting rib fractures in children investigated for SPA has not yet been assessed. A research grant for doing such a study was secured last year, but unfortunately, the Siemens Healthcare company has confirmed that the software has not yet been developed for assessing the ribs of infant and young children and the money was returned to the funders. If the effectiveness and feasibility of rib reformatting software are proven in children, this tool will empower radiologists' decision-making in reporting the number and location of rib fractures in children suspected of having been physically abused, that has diagnostic and medicolegal importance. Additionally, the software may reduce the reading time in diagnosing rib fractures in clinical practice.

In cases of suspected child abuse, radiologists are often asked to estimate the date of fractures; such information has clinical and medicolegal implications [18]. Although dating of fractures to the extent of identifying acute and healing phases is sufficient in clinical practice to assess the consistency of timing of injury with the history provided, the specific timescale is often required by police and safeguarding team to identify or exclude potential perpetrators and for decision-making regarding the optimum placement of the child, respectively [18]. The expert paediatric radiologist who is appointed by the court is often required to give the most likely timescale of fractures in SPA cases in children; often that is a broad timescale (in weeks) [18]. Limited studies are available in the literature concerning dating fractures in children, and some factors that may affect the healing timeline, such as patient age, fracture location and fracture type (displaced, complete or incomplete) have not been evaluated. There is a need to improve the scientific evidence base in radiological dating of fractures in children with SPA, especially for highly specific fractures of abuse such as rib fractures. Further studies are needed to examine the effect of patient age on aspects of fracture healing (such as SPNBF and callus formation) in young patient

age cohorts (0–1 year and 1–2 years). Additionally, there is also needed for the assessment of fracture healing between different locations, which may begin broadly from fractures in different bone locations such as the upper and lower limbs before being narrowed within the same bone location such as the upper and lower ribs. Variations in fracture healing in ribs between cartilaginous (such as CCJ fractures) and non-cartilaginous fractures also need to be evaluated. Rib fracture types (buckle, complete and fracture with/without dislocation) may affect the fracture healing process. Such studies should be performed with a large collaborative multicentre with a large sample size and a standardised definition of the radiological features of fracture healing to reduce the variation between observers.

If CT becomes the standard clinical imaging for rib fracture identification in cases of SPA in children, dating of rib fractures will be determined from CT scans. In this thesis, a preliminary study (Chapter Five) shows the feasibility of dating rib fractures using chest CT in children with SPA and demonstrates moderate and substantial agreement with the current reference standard used in clinical practice (i.e., chest radiography) in assessing healing features and broad timeframes of rib fractures (acute vs. healing), respectively. Callus formation may serve as a guide for expert paediatric radiologists to estimate the specific timescale of rib fractures from CT scans. Further research with a large sample size to provide more detailed assessment of the correlation of CT-based features of rib fracture healing with known fracture age (by CXR as reference standard) is needed to support legal investigations if chest CT is to become the clinical standard for rib fracture identification in cases of SPA in children.

The higher radiation dose of chest CT compared to chest radiography is of concern and prevents the routine use of chest CT in clinical practice for assessing rib fractures in children investigated for SPA. In this thesis, the experimental study on animal subjects shows that the chest CT protocol can be optimised to achieve a radiation dose (0.32 mSv at Centre 1 and 0.2 mSv at Centre 2) approaching the standard dose for six CXR views (0.1 mSv) without compromising the diagnostic image quality. However, further low-dose CT (LDCT) chest studies are needed to validate the preliminary results. Due to the ethical challenge of irradiating children for research purposes, future studies to develop LDCT protocol for diagnosing rib fractures in children with SPA are proposed to be initially performed on PM children with SPA or designed child phantoms with simulated acute and healing rib fractures to resemble cases with SPA. When the feasibility of the developed LDCT protocol in detecting rib fractures in PM children or the

phantom is proven, the next step would be a pilot study to assess the accuracy of the developed LDCT protocol in live children with SPA.

It is arguable that a standard CT protocol should be used if chest CT becomes the clinical standard for rib fracture identification in cases of SPA in children. The LDCT protocol may result in suboptimal visualisation of subtle fractures, leading to repeat CT scans with subsequent increased radiation exposure in children. Furthermore, the radiation exposure associated with standard chest CT for diagnosing rib fractures in children with SPA is arguably justified, given that the risk of a missed diagnosis of abuse exceeds the risk of radiation exposure. On the other hand, the argument can be made that using LDCT protocol in children is important to minimise the long-term risks associated with radiation exposure because children are more radiosensitive and have a longer expected life span [19, 20]. Moreover, advancements in CT technology have allowed substantial reduction in radiation dose while maintaining diagnostic image quality in paediatric CT imaging [21-24]. A recent study has shown that implementing photon-counting detector CT technology in paediatric chest CT imaging has achieved a radiation dose of 0.19 mSv without compromising diagnostic image quality [25].

A recent preliminary study has investigated the use of whole-body LDCT SkS for detecting occult bony injury in live children with SPA [6]. The study included ten infants under 1 year of age, using whole-body LDCT SkS due to factors including children who were not stable for conventional SkS, coronavirus disease (COVID) restrictions and parental choice. The results showed whole-body LDCT as SkS detected additional rib fractures in two patients which were missed on the additional imaging (i.e., CXR) performed as a part of routine clinical care. In a patient who had ante-mortem and PM whole-body LDCT SkS, 5 out of 7 metaphyseal fractures were initially missed on ante-mortem whole-body LDCT SkS but seen on high-dose PM whole-body LDCT SkS. The reported radiation dose of whole-body LDCT SkS ranged from 0.73 to 1.46 mSv. There are advantages and disadvantages of implementing whole-body LDCT SkS instead of radiographic SkS for detecting fractures in live children with SPA. The advantages of implementing whole-body LDCT SkS in live children with SPA include avoiding physically manipulating an infant's body, reducing the examination time, providing 3D images to illustrate the injuries in the courts and improving the detection of fractures (except for metaphyseal fractures), leading to immediate evidence of injury and allowing earlier decision for management of children [6]. On the other hand, the disadvantages and challenges of using whole-body LDCT SkS include a potentially low

sensitivity in detecting metaphyseal fractures, which is considered to be highly specific for child abuse [6]. To the best of my knowledge, the diagnostic accuracy of CT in detecting metaphyseal fractures in live children with SPA apparently has not been assessed yet [26], and future study is needed. Additionally, the radiation dose of whole-body LDCT SkS [6] is still high in comparison to standard radiographic SkS [27, 28]. Moreover, whole-body LDCT SkS may require sedation, especially in older children, to prevent motion artefacts to avoid repeat imaging. Furthermore, reporting and image reconstruction of the whole-body LDCT SkS examination is time-consuming. Arguably, given the improvement in CT technology in reducing radiation dose and improving spatial resolution using photon-counting detector CT technology [29-31] as well as the previously mentioned advantages of whole-body LDCT SkS, radiographic SkS may be replaced by a whole-body LDCT SkS. In clinical practice, whole-body LDCT SkS has replaced radiographic SkS for diagnosis of multiple myeloma in adults [32]. Due to ethical approval challenges, further phantom and PM research using photon-counting detector CT technology is required to better understand the role of whole-body LDCT SkS in evaluating bony injuries in children with SPA.

Child abuse is a serious worldwide problem, and early recognition and diagnosis are vital for providing timely safeguarding and improving the child health outcomes of the affected children. In recent decades, Saudi Arabia has endeavoured to improve child welfare by establishing the National Family Safety Program (NFSP), which is focused on preventing child abuse [33, 34]. Radiological imaging plays an important role in the diagnosis of children who may have been physically abused because the history offered is often inconclusive or misleading and the injuries are often clinically occult [35]. In light of the result of the survey study assessing the current practice, knowledge and awareness of child abuse among radiologic technologists and radiologists in Saudi Arabia (Chapter Seven), more extensive work is needed to improve the role of radiology departments in Saudi Arabia in imaging children with SPA. It is crucial that radiology departments have a clear imaging protocol in place for imaging children with SPA. Therefore, it is recommended that the Ministry of Health in Saudi Arabia in collaboration with national radiology societies in Saudi Arabia, including the Saudi Society of Medical Radiologic Technology (SSMRT) and the Radiological Society of Saudi Arabia (RSSA), should endorse one of the widely recognised international imaging guidelines, including those from the American College of Radiology and the Society for Pediatric Radiology (ACR-SPR) [36] and the RCR-SCoR [5], as evidence-based best practice.

Radiologic technologists and radiologists play an integral role in the diagnosis of children investigated for SPA. Radiologic technologists are responsible for performing SkS to obtain high-quality diagnostic images, which have both medical and legal implications [5]. Clinical radiologists play a crucial role in evaluating SkS images by differentiating traumatic injuries from normal variants or metabolic conditions and suggesting the mechanisms and most likely timeframe of injuries [37, 38]. To promote professional development in this important facet of clinical practice in Saudi Arabia, dedicated training courses for radiologic technologists and radiologists are required in imaging and reporting SPA in children. Such training courses can be organised by national radiology societies. Furthermore, dedicated workshops/lectures in imaging and reporting of SPA should be included in the programme of the annual national RSSA meeting, which should also host national and international speakers with an interest in imaging children with SPA.

The radiology departments should have at least one dedicated paediatric radiologist for reporting SkS imaging [5]. However, a paediatric radiologist may not be available in every hospital in Saudi Arabia, and therefore, such hospitals could forge links/networks with paediatric radiologists to facilitate access to timely reports on SPA imaging; this could facilitate quicker decision-making. Interestingly, the survey showed a lack of knowledge among radiologic technologists and radiologists in Saudi Arabia regarding reporting procedures for suspected child abuse at their hospitals. It is recommended that child protection units in the hospitals in Saudi Arabia establish frequent lectures/workshops for healthcare professionals to increase awareness about the NFSP and the reporting procedures that should be followed in cases where child abuse is suspected.

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Chapter Nine

Appendices

Contribution Statement:

- Compiled the chapter: **N.M.A.**

9. Appendices

8.1 Appendix 1. Search strategy and terms used in the systematic review

Medline

#	Searches	Results
1	Infant/	783193
2	(paediatric* or pediatric*).mp.	395627
3	(child* or babies or baby or toddler*).mp.	2457496
4	(Adolescent or Young*).mp.	2875468
5	1 or 2 or 3 or 4	4437538
6	Child Abuse/	21907
7	(battered child or shaken baby or battered baby).mp.	1707
8	(non-accidental trauma or nonaccidental trauma).mp.	380
9	(non-accidental injur* or nonaccidental injur* or NAT).mp.	7578
10	Physical Abuse/	585
11	(Occult skeletal trauma or Occult injur*).mp.	257
12	(Inflicted injur* or unexplained inju*).mp.	872
13	6 or 7 or 8 or 9 or 10 or 11 or 12	31265
14	rib fractur*.mp.	4547
15	Costal fractur*.mp.	67
16	(thoracic Injur* or Chest Injur*).mp.	14176
17	Rib Fractures/	3040
18	14 or 15 or 16 or 17	17558
19	Tomography, X-Ray Computed/	375378
20	Thoracic CT.mp.	1400
21	Chest CT.mp.	7177
22	CT.mp.	336347
23	19 or 20 or 21 or 22	563591
24	5 and 13 and 18 and 23	47
25	limit 24 to (english language and yr="1980 -Current")	41

Web of Science database

#	Searches	Results
1	TS=(Infant* OR Newborn)	1,532,622
2	TS=(paediatric* OR pediatric*)	1,814,713
3	TS=(child* or (babies or baby) or toddler*)	3,570,524
4	TS=(Adolescent or Young*)	3,682,274
5	#4 OR #3 OR #2 OR #1	6,753,712
6	TS=(Child* Abuse)	95,299
7	TS=(battered child* OR shaken baby OR battered baby)	5,606

8	(TS=(non-accidental trauma or nonaccidental trauma)	1,126
9	Ts=(non-accidental injur* or nonaccidental injur* or NAT)	45,021
10	Ts=Physical Abuse	39,537
11	TS=(Occult skeletal trauma or Occult injur*)	5,604
12	TS=(unexplained injur*)	3,627
13	TS=(Inflicted injur*)	7,201
14	#13 OR #12 OR #11 OR #10 OR #9 OR #8 OR #7 OR #6	176,374
15	Ts=rib fractur*	9,867
16	ts=thoracic Injur*	46,280
17	ts=Costal fractur*	388
18	TS=(thoracic Injur* or Chest Injur*)	68,448
19	#18 OR #17 OR #16 OR #15	75,721
20	TS=(Computed tomography OR CT)	1,159,724
21	ts=chest CT	41,455
22	ts=Thoracic CT	26,476
23	#22 OR #21 OR #20	1,159,724
24	#23 AND #19 AND #14 AND #5	220
25	#23 AND #19 AND #14 AND #5 Refined by: LANGUAGES: (ENGLISH) Timespan=1980-2020	201

Cochrane Library

#	Searches	Results
1	MeSH descriptor: [Infant] explode all trees	16136
2	("paediatric*" or "pediatric*"):ti,ab,kw	31299
3	child* or babies or baby or toddler*):ti,ab,kw	152842
4	(Adolescent or Young*):ti,ab,kw	201410
5	#1 OR #2 OR #3 OR #4	312145
6	MeSH descriptor: [Child Abuse] explode all trees	503
7	("battered child*" or "shaken baby" or "battered baby"):ti,ab,kw	19
8	("non-accidental trauma" or "nonaccidental trauma"):ti,ab,kw	5
9	("non-accidental injur*" or "nonaccidental injur*" or	253
10	MeSH descriptor: [Physical Abuse] explode all trees	16
11	("Occult skeletal trauma" or "Occult injur*"):ti,ab,kw	0
12	("Inflicted injur*" or "unexplained inju*"):ti,ab,kw	0
13	#6 OR #7 OR #8 OR #9 OR #10 OR #11 OR #12	787
14	("rib fractur*"):ti,ab,kw	282
15	("Costal fractur*"):ti,ab,kw	4
16	("thoracic Injur*" or "Chest Injur*"):ti,ab,kw	1

17	MeSH descriptor: [Rib Fractures] explode all trees	79
18	#14 OR #15 OR #16 OR #17	283
19	MeSH descriptor: [Tomography, X-Ray Computed] explode all trees	4826
20	("Thoracic CT"):ti,ab,kw	75
21	("Chest CT"):ti,ab,kw	466
22	(CT):ti,ab,kw	74831
23	#19 OR #20 OR #21 OR #22	76872
24	#23 AND #18 AND #13 AND #5	0

8.2 Appendix 2: Ethical approval obtained from The Health Research Authority (United Kingdom) for the main study presented in Chapter Four



Professor Amaka C Offiah
Chair of Paediatric Musculoskeletal Imaging and
Honorary Consultant Paediatric Radiologist
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Sheffield Children's NHS Foundation Trust
Western Bank, Sheffield
S10 2THN/A

Email: approvals@hra.nhs.uk
HCRW.approvals@wales.nhs.uk

21 June 2021

Dear Professor Offiah

**HRA and Health and Care
Research Wales (HCRW)
Approval Letter**

Study title:	Rib fracturE diagnosis in suspecTed abusE: comPUted Tomography Or Radiographs?
IRAS project ID:	294838
Protocol number:	N/A
REC reference:	21/HRA/2368
Sponsor	Sheffield Children's NHS Foundation Trust

I am pleased to confirm that [HRA and Health and Care Research Wales \(HCRW\) Approval](#) has been given for the above referenced study, on the basis described in the application form, protocol, supporting documentation and any clarifications received. You should not expect to receive anything further relating to this application.

Please now work with participating NHS organisations to confirm capacity and capability, in line with the instructions provided in the "Information to support study set up" section towards the end of this letter.

How should I work with participating NHS/HSC organisations in Northern Ireland and Scotland?

HRA and HCRW Approval does not apply to NHS/HSC organisations within Northern Ireland and Scotland.

If you indicated in your IRAS form that you do have participating organisations in either of these devolved administrations, the final document set and the study wide governance report

8.3 Appendix 3: Ethical approval was not required to use deceased rabbits in the study presented in Chapter Six



Nasser M Alzahrani <nmalzahrani1@sheffield.ac.uk>

Use killed animal (purchase from a butcher/company) for a study

Medical School Ethics <medschoolethics@sheffield.ac.uk>
To: Nasser M Alzahrani <nmalzahrani1@sheffield.ac.uk>

28 August 2020 at 09:47

Hi Nasser,

This is the response we've had regards your query:

There is no ethics needed if the researcher is only using abattoir/butcher-supplied meat. Although after use the tissue remaining would be considered as anatomical waste and would need to be disposed of as HA material (i.e. the waste tissue must be incinerated). Abattoirs tend to only use animals that are of an age used for human consumption if the researcher needs very young piglets as these would not be processed in abattoirs unless the animals were ill/needing euthanasia (in which they wouldn't enter the food chain).

Ethics/personal licence (and project licence) is needed if the animals were alive or euthanised by the researcher as they would need techniques which require these.

I hope that answers your question

Best Wishes
Sarah

8.4 Appendix 4: Ethical approval obtained from the University of Sheffield Research Ethics Committee for the survey study (Chapter Seven)



Downloaded: 29/09/2021

Approved: 29/09/2021

Nasser Alzahrani
Registration number: 190308230
Medical School
Programme: PhD/OCP CLINICAL FT

Dear Nasser

PROJECT TITLE: Professional Practice and Awareness of Child Abuse Among Radiologists and Radiographers In Saudi Arabia: Where Do We Stand?

APPLICATION: Reference Number 043217

On behalf of the University ethics reviewers who reviewed your project, I am pleased to inform you that on 29/09/2021 the above-named project was **approved** on ethics grounds, on the basis that you will adhere to the following documentation that you submitted for ethics review:

- University research ethics application form 043217 (form submission date: 23/09/2021); (expected project end date: 01/02/2022).

If during the course of the project you need to [deviate significantly from the above-approved documentation](#) please inform me since written approval will be required.

Your responsibilities in delivering this research project are set out at the end of this letter.

Yours sincerely

Charlotte Claxton
Ethics Administrator
Medical School

Please note the following responsibilities of the researcher in delivering the research project:

- The project must abide by the University's Research Ethics Policy:
<https://www.sheffield.ac.uk/rs/ethicsandintegrity/ethicspolicy/approval-procedure>
- The project must abide by the University's Good Research & Innovation Practices Policy:
https://www.sheffield.ac.uk/polopoly_fs/1.671066!/file/GRIPPolicy.pdf
- The researcher must inform their supervisor (in the case of a student) or Ethics Administrator (in the case of a member of staff) of any significant changes to the project or the approved documentation.
- The researcher must comply with the requirements of the law and relevant guidelines relating to security and confidentiality of personal data.
- The researcher is responsible for effectively managing the data collected both during and after the end of the project in line with best practice, and any relevant legislative, regulatory or contractual requirements.

8.5 Appendix 5: Survey version distributed to radiologic technologists (Chapter Seven)

Professional Practice and Awareness of Child Abuse Among Radiologists and Radiologic technologists in Saudi Arabia

Dear Participant,

You are invited to participate in a web-based survey on professional practice and awareness of child abuse among radiologists and radiographers in Saudi Arabia. This survey is part of a research project concerning the radiological investigation of suspected physical abuse in children which is being conducted by Nasser Alzahrani, a student at the University of Sheffield, United Kingdom, under the primary supervision of Professor Amaka C Offiah

The survey should take no longer than 5 minutes to complete.

Your participation in this survey is voluntary. You may exit the survey without submission at any time and your answers will not be collected. This study has received a favourable opinion by the University Research Ethics Committee.

There are no risks associated with participating in this study. There are no costs or payments associated with your participation in the study. However, your responses may help us learn more about the current practice and knowledge of radiologists and radiographers in Saudi Arabia regarding suspected child abuse.

The survey is anonymous. No identifiable information, such as name, sex, date of birth, contact information or IP address, will be collected. Your survey answers will be sent to a Google Form where the data will be stored in password-protected electronic format. No one will be able to identify you or your answers, and no one will know whether you participated in the study.

If you have any questions about the study, please contact Mr Alzahrani via email at nmalzahrani1@sheffield.ac.uk

If you feel you have not been treated according to the descriptions in this form, or that your rights as a participant in research have not been honoured during the course of this project, or you have any questions, concerns, or complaints that you wish to address to someone other than the investigator, you may contact the University Data Protection Officer at dataprotection@sheffield.ac.uk

By completing and submitting this survey, you are indicating your consent to participate in the study. Your participation is appreciated.

Many thanks for your time and cooperation.

*Required

Demographics

1. Nationality *

Mark only one oval.

- ☐ Saudi
☐ Non-Saudi

2. Place of work *

Mark only one oval.

- ☐ Ministry of Health
☐ Universities' Hospital
☐ National Guard Hospital
☐ King Faisal Specialist Hospital & Research Centre
☐ Armed Forces Hospital
☐ Security Forces Hospital
☐ John Hopkins/Aramco Hospital
☐ Royal Commission Hospital
☐ Private Hospital
☐ Other: _____

3. What type of hospital do you work in? *

Mark only one oval.

- ☐ Medical city / Speciality hospital
- ☐ General hospital
- ☐ Primary health care centre
- ☐ Other: _____

4. In which province are you working? *

Mark only one oval.

- ☐ Riyadh
- ☐ Makkah
- ☐ Madinah
- ☐ Eastern
- ☐ Al-Jawf
- ☐ Al-Baha
- ☐ Qassim
- ☐ Aseer
- ☐ Tabuk
- ☐ Jazan
- ☐ Najran
- ☐ Northern Borders
- ☐ Hail
- ☐ Other: _____

5. What is your highest academic qualification? *

Mark only one oval.

- ☐ Diploma
- ☐ Bachelor
- ☐ Master
- ☐ PhD or other training certificates (i.e., Board)

6. How many years' experience do you have as a radiographer? *

Mark only one oval.

- ☐ Less than 5 years
- ☐ 5 -10 years
- ☐ 11-15 years
- ☐ More than 15 years

7. Which imaging unit do you mostly cover? *

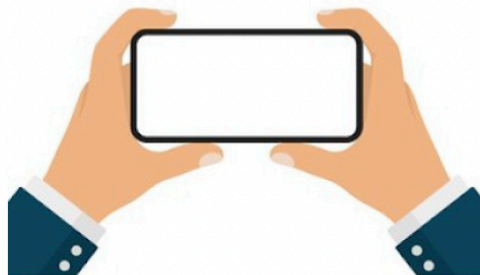
Mark only one oval.

- ☐ General X-ray
- ☐ Magnetic Resonance Imaging (MRI)
- ☐ Fluoroscopy
- ☐ Dental X-ray
- ☐ Computed Tomography (CT)
- ☐ Mammography
- ☐ Nuclear Medicine
- ☐ Ultrasound
- ☐ Dual energy X-ray absorptiometry (DEXA)
- ☐ Interventional Radiology
- ☐ Other: _____

knowledge about child
abuse

All questions relate to children below 2 years of age (i.e., children who have NOT reached their second birthday)

If you are using your smartphone, please rotate the screen to landscape



8. Do you consider the following acts as abusive towards children? *

Mark only one oval per row.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Beating child for misbehaviour leaving body marks	☐	☐	☐	☐	☐
Leaving child alone in the home for long hours	☐	☐	☐	☐	☐
Burning child for misbehaviour	☐	☐	☐	☐	☐
Verbal humiliation	☐	☐	☐	☐	☐
Refusing necessary medical treatment or surgical intervention to child	☐	☐	☐	☐	☐

9. Do you consider the following statements as a risk factor for child abuse? *

Mark only one oval per row.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Child with disability	☐	☐	☐	☐	☐
Parent or caregiver below 16 years old	☐	☐	☐	☐	☐
Parent or caregiver with mental health illness	☐	☐	☐	☐	☐
Low socio-economic status	☐	☐	☐	☐	☐
Parent or caregiver who was abused as a child	☐	☐	☐	☐	☐
Parent or caregiver using alcohol or illicit drug	☐	☐	☐	☐	☐

10. To what extent do you agree or disagree with the following statement *

Mark only one oval per row.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
I understand the meaning of the term "inflicted injury" or "physical abuse" or "non-accidental injury" in children?	☐	☐	☐	☐	☐

Radiological reporting and imaging protocol

11. Does your practice cover the imaging of paediatric patients (children 0 to 18 years)? *

Mark only one oval.

- ☐ Yes
☐ No

12. If you answered "Yes", then approximately how many children with suspected physical abuse do you image per year?

Mark only one oval.

- ☐ 1-10
☐ 11-20
☐ 21-30
☐ 31-40
☐ 41-50
☐ 51-60
☐ 61-70
☐ 71-80
☐ 81-90
☐ 91-100
☐ > 100

13. Is there an imaging protocol (i.e. skeletal survey) in your hospital for children below 2 years' old with suspected physical abuse? *

Mark only one oval.

- ☐ Yes
☐ No

14. If you answered "Yes" >> what is the protocol?

15. Are you aware of the international guidelines for imaging children with suspected physical abuse? *

Mark only one oval.

- ☐ Yes
☐ No

16. If you answered "Yes", which guidelines are you aware of?

Tick all that apply.

- ☐ ACR-SPR
☐ RCR-SCoR
☐ Other: _____

17. Have you received training (i.e. courses, workshops, workplace mentoring ...etc) in paediatric radiology? *

Mark only one oval.

- ☐ Yes
☐ No

18. If you answered "Yes" >> Did the training discuss child injuries related to suspected physical abuse?

Mark only one oval.

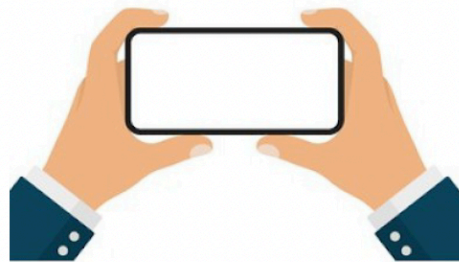
- ☐ Yes
☐ No

19. What type of training did you receive?

Tick all that apply.

- ☐ Local course
☐ Local workshop
☐ Local conference
☐ International course
☐ International workshop
☐ International conference
☐ Other: _____

If you are using your smartphone, please rotate the screen to landscape



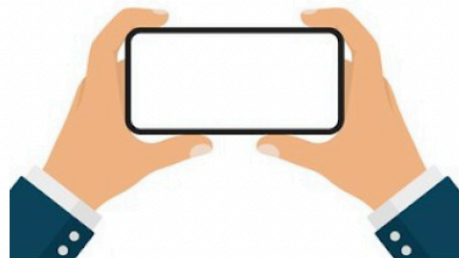
20. To what extent do you agree or disagree with the following statements *

Mark only one oval per row.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
I am competent to deal with a child in a case of suspected physical abuse	☐	☐	☐	☐	☐
I need training in evaluating and dealing with children with suspected physical abuse	☐	☐	☐	☐	☐

Knowledge about child abuse reporting procedure

If you are using your smartphone, please rotate the screen to landscape



21. To what extent do you agree or disagree with the following statements *

Mark only one oval per row.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
I am familiar with the policy in my hospital for reporting and acting in cases where I suspect child abuse	☐	☐	☐	☐	☐
It is legally mandatory in Saudi Arabia to report child abuse	☐	☐	☐	☐	☐
I am familiar with the National Family Safety Program (NFSP)"	☐	☐	☐	☐	☐

22. Additional comments

8.6 Appendix 6: Survey version distributed to radiologists (Chapter Seven)

Professional Practice and Awareness of Child Abuse Among Radiologists and Radiologic technologists in Saudi Arabia

Dear Participant,

You are invited to participate in a web-based survey on professional practice and awareness of child abuse among radiologists and radiographers in Saudi Arabia. This survey is part of a research project concerning the radiological investigation of suspected physical abuse in children which is being conducted by Nasser Alzahrani, a student at the University of Sheffield, United Kingdom, under the primary supervision of Professor Amaka C Offiah.

The survey should take no longer than 5 minutes to complete.

Your participation in this survey is voluntary. You may exit the survey without submission at any time and your answers will not be collected. This study has received a favourable opinion by the University Research Ethics Committee.

There are no risks associated with participating in this study. There are no costs or payments associated with your participation in the study. However, your responses may help us learn more about the current practice and knowledge of radiologists and radiographers in Saudi Arabia regarding suspected child abuse.

The survey is anonymous. No identifiable information, such as name, sex, date of birth, contact information or IP address, will be collected. Your survey answers will be sent to a Google Form where the data will be stored in password-protected electronic format. No one will be able to identify you or your answers, and no one will know whether you participated in the study.

If you have any questions about the study, please contact Mr Alzahrani via email at nmalzahrani1@sheffield.ac.uk

If you feel you have not been treated according to the descriptions in this form, or that your rights as a participant in research have not been honoured during the course of this project, or you have any questions, concerns, or complaints that you wish to address to someone other than the investigator, you may contact the University Data Protection Officer at dataprotection@sheffield.ac.uk

By completing and submitting this survey, you are indicating your consent to participate in the study. Your participation is appreciated.

Many thanks for your time and cooperation.

*Required

Demographics

1. Nationality *

Mark only one oval.

- ☐ Saudi
☐ Non-Saudi

2. Place of work *

Mark only one oval.

- ☐ Ministry of Health
☐ Universities' Hospital
☐ National Guard Hospital
☐ King Faisal Specialist Hospital & Research Centre
☐ Armed Forces Hospital
☐ Security Forces Hospital
☐ John Hopkins/Aramco Hospital
☐ Royal Commission Hospital
☐ Private Hospital
☐ Other: _____

3. What type of hospital do you work in? *

Mark only one oval.

- ☐ Medical city / Speciality hospital
- ☐ General hospital
- ☐ Primary health care centre
- ☐ Other: _____

4. In which province are you working? *

Mark only one oval.

- ☐ Riyadh
- ☐ Makkah
- ☐ Madinah
- ☐ Eastern
- ☐ Al-Jawf
- ☐ Al-Baha
- ☐ Qassim
- ☐ Aseer
- ☐ Tabuk
- ☐ Jazan
- ☐ Najran
- ☒ Northern Borders
- ☐ Hail
- ☐ Other: _____

5. What is your job title? *

Mark only one oval.

- ☐ Resident radiologist
- ☐ Specialist radiologist
- ☐ Consultant radiologist

6. If you answered "Resident radiologist" >> what is your stage/year of training?

Mark only one oval.

- ☐ 1st year
- ☐ 2nd year
- ☐ 3rd year
- ☐ 4th year

7. How many years' experience do you have as a radiologist? *

Mark only one oval.

- ☐ Less than 5 years
- ☐ 5 -10 years
- ☐ 11-15 years
- ☐ More than 15 years

8. Are you a paediatric radiologist? *

Mark only one oval.

- ☐ Yes
☐ No

9. If you answered "Yes", how many years' experience do you have as a paediatric radiologist?

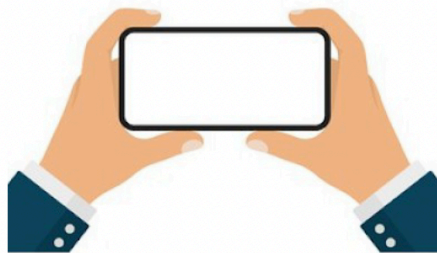
Mark only one oval.

- ☐ Less than 5 years
☐ 5 -10 years
☐ 11-15 years
☐ More than 15 years

knowledge about child abuse

All questions relate to children below 2 years of age (i.e., children who have NOT reached their second birthday)

If you are using your smartphone, please rotate the screen to landscape



10. Do you consider the following acts as abusive towards children? *

Mark only one oval per row.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Beating child for misbehaviour leaving body marks	☐	☐	☐	☐	☐
Leaving child alone in the home for long hours	☐	☐	☐	☐	☐
Burning child for misbehaviour	☐	☐	☐	☐	☐
Verbal humiliation	☐	☐	☐	☐	☐
Refusing necessary medical treatment or surgical intervention to child	☐	☐	☐	☐	☐

11. Do you consider the following statements as a risk factor for child abuse? *

Mark only one oval per row.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Child with disability	☐	☐	☐	☐	☐
Parent or caregiver below 16 years old	☐	☐	☐	☐	☐
Parent or caregiver with mental health illness	☐	☐	☐	☐	☐
Low socio-economic status	☐	☐	☐	☐	☐
Parent or caregiver who was abused as a child	☐	☐	☐	☐	☐
Parent or caregiver using alcohol or illicit drug	☐	☐	☐	☐	☐

12. To what extent do you agree or disagree with the following statement *

Mark only one oval per row.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
I understand the meaning of the term "inflicted injury" or "physical abuse" or "non-accidental injury" in children?	☐	☐	☐	☐	☐

Radiological reporting and imaging protocol

13. Does your practice cover paediatric patients (children 0 to 18 years)? *

Mark only one oval.

- ☐ Yes
☐ No

14. If you answered "Yes", then approximately how many cases of suspected child abuse do you report on per year?

Mark only one oval.

- ☐ 1-10
☐ 11-20
☐ 21-30
☐ 31-40
☐ 41-50
☐ 51-60
☐ 61-70
☐ 71-80
☐ 81-90
☐ 91-100
☐ > 100

15. Is there an imaging protocol (i.e. skeletal survey) in your hospital for children below 2 years' old with suspected physical abuse? *

Mark only one oval.

- ☐ Yes
☐ No

16. If you answered "Yes" – what is the protocol?

17. Are you aware of the international guidelines for imaging children with suspected physical abuse? *

Mark only one oval.

☐ Yes

☐ No

18. If you answered "Yes", which guidelines are you aware of?

Tick all that apply.

☐ ACR-SPR

☐ RCR-SCoR

☐ Other: _____

19. Have you received training (i.e. courses, workshops, ...etc) in evaluating injury in children related to suspected physical abuse? *

Mark only one oval.

☐ Yes

☐ No

20. If you answered "Yes", what type of training did you receive?

Tick all that apply.

☐ Local course

☐ Local workshop

☐ Local conference

☐ International course

☐ International workshop

☐ International conference

☐ Other: _____

21. Is there a paediatric radiologist in your hospital? *

Mark only one oval.

☐ Yes

☐ No

22. Is there a named radiologist in your hospital to report cases with suspected abuse? *

Mark only one oval.

☐ Yes

☐ No

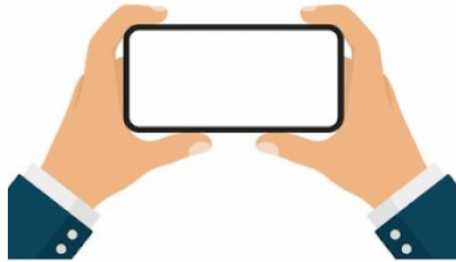
23. Are the radiological images of suspected child abuse reported by at least 2 radiologists in your hospital? *

Mark only one oval.

☐ Yes

☐ No

If you are using your smartphone, please rotate the screen to landscape



24. To what extent do you agree or disagree with the following statements *

Mark only one oval per row.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
I have the confidence to handle suspected physical abuse in children	☐	☐	☐	☐	☐
I am aware of the radiological signs of inflicted injury in children	☐	☐	☐	☐	☐
I need training in radiological reporting of suspected child abuse	☐	☐	☐	☐	☐

Knowledge about child abuse reporting procedure

If you are using your smartphone, please rotate the screen to landscape



25. To what extent do you agree or disagree with the following statements *

Mark only one oval per row.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
I am familiar with the policy in my hospital for reporting and acting in cases where I suspect child abuse	☐	☐	☐	☐	☐
It is legally mandatory in Saudi Arabia to report child abuse	☐	☐	☐	☐	☐
I am familiar with the National Family Safety Program (NFSP)*	☐	☐	☐	☐	☐

26. Additional comments:

8.7 Appendix 7: Responders' answers regarding other questions of survey (Chapter Seven)

	Radiologic technologists n=224 n (%)	Radiologists n=91 n (%)
Place of work		
Ministry of Health	109 (48.7)	51 (56)
Universities' Hospital	30 (13.4)	11 (12.1)
National Guard Hospital	13 (5.8)	6 (6.6)
King Faisal Specialist Hospital & Research Centre	13 (5.8)	4 (4.4)
Armed Forces Hospital	16 (7.1)	6 (6.6)
Security Forces Hospital	11 (4.9)	3 (3.3)
John Hopkins/Aramco Hospital	4 (1.8)	0
Royal Commission Hospital	1 (0.4)	0
Private Hospital	27 (12.1)	10 (11)
I understand the term "inflicted injury" or "physical abuse" or "non-accidental injury" in children?		
Strongly disagree	10 (4.5)	2 (2.2)
Disagree	23 (10.3)	3 (3.3)
Neutral	37 (16.5)	1 (1.1)
Agree	106 (47.3)	31 (34.1)
Strongly agree	48 (21.4)	54 (59.3)
$(P<0.001)^*$		
Does your practice cover imaging of paediatric patients (children 0 to 18 years)?		
Yes	206 (92.0)	76 (83.5)
No	18 (8.0)	15 (16.5)
If you answered "Yes", then approximately how many children with suspected physical abuse do you image/report per year? ^a		
1 - 10	138/206 (66.9)	43/76 (56.5)
11 - 20	37/206 (17.9)	21/76 (27.6)
21 - 30	13/206 (6.3)	4/76 (5.2)
31 - 40	4/206 (2.0)	0
41 - 50	4/206 (2.0)	1/76 (1.3)
51- 60	0	1/76 (1.3)
61 - 70	2/206 (1)	0
71 - 80	1/206 (0.5)	0
81-90	0	0
91-100	0	0
> 100	3/206 (1.4)	2/76 (2.6)
Blank	4/206 (2)	4/76 (5.3)
If you answered "Yes", which guidelines are you aware of? ^b		
ACR-SPR	21/31 (67.8)	29/36 (80.6)
RCR-SCoR	6/31 (19.3)	4/36 (11.1)
ACR-SPR and RCR-SCoR	4/31 (12.9)	3/36 (8.3)
Others	0/31	0/36

If you answered "Yes", did the training discuss child injuries related to suspected physical abuse? ^c		
Yes	19/59 (32.2)	NA
No	38/59 (64.4)	
Blank	2/59 (3.4)	
What type of training did you receive? ^d		
International conference and/or course and/or workshop	4/59 (6.8)	8/18 (44.4)
Local conference and/or course and/or workshop	37/59 (62.7)	6/18 (33.3)
Other: clinical fellowship	1/59 (1.7)	0
Other: verbal from the seniors	1/59 (1.7)	0
Other: workplace mentoring	1/59 (1.7)	0
Others: sessions during the residency	N/A	2/18 (11.1)
Blank	15/59 (25.4)	2/18 (11.1)
If you answered "Yes" – what is the protocol? ^e		
Ap & lateral skull including cervical spine, ap chest, abdomen & pelvis including thoracolumbar spine, lateral thoracolumbar spine, AP both upper limbs, bilateral both lower limbs, both feet, both hands”		
Child abuse skeletal x-survey and some cases need CT and MRI”		
CXR and skull		
Images for each limb + skull + chest + abdomen + pelvis + spine		
Skeletal survey, CT MRI brain		
Skeletal survey, CT scan head and abdominal US		
Skeletal survey		
Skeletal x ray. Abdominal ultrasound		
Two views for each organ skull spine chest and one view for pelvis upper and lower limbs		
Xray skull limbs abdomen chest		
Ap & lateral brain, Ap & lateral chest, two views of extremity		
skeletal survey one exposure only for the whole skeleton		

* Denotes statistical significance ($p < 0.05$)

^a For those who answered "Yes" to the following question "Does your practice cover imaging of paediatric patients (children 0 to 18 years)?"

^b For those who answered "Yes" to the following question "Are you aware of the international guidelines for imaging children with suspected physical abuse?"

^c For radiologic technologists who answered "Yes" to the following question "Have you received training (i.e., courses, workshops, workplace mentoring, etc) in paediatric radiology?"

^d For radiologic technologists and radiologists who answered "Yes" to the following question "Have you received training (i.e. courses, workshops, workplace mentoring, etc) in paediatric radiology?" and "Have you received training (i.e. courses, workshops, etc) in evaluating injury in children related to suspected physical abuse?", respectively.

^e For radiologic technologists and radiologists who answered "Yes" to the following question "Is there an imaging protocol (i.e., skeletal survey) in your hospital for children below 2 years' old with suspected physical abuse?"

8.8 Appendix 8: The email was sent to the ESPR Child Abuse Taskforce to collect eligible cases and recruit observers for the RECEPTOR study (Chapter Four)



Nasser M Alzahrani <nmalzahrani1@sheffield.ac.uk>

Fwd: ESPR Child abuse taskforce: Role of CT in detecting rib fractures in children

8 February 2021 at 19:17

From: ESPR Office <office@espr.org>

Sent: 21 January 2021 14:12

To: OFFIAH, Amaka (SHEFFIELD CHILDREN'S NHS FOUNDATION TRUST)
<amaka.offiah@nhs.net>

Subject: ESPR Child abuse taskforce: Role of CT in detecting rib fractures in children

Dear All,

I hope you are doing well and wish you the best for 2021.

I am writing with regard to a multicenter retrospective study we are conducting that aims to assess the diagnostic accuracy of computed tomography (CT) in the detection of rib fractures in children investigated for suspected physical abuse.

We aim to obtain the relevant images of 108 children who have received chest CT examinations and initial and follow-up (AP and both oblique) chest radiographs as part of skeletal surveys for suspected abuse.

We would appreciate it if, in the first instance, you could respond to the questions here:
<https://forms.gle/czT6CVCPJwMhEovQ7>.

Further details including study protocol will be sent to all those who show an interest.

Your level of contribution to the project will determine your authorship or acknowledgement status on all related publications.

Deadline for submission of responses is January 31st 2021.

Thank you and best wishes,
Professor Amaka C Offiah
Chair, ESPR Child Abuse Task Force

European Society of Paediatric Radiology – ESPR
Society Management

ESPR Office: [Am Gestade 1, 1010 Vienna, Austria](#)
Phone: +43 1 5334064-921
mail: office@espr.org
web: www.espr.org

8.9 Appendix 9: Publications arising during PhD course

8.9.1 Paper 1 - published in European Radiology, 2021. DOI: <https://doi.org/10.1007/s00330-021-07775-3>

European Radiology
<https://doi.org/10.1007/s00330-021-07775-3>

PAEDIATRIC



The diagnostic performance of chest computed tomography in the detection of rib fractures in children investigated for suspected physical abuse: a systematic review and meta-analysis

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Abstract

Objectives To assess the diagnostic performance of chest CT in the detection of rib fractures in children investigated for suspected physical abuse (SPA).

Methods Medline, Web of Science and Cochrane databases were searched from January 1980 to April 2020. The QUADAS-2 tool was used to assess the quality of the eligible English-only studies following which a formal narrative synthesis was constructed. Studies reporting true-positive, false-positive, true-negative, and false-negative results were included in the meta-analysis. Overall sensitivity and specificity of chest CT for rib fracture detection were calculated, irrespective of fracture location, and were pooled using a univariate random-effects meta-analysis. The diagnostic accuracy of specific locations along the rib arc (anterior, lateral or posterior) was assessed separately.

Results Of 242 identified studies, 4 met the inclusion criteria. Of these, 2 were included in the meta-analysis. Chest CT identified 142 rib fractures compared to 79 detected by initial skeletal survey chest radiographs in live children with SPA. Post-mortem CT (PMCT) has low sensitivity (34%) but high specificity (99%) in the detection of rib fractures when compared to the autopsy reference standard. PMCT has low sensitivity (45%, 21% and 42%) but high specificity (99%, 97% and 99%) at anterior, lateral and posterior rib locations, respectively.

Conclusions Chest CT detects more rib fractures than initial skeletal survey chest radiographs in live children with SPA. PMCT has low sensitivity but high specificity for detecting rib fractures in children investigated for SPA.

Key Points

- PMCT has low sensitivity (34%) but high specificity (99%) in the detection of rib fractures; extrapolation to CT in live children is difficult.
- No studies have compared chest CT with the current accepted practice of initial and follow-up skeletal survey chest radiographs in the detection of rib fractures in live children investigated for SPA.

Keywords Systematic review · Tomography, X-ray computed · Child abuse · Rib fracture · Physical abuse

Abbreviations

3D	Three-dimensional
ACR	American College of Radiology
ALARA	As low as reasonably achievable

CI	Confidence interval
CXR	Chest radiographs
ESPR	European Society of Paediatric Radiology
FN	False negative

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Springer

FP	False positive
LDCT	Low-dose computed tomography
MDCT	Multidetector computed tomography
mSv	millisievert
NPV	Negative predictive value
PMCT	Post-mortem CT
PPV	Positive predictive value
PRISMA	Preferred Reporting Items for Systematic Review and Meta-Analysis
QUADAS-2	Quality Assessment of Diagnostic Accuracy Studies 2
RCPCH	Royal College of Paediatrics and Child Health
RCR	Royal College of Radiologists
SCoR	Society and College of Radiographers
SkS	Skeletal survey
SPA	Suspected physical abuse
SPR	Society for Pediatric Radiology
TN	True negative
TP	True positive

Introduction

Physical child abuse is one of the leading causes of child morbidity and mortality worldwide [1, 2]. Physical abuse is defined by the World Health Organization as “acts that cause actual physical harm or have the potential for harm” [3]. In 2013, the prevalence of physical child abuse in the European Region was approximately 23% (44 million children) [4]. Physical abuse is more common in children aged less than 2 years [5, 6], in particular children less than 12 months, who are typically pre-ambulant (those who will typically go on to walk in the future) or non-ambulant (those who will never walk, e.g. wheelchair-bound) who are unable to localise their pain or communicate a history of injury [6, 7].

Following cutaneous injuries, fractures are the second most common finding associated with physical abuse [8]. Rib fractures are strongly associated with physical abuse in infants and young children [9–12] with positive predictive values (PPVs) of 95% and 66% in children under 3 [13] and 4 years of age [14], respectively. Rib fractures are uncommon following accidental trauma in children under the age of 3 years due to the plastic nature of the thoracic cage in this age group [13, 15].

Radiological imaging is an essential tool in the investigation of suspected physical abuse (SPA) in children where the history provided is considered to be inconclusive or incongruent with the clinical examination [16]. International guidelines for skeletal surveys (SkS) have been published by the American College of Radiology (ACR) and the Society for Pediatric Radiology (SPR) [17]; and the Royal College of Radiologists (RCR) and the Society of College of Radiographers (SCoR) endorsed by Royal College of

Paediatrics and Child Health (RCPCH) [18], recognised by the European Society of Paediatric Radiology (ESPR) as the gold standard for the investigation of SPA across Europe [19].

These guidelines state that chest radiography is the standard imaging modality employed in the evaluation of the thorax in children suspected of having been physically abused [17, 18]. However, initial chest radiographs (CXR) are often unable to detect acute, non-displaced and incomplete rib fractures [20]. Sanchez et al [21] found that 17% of rib fractures studied (total 105 fractures) in cases of SPA were not visualised on CXR. Recent studies have shown that oblique projections of the thorax have improved the detection of rib fractures in SPA [22–24], both on initial (acute) and follow-up (healing) SkS. However, even with additional oblique views of the thorax, acute rib fractures are often difficult to detect [6, 25] due to fracture lines potentially being masked by overlying lung and vascular markings [26, 27], in addition to being superimposed over other anatomical structures [20]. The rationale behind the inclusion of the CXR as part of the follow-up SkS 11–14 days after the initial SkS relates to the formation of callus associated with rib fracture healing [7], thereby increasing their conspicuity and improving the detection of those fractures not visualised on the initial SkS [28–30].

It has been shown that chest computed tomography (CT) improves the detection of acute and healing rib fractures in live [31] and post-mortem (PM) children [26]. Unlike CXR, chest CT can more accurately diagnose acute rib fractures and could offer immediate evidence of inflicted injury. The use of chest CT may avoid follow-up CXR at possibly comparable radiation doses [21, 32].

We systematically reviewed the available evidence concerning the diagnostic performance of chest CT in the detection of rib fractures in live and post-mortem children with suspected or confirmed physical abuse in comparison to the established reference standard of CXR and/or autopsy. The primary objective was to evaluate whether the diagnostic performance of chest CT is comparable to other established standard methods of diagnosing rib fractures in children with SPA. The second objective was to assess the diagnostic accuracy (sensitivity and specificity) of chest CT in the detection of rib fractures at different anatomical locations (anterior, lateral and posterior) along the rib arc.

Methods

The study protocol for this systematic review was registered on PROSPERO (registration number: CRD42020179550) and the study was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement guidelines [33].

Data sources and searches

Medline, Web of Science and Cochrane databases were searched for eligible articles published in English between January 1980 and April 2020. The search strategy and terms used are provided in the [Electronic Supplementary Material](#). The reference lists of all included articles were searched for additional articles not captured in the initial search.

Study selection

Study inclusion and exclusion criteria were developed based on population, intervention, comparator and outcomes (PICO) criteria:

- P: Children (0–18 years [34]) with suspected or known rib fractures resulting from confirmed or SPA
- I: Chest CT imaging
- C: CXR and/or autopsy
- O: Diagnostic accuracy of CT in the detection of rib fractures in children resulting from confirmed or SPA

Studies satisfying the following criteria were included: (1) study participants aged up to 18 years old with suspected or known rib fractures resulting from physical abuse; (2) chest CT used as a diagnostic tool to detect rib fractures; (3) the diagnostic performance of chest CT compared to the reference standards of either CXR and/or autopsy was reported; (4) for meta-analysis, the absolute numbers of true positives (TP), true negatives (TN), false positives (FP), and false negatives (FN) were reported or could be derived to calculate sensitivity and specificity. We excluded (1) studies performed on animals and/or phantoms; (2) studies where the manuscript body was not in English; (3) case reports, review articles, editorial/comment papers and abstracts of conference meetings. Following the removal of duplicates, study titles and abstracts were screened by one reviewer (N.M.A.). Full-text screening of potentially eligible studies was then performed to further confirm eligibility. A consensus opinion was sought by two reviewers (A.J. and A.C.O.) to resolve any uncertainties.

Data extraction and quality assessment

Data were extracted from the eligible studies using a predesigned data collection form which included author; publication year; study design; sample size and number of ribs reviewed; mean age; reference test; CT imaging protocol; the time interval between the reference standard and CT imaging and the study primary outcome. For this systematic review, the acceptable time intervals between the index test (chest CT) and the reference standards were ≤ 48 h (CXR) and/or ≤ 1 week (autopsy). For meta-analyses, TP, TN, FP and FN were derived and pooled from the

included studies to assess the diagnostic performance of chest CT. Four reviewers (N.M.A., A.J., M.P., A.C.O.) independently assessed the quality of the included studies using the Quality Assessment of Diagnostic Accuracy Studies 2 (QUADAS-2) tool [35]. Discrepancies between reviewers were resolved by consensus.

Data synthesis and analysis

We performed a formal narrative synthesis of the findings from the eligible studies which included a summary of the study characteristics and outcome measures regarding the diagnostic performance of chest CT. To perform a meta-analysis, summary measures of TP, FP, TN and FN rates were calculated for individual studies to express the diagnostic performance of chest CT imaging in terms of sensitivity, specificity, positive predictive value (PPV) and negative predictive value (NPV) with respect to the detection of rib fractures. To assess the overall diagnostic performance of chest CT against the reference standards, the diagnostic accuracy measures reported for all rib fractures in each study were pooled with those that utilised the same reference standard. Separately, to assess the diagnostic accuracy of chest CT in the detection of rib fractures based on specific locations along the rib arc (anterior, lateral and posterior), the diagnostic accuracy measures reported in studies were pooled with those using the same reference standard for each location. A meta-analysis was performed when at least two studies met the criteria.

Forest plots estimating the sensitivity and specificity with 95% confidence intervals (CIs) were created using a univariate random-effects model. Moreover, a receiver operator characteristic (ROC) curve was generated to calculate the area under the curve (AUC).

Heterogeneity between studies included in the meta-analysis was assessed using the I^2 statistic with heterogeneity categorised by low (0–40%), moderate (50–75%), and high (> 75%) [36]. Meta-analyses were performed using STATA 14 package metandi (STATA Corporation).

Results

Search strategy

Of 242 articles identified, 42 duplicates and 178 articles were excluded on the basis of title and abstract. Of the 22 full-text articles extracted, 18 did not fulfil the inclusion criteria. The remaining 4 articles were included for qualitative synthesis. Of these, two studies [21, 31] were excluded from the meta-analysis because the TP, TN, FP and FN values were not reported or could not be derived.

Figure 1 illustrates the search strategy and study selection process.

Study characteristics and quality assessment

The characteristics and main findings of the included studies are summarised in Table 1. These observational retrospective studies included a total of 109 children. The mean age per study ranged from 2.5 to 12 months, with a mean age of 6 months across all studies. The reference standards against which chest CT was compared were CXR from initial SkS in two studies (time interval 1 day) and autopsy in the remaining two (time interval 0 to 5 days, median 2 days). The tube voltage (kilovolts, kV) and current (milliamperes, mA) settings for chest post-mortem CT (PMCT) were 120 kV and 200–355 mA and 100 kV and 15 mA in live children, respectively.

Table 2 summarises the results of the quality assessment of the 4 included studies. In the patient selection domain, three studies [21, 25, 31] were assessed as having an unclear risk of bias due to poor sampling procedure reporting. One study [21] was scored as having an unclear risk of bias in the index test

domain as it was unclear whether the chest CT results were interpreted without knowledge of reference standard results. In the reference standard domain, two studies [21, 26] were judged as having an unclear risk of bias because they did not offer information on whether the reference standard was interpreted without knowledge of the results of the index test. Regarding applicability concerns, one study [21] had a high risk of concern in the index test domain because chest CT was only performed in children with normal initial CXR: this affects the diagnostic accuracy as all children with positive and negative initial CXR were supposed to have chest CT. Additionally, one study [31] had an unclear risk of concern in the patient selection domain because information about the clinical indication for patients who underwent CT examinations was not provided.

Diagnostic performance of chest CT

Two retrospective studies [21, 31] demonstrated superior diagnostic accuracy of chest CT in the detection of rib fractures compared to initial CXR. Sanchez et al [21] reported that chest

Fig. 1 Flowchart of the study selection process

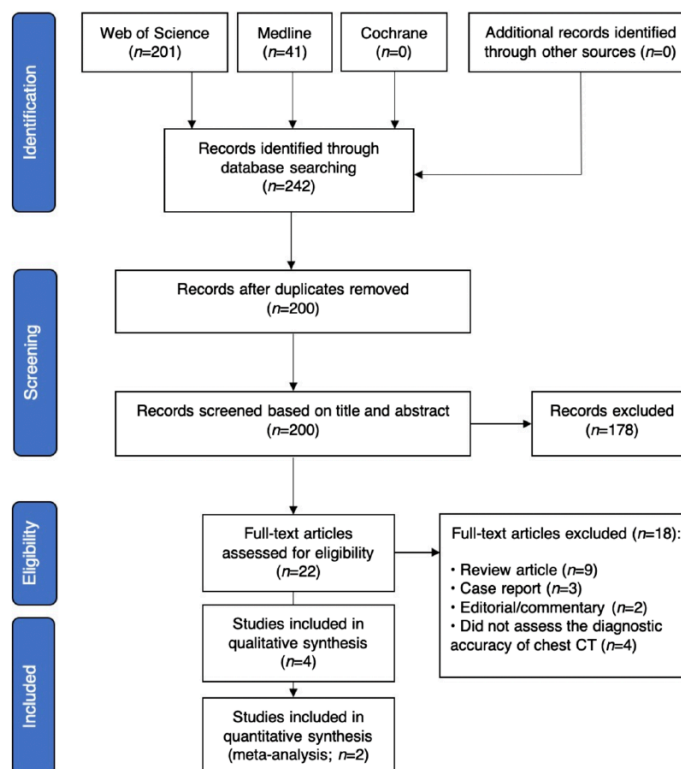


Table 1 Characteristics and main findings of the included studies

Study	1	2	3	4
Author (year) Study design (recruitment start and end dates)	Wootton-Gorges et al (2008) [31] Retrospective (between 1999 and 2004)	Hong et al (2011) [26] Retrospective (between January 2007 and October 2009)	Sanchez et al (2018) [21] Retrospective (between January 2008 and January 2012)	Shelmerdine et al (2018) [25] Retrospective (between January 2012 and January 2017)
Sample size/number of reviewed ribs	12/225 ribs	56/1318 ribs reviewed at primary (clinical) interpretation and 298 ribs reviewed at research radiologist's interpretation	16 (only 5 of whom had both CXR and chest CT) / Not reported	25/600 ribs (12 pairs of ribs in 25 children)
Mean age (range)	Mean age 2.5 months (1.2 to 5.6 months)	Mean age 12 months (8 days to ~93 months); 46 children < 24 months)	Mean age 6 months (1 to 11 months)	Median age 4 months (17 days to 7 years)
Reference test	Initial CXR (AP and lateral projections)	Autopsy	Initial CXR (AP, lateral, right and left oblique projections)	Autopsy
CT imaging protocol	Not reported	- Either 8 multi-slice helical CT (GE), 128-slice MDCT (GE) or 16-slice CT (Philips) 120 kV, 320 and 355 mA, 0.53 and 0.93 mm pitch, rotation time 0.75 and 0.80 s - Slice thickness reconstruction 0.80–0.62 mm 3D reconstruction	100 kV, 15 mA, 1 mm pitch, rotation time 0.5 s - Adaptive iterative reconstruction blend of 20%	64-slice MDCT (Siemens) - Collimation 0.62 mm 120 kV, 200–350 mA, 1 mm pitch - Slice thickness reconstruction (1 mm)
Time interval between the reference standard and CT imaging	1 day	Not reported	1 day	Median 2 days (range 0 to 5 days)
The study primary outcome	- Chest CT = 131 rib fractures - CXR = 79 rib fractures - CT more sensitive in the detection of rib fractures based upon anatomical position than CXR in the detection of rib fractures at all anatomical positions ($p < 0.01$), except in lateral location - Two radiologists reviewed the chest CT studies	101 rib fractures at autopsy (standard) - Two image interpretation methods were used for the detection of rib fractures by fracture locations: A. Primary (clinical) interpretation—chest CT showed sensitivity 51.5% and specificity 99.7% for detecting rib fractures by fracture locations B. Radiologist interpretation = 13 children: 12 with rib fractures at autopsy and 1 false positive at chest radiograph primary interpretation; chest CT showed sensitivity 85.1% and specificity 99.4% for detecting rib fractures by fracture locations - Two radiologists reviewed chest CT (3 studies reviewed by one radiologist) at primary (clinical) interpretation; radiologist interpretation performed by one radiologist only	- Chest CT = 11 rib fractures all missed on initial CXR 7 rib fractures identified on follow-up† CXR (1–2 weeks) in patients who did not have chest CT - The number of radiologists who reviewed chest CT was not reported	136 rib fractures at autopsy (standard) - Chest CT for detection of rib fractures: - at specified locations=sensitivity 44.9% and specificity 97% - PM CXR for detection of rib fractures: - at specified locations=sensitivity 13.5% and specificity 97.9%; the sensitivity and specificity of PM CXR at specific locations along rib arc was 15% and 97% at anterior, 0.8% and 98% at lateral, 27% and 98% at posterior, respectively - Thirty-five radiologists reviewed the CT chest studies and thirty-eight reviewed the CXR studies

*The location of the rib fractures was divided into three segments: anterior fracture includes costochondral, anterior and anterolateral; posterior fracture includes costovertebral, posterior and posterolateral; and lateral. Calculated as follows [anterior = (anterior + anterolateral) / 2]

† Follow-up skeletal survey

3D, three-dimensional; AP, anteroposterior; CT, computed tomography; CXR, chest radiographs; GE, General Electric; kV, kilovolts; mA, milliamperes; MDCT, multidetector computed tomography; mm, millimeter; PM, post-mortem; s, seconds

Table 2 Quality assessment of included studies

Study	Risk of bias				Applicability concerns		
	Patient selection	Index test	Reference standard	Flow and timing	Patient selection	Index test	Reference standard
Hong et al [26]	1	1	2	1	1	1	1
Sanchez et al [21]	2	2	2	1	1	3	1
Shelmerdine et al [25]	2	1	1	1	1	1	1
Wootton-Gorges et al [31]	2	1	1	1	2	1	1

Low risk = 1; unclear risk = 2; high risk = 3

CT detected 11 rib fractures that were missed on initial CXR. Wootton-Gorges et al [31] observed 131 rib fractures on chest CT compared to 79 on CXR. Additionally, Wootton-Gorges et al [31] reported that chest CT performed better in detecting rib fractures along the rib arc ($p < 0.01$), except for lateral locations.

The retrospective studies by Hong et al [26] and Shelmerdine et al [25] compared the diagnostic accuracy of chest CT to autopsy in the detection of rib fractures. Chest CT reported sensitivity (51.5% and 44.9%, respectively) and specificity (99.7% and 97.0%, respectively) in the detection of rib fractures at specific locations. Hong et al [26] noted that the sensitivity for detecting rib fractures at specific locations increased from 51.5% at primary (clinical) interpretation to 85.1% following radiologist interpretation.

We grouped two studies ($n = 81$ children) regarding the diagnostic performance of chest CT as compared to autopsy in the detection of rib fractures: Table 3 presents the sensitivity and specificity of chest CT. Forest plots for overall chest CT diagnostic performance demonstrated sensitivity 34% (95% CI 18–55%) and specificity 99% (95% CI 94–100%) (Fig. 2) and PPV 95% (95% CI 91–100%), NPV 59% (95% CI 58–61%) and AUC 79% (95% CI 75–82%). Significant heterogeneity existed for both sensitivity and specificity ($P = 99\%$). The pooled diagnostic sensitivity and specificity of chest CT in the detection of rib fractures along the rib arc were 45% and 99% at anterior locations, 21% and 99% at lateral locations and 42% and 97% at posterior locations, respectively.

Discussion

This systematic review and meta-analysis provides an overview of the diagnostic performance of chest CT in the detection of rib fractures in children with SPA. This study demonstrates that chest CT detects more rib fractures than initial CXR. The overall diagnostic performance of PMCT is 34% sensitivity and 99% specificity in the detection of rib fractures

when compared to autopsy, whilst PM CXR showed a sensitivity of 13.5% and 28% and specificity of 97% and 99% [25, 26]. Overall, PMCT exhibited the lowest sensitivity for lateral rib fracture locations, with sensitivities of 45%, 21% and 42% at anterior, lateral and posterior locations, respectively. The diagnostic performance of PM CXR at specific rib fracture locations reported in two of the included studies [25, 26] was sensitivity: 8% and 15.8% at anterior, 80% and 0.8% at lateral and 29% and 27% at posterior rib fracture locations, respectively. PM CXR pooled sensitivities, specificities and meta-analyses were not performed due to the different projections obtained in the included studies: 3 projections (AP, right and left obliques) were utilised by Shelmerdine et al [25] whereas only 2 projections (AP and lateral) were used by Hong et al [26]. It has been reported by Hong et al [26] that PM CXR missed 42 anterior rib fractures whilst 27 anterior rib fractures were missed on CT in children who underwent cardiopulmonary resuscitation.

Notably, chest CT detected more rib fractures than initial CXR in abused live children. In 2 studies, chest CT identified 142 rib fractures compared to 79 detected by initial CXR [21, 31]. This is because CT provides high-resolution cross-sectional images of the thoracic cage with volumetric and multi-planar reconstructions [37] eliminating the contributing factors which obscure rib fractures on CXR; in particular, acute and/or non-displaced fracture where callus formation, indicative of healing, is not present [7].

The overall low sensitivity (34%) and high specificity (99%) of PMCT in this systematic review are consistent with the results of a study validating PMCT against autopsy in the detection of rib fractures in adults (low sensitivity of 58% and high specificity of 97%) [38]. A possible explanation of this low sensitivity is that PMCT may not accurately detect reattached rib fracture edges on autopsy [38]. Moreover, autopsy is not a perfect reference standard due to its fallibility with respect to partial rib fractures which are more easily detected by PMCT [38]. Interestingly, Hong et al [26] observed that PMCT sensitivity increases from 51.1% at primary (clinical) interpretation to 85.1% at radiologist interpretation: not an

Table 3 Diagnostic performance measures (sensitivity and specificity) of chest CT in the detection rib fractures

Study	Reference test	Fracture location along rib arc*	Number of ribs included in analysis	Number of observations	Number of rib fractures identified by the reference test	TP	TN	FP	FN	Sensitivity %	Specificity %
Hong et al [26]	Autopsy	Anterior			49	16	2587	3	33	33	100
		Lateral	1318	N/A	5	0	1313	3	5	0	100
		Posterior			47	36	2589	12	11	77	100
Shelmerdine et al [25]	Autopsy	Anterior			111	1769	15 783	1332	2116	46	92
		Lateral	600	21 000 [†]	10	164	19 574	901	361	31	96
		Posterior			15	164	6479	1081	1011	14	86

*The location of the rib fractures was divided into three segments: anterior fracture includes = costochondral, anterior and anterolateral; posterior fracture includes = costovertebral, posterior and posterolateral; and lateral

[†] Calculated as 25 cases $\times$ 24 ribs $\times$ 35 reporters

FN, false negative; FP, false positive; N/A, not applicable; TN, true negative; TP, true positive

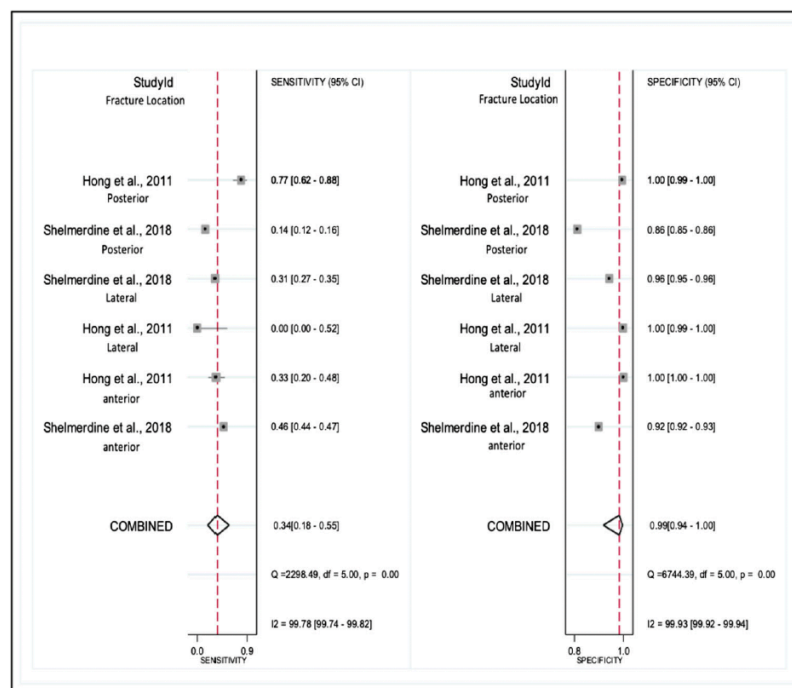
unexpected result given that the interpretation was performed by an experienced radiologist (22 years' experience). High heterogeneity in reported sensitivity and specificity was observed among the included studies which could be secondary to the differences in radiologists' experience and the imaging protocols employed.

Concerns regarding the relatively high radiation exposure have traditionally made chest CT a less desirable option in the routine clinical investigation of SPA in live children [39]. It is well-documented that children are more vulnerable to the effects of ionising radiation and potential future risk of radiation-induced cancer than adults, in addition to a greater time over which the consequences of radiation exposure may be borne out [40–43]. However, adjusting the scanning parameters (e.g. mA, kV and pitch) and the use of iterative reconstruction reduces the radiation dose and the consequent potential risk and concerns regarding radiation-induced cancers [44, 45]. Recently, a developed low-dose chest CT (LDCT) protocol for the detection of rib fractures in children with SPA employed radiation doses approaching those of standard CXR without compromising diagnostic quality [21, 32].

The risk of exposure to ionising radiation in the case of chest CT should be balanced against the risk of missed diagnoses of physical child abuse, in particular, missing occult acute rib fractures on initial SkS CXR [21]. Given that follow-up SkS imaging is not guaranteed (as children are reliant on their caregiver/parent to return them to the hospital for follow-up imaging), children may remain in an abusive environment, which risks sustaining a further, potentially fatal, injury [46]. Chest CT demonstrates a higher sensitivity in the detection of acute rib fractures in live children who may have been abused, thus potentially rendering the follow-up SkS CXR redundant. Moreover, this would result in an overall reduction in radiation burden if LDCT protocols are utilised and may facilitate more prompt and appropriate management in cases of child protection.

This study has several limitations. First, a small number of studies ($n = 2$) were included in the meta-analysis which is insufficient to accurately evaluate the diagnostic performance of PMCT in the detection of rib fractures. Therefore, the results of the meta-analysis should be interpreted cautiously. Notably, the results of this meta-analysis should be restricted to the diagnostic performance of chest CT in PM children. The image quality of chest PMCT examinations may be higher than in live children (given that dose restrictions are not a consideration) which may increase its diagnostic accuracy. Second, all included studies were retrospective. Third, whilst the reference standards used to assess the accuracy of the chest CT in the detection of rib fractures and skill of the radiologist reading them are those used in current clinical practice, they themselves are imperfect. Fourth, although physical abuse is not common over the age of 2 years, our search criteria included participant age up to 18 years to ensure that we

Fig. 2 Forest plot of the overall sensitivity and specificity with 95% confidence intervals of chest CT in the detection of rib fractures



captured all relevant papers. In total, 13 children (11.9%) were over the age of 2 years, with a mean age of 6 months across all 4 papers; therefore, we believe the results of this review are applicable to cases of SPA. Finally, this systematic review might be prone to publication bias given that the literature search was restricted to English language studies only.

Although chest CT shows promising results in the detection of acute and healing rib fractures, further research is required to better elucidate its diagnostic performance. Ideally, the diagnostic accuracy of chest CT (compared to a reference standard of initial and follow-up CXR from SkS) should be evaluated in a prospective study with a large cohort of live children. Additionally, to adhere to the ALARA principle, evaluation of a LDCT chest protocol to reduce exposure to ionising radiation could be conducted prior to formal implementation in clinical practice.

In conclusion, the diagnostic performance of chest CT for detecting rib fractures in children suspected of having been physically abused has not previously been systematically evaluated in the literature. Chest CT detects more rib fractures than initial CXR in children with SPA. PMCT has a low sensitivity but high specificity for

detecting rib fractures (especially in lateral locations) compared to autopsy.

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Declarations

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Statistics and biometry Farag Shuweihdi is a research fellow and a Medical Statistician at the Leeds Institute of Health Sciences, University of Leeds, Leeds.

Informed consent Written informed consent was not required for this systematic review and meta-analysis.

Ethical approval Institutional Review Board approval was not required for this systematic review and meta-analysis.

Methodology

- Systematic review
- Meta-analysis

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Professional practice and awareness of child abuse among radiologists and radiologic technologists: results from Saudi Arabia

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Abstract

Background The knowledge, awareness and professionalism of health care providers in the field of child protection are crucial in identifying and reporting suspected child abuse. Radiologic technologists and radiologists play a vital role in the diagnosis of suspected physical child abuse.

Objective To assess current practice, knowledge and awareness of child abuse among radiologic technologists and radiologists in Saudi Arabia.

Materials and methods We distributed an internet-based questionnaire to radiologic technologists and radiologists working in Saudi Arabia via national radiology societies and social media channels over a 6-week period (27 October to 8 December 2021). Survey questions covered knowledge regarding child abuse, professional practice in radiology departments in Saudi Arabia in cases of suspected physical abuse (SPA), and knowledge of the national legislation and reporting and acting procedures in child abuse.

Results A total of 315 respondents (224 radiologic technologists and 91 radiologists) participated in this study. The median score for knowledge of abuse was higher amongst radiologists (4.8) than radiologic technologists (4.0); $P < 0.001$. In total, 210 (93.8%) radiologic technologists and 61 (67.0%) radiologists reported that there was no protocol (i.e. skeletal survey) at their hospital for imaging children with SPA. Most radiologic technologists had no training in paediatric radiology (165/224, 73.7%) and most radiologists had received no training in evaluating imaging performed for SPA (73/91, 80.2%). More than half of respondents — 131 (58.5%) radiologic technologists and 44 (48.4%) radiologists — were not familiar with the reporting and acting procedures at their hospitals in cases of child abuse.

Conclusion Although radiologic technologists and radiologists in Saudi Arabia have good knowledge and awareness of child abuse in general, they lack specific knowledge of the reporting and acting procedures at their hospitals in cases of suspected child abuse. National imaging guidelines and training courses are needed to develop appropriate skills in the recognition, imaging and reporting of SPA in infants and young children in Saudi Arabia.

Keywords Child abuse · Infants · Paediatric radiology · Radiography · Radiologic technologists · Radiologists · Skeletal survey · Survey

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Introduction

Child abuse, a significant worldwide problem with serious long-term consequences, has been defined by the World Health Organization as “every kind of physical, sexual, emotional abuse, neglect or negligent treatment, commercial or other exploitation resulting in actual or potential harm to the child’s health, survival, development or dignity in the context of a relationship of responsibility, trust or power” [1]. Globally, it has been estimated that 1 billion children experience abuse over the course of 1 year [2], which might be underestimated given that abuse can go unreported or be incorrectly reported as other causes of death, such as falls and drowning.

Child abuse recognition is challenging and complex, more so in developing countries because of the perceived lack of awareness of child abuse and lack of institutional legislation on child protection, in addition to societal influences and cultural contexts. In Saudi Arabia, child abuse was not well reported until 1990 because of a lack of awareness amongst health care professionals alongside the belief that reporting might affect reporter job security [3, 4]. In recent decades, Saudi Arabia has worked to improve child welfare by ratifying the United Nations Convention on the Rights of the Child (CRC) [5] and, in 2004, by establishing the National Family Safety Program (NFSP), which is concerned with the prevention of child abuse, neglect and domestic violence [3, 5] and which elaborates on the role of the health care system and the regulations around cases of child abuse. At the time of this writing, the National Health Council, the highest health services authority in Saudi Arabia, had accredited 62 major hospitals as hospital-based child protection centres — hospitals with child protection units that deal with issues relating to safeguarding children and young people [6]. Moreover, health care professionals in Saudi Arabia are now legally obliged to report child abuse [3, 7].

Although paediatricians and general practitioners play a vital role in identifying suspected child abuse, the diagnosis is not straightforward and requires a multidisciplinary team approach. Diagnostic medical imaging is instrumental in the diagnosis of suspected physical abuse (SPA) in infants and young children. As the first health care professionals to view any radiographic imaging obtained, radiologic technologists (health care professionals who are trained and qualified to perform diagnostic imaging examinations using various imaging modalities, also known as radiographers or technicians) play a crucial role in raising the suspicion of SPA to colleagues and radiologists through the identification of the suspicious radiographic findings such as rib and metaphyseal fractures, multiple fractures at different stages of healing [8], and potentially inappropriate interactions

between caregivers and the child [9]. Clinical radiologists (specialist medical doctors who are trained and qualified to interpret and report upon medical imaging to diagnose injuries and diseases) play a pivotal role in SPA through the identification and reporting of acute and healing fractures when physical abuse is not suspected or when injuries are not clinically apparent (occult) or disclosed (e.g., intracranial haemorrhage) [10, 11].

Knowledge, awareness and adequate training of all health care professionals regarding child abuse are crucial to the identification and reporting of suspected cases. Whilst a few studies in the published literature have assessed the knowledge and awareness of interns, medical students, paediatricians and general practitioners in suspected child abuse in Saudi Arabia [4, 7, 12–14], they report that paediatricians [7, 12] and general practitioners [13] have a “satisfactory” knowledge of child abuse. To the best of the authors’ knowledge, a study assessing current practice, knowledge and awareness of radiologists and radiologic technologists in relation to child abuse in Saudi Arabia has not been performed.

Materials and methods

We obtained ethics approval from the University of Sheffield Research Ethics Committee before commencing data collection.

Survey development

We created an online survey using the Google Forms web-based platform (Mountain View, CA). There were two groups of study participants: radiologic technologists and radiologists. The survey included 22 open and 26 closed questions for radiologic technologists (Online Supplementary Material 1) and radiologists (Online Supplementary Material 2), respectively. All responses were anonymised. No personal identifiable information was collected.

Prior to conducting the survey, we undertook a pilot study with seven radiologic technologists and five radiologists and made minor changes based on this initial participant feedback (regarding question wording). The survey comprised four sections. The first section related to demographic and job information. The second assessed child abuse knowledge, including the recognition of abusive acts towards children, risk factors for child abuse [15, 16] and comprehension of the various terms used when describing physical child abuse. The third section of the survey investigated professional practice in dealing with SPA in radiology departments in Saudi Arabia. The final section assessed knowledge

regarding national legislation and reporting procedures and actions in child abuse.

Survey distribution

We distributed the survey to the membership of national radiology societies in Saudi Arabia, including the Saudi Society of Medical Radiologic Technology (SSMRT) and the Radiological Society of Saudi Arabia (RSSA), via email and social media channels. Additionally, the Saudi Commission for Health Specialties (SCFHS), a national official scientific commission that regulates health care-related practices in Saudi Arabia, sent a participation email invitation to all radiologic technologists and radiologists registered on the SCFHS database. Furthermore, the survey was circulated via the professional network of the first author (snowball sampling) and social media channels (Twitter and established WhatsApp and Telegram groups of radiologic technologists and radiologists working in Saudi Arabia). We collected responses over a 6-week period (27 October to 8 December 2021), sending two reminder emails/messages at fortnightly intervals to maximise the response rate.

Statistical analysis

Statistical analyses were conducted using SPSS Statistics (v. 27; IBM, Armonk, NY) and R software (v. 4.1.3; The R Foundation, Vienna, Austria) to visualise the data for the 5-point questions. Categorical variables were expressed as counts and percentages. For between comparisons (i.e. radiologic technologists versus radiologists), we used the Mann–Whitney *U* test for ordinal variables and the chi-square test for percentages. $P < 0.05$ was significant.

Results

Respondent demographics

Of the 315 respondents, 224 (71.1%) were radiologic technologists and 91 (28.9%) were radiologists; those from Saudi Arabia (radiologic technologists, 193/224, 86.2%; radiologists 56/91, 61.5%) were represented more than other nationalities. Most participants worked at the Ministry of Health (radiologic technologists, 109/224, 48.7%; radiologists, 51/91, 56.0%; Online Supplementary Material 3). More than half of the radiologic technologists and radiologists worked at general hospitals (142/224, 63.4%, and 56/91, 61.5%, respectively). Most respondents were from the Western province (radiologic technologists, 37.9%, 85/224; radiologists, 48.4%, 44/91), followed by the central province of Saudi Arabia (radiologic technologists, 28.1%, 63/224; radiologists, 18.7%, 17/91).

Most radiologic technologists had completed an undergraduate bachelor's degree as their highest level of educational attainment (142/224, 63.4%), with 34.4% (77/224) reporting less than 5 years of clinical experience and 38.4% (86/224) reporting 5–10 years of experience. Most radiologic technologists worked in a general department (133/224, 59.4%), followed by CT (34/224, 15.2%), US (21/224, 9.4%), MRI (19/224, 8.5%) and nuclear medicine (7/224, 3.1%).

Consultant radiologists (medical doctors who have completed a postgraduate specialist radiology training programme, which can include subsequent further specialist clinical training in the form of a postgraduate fellowship, allowing them to be registered as a specialist medical practitioner in their home country, with at least 3–5 years post completion of a specialist training programme) represented more than half of the radiologist respondents (52/91, 57.1%). This group was followed by specialist radiologists (medical doctors who have completed a specialist radiology training programme but have not completed the required 3–5 years of experience post specialist training and thus are not yet consultants) at 35/91 (38.5%) and residents at 4/91 (4.4%). Radiologists' reported years of experience were less than 5 years (5/91, 5.5%), 5–10 years (33/91, 36.3%), 11–15 years (32/91, 35.2%) and more than 15 years (21/91, 23.1%). Consultant paediatric radiologists (consultant radiologists with a special interest/fellowship in paediatric radiology) comprised 17.6% (16/91) of the sample, of whom 62.5% (10/16) had 5–10 years of experience. Respondent demographic characteristics and job information are presented in Table 1. Unlike the United Kingdom (UK) and the United States, radiologists in Saudi Arabia need to work for 3–5 years after completing their specialist training/fellowship to become registered as a consultant on the national register. Radiologists can complete the specialist training either overseas or locally (i.e. Saudi Board of Radiology for 4 years).

Knowledge regarding child abuse

We assessed several aspects of knowledge regarding child abuse: recognition of abusive acts towards children, recognition of risk factors for child abuse, and understanding of the various terms relating to physical child abuse. The survey asked participants their thoughts about five abusive acts towards children and their responses are presented in Fig. 1. Although both groups had good knowledge regarding the acts of child abuse, radiologists tended to demonstrate a higher score in all five items compared to radiologic technologists, with median scores of 4.8 and 4.0, respectively ($P < 0.001$).

When asked about risk factors for child abuse, the responses varied among radiologic technologists and radiologists (Fig. 2). More than half of radiologists believed that low socioeconomic status is a risk factor for child abuse (48/91,

Table 1 Demographic and professional characteristics of participants ($n=315$)

Variables	Radiologic technologists ($n=224$)		Radiologists ($n=91$)	
Nationality	n (%)		n (%)	
Saudi	193 (86.2)		56 (61.5)	
Non-Saudi	31 (13.8)		35 (38.5)	
Type of hospital	n (%)		n (%)	
Medical city/speciality hospital	60 (26.8)		34 (37.4)	
General hospital	142 (63.4)		56 (61.5)	
Primary health care centres	22 (9.8)		1 (1.1)	
Region of work	n (%)		n (%)	
Central province	63 (28.1)		17 (18.7)	
Western province	85 (37.9)		44 (48.4)	
Eastern province	21 (9.4)		10 (11.0)	
Southern province	40 (17.9)		14 (15.4)	
Northern province	15 (6.7)		6 (6.6)	
Qualification	n (%)		Job title	n (%)
Diploma	55 (24.6)		Resident radiologist	4 (4.4)
Bachelor	142 (63.4)		Specialist radiologist	35 (38.5)
Master	18 (8.0)		Consultant radiologist	52 (57.1)
PhD or other training certificates (i.e. Board)	9 (4.0)			
Imaging unit mostly covered	n (%)		Specialisation	n (%)
General radiography	133 (59.4)		Paediatric radiologist	16 (17.6)
MRI	19 (8.5)		Non-paediatric radiologist	75 (82.4)
Fluoroscopy	0			
Dental radiography	2 (0.9)			
CT	34 (15.2)			
Mammography	2 (0.9)			
Nuclear medicine	7 (3.1)			
Ultrasound	21 (9.4)			
DEXA	1 (0.4)			
Interventional radiology	5 (2.2)			
Years of experience	n (%)		n (%)	
Less than 5	77 (34.4)		5 (5.5)	
5–10	86 (38.4)		33 (36.3)	
11–15	40 (17.9)		32 (35.2)	
More than 15	21 (9.4)		21 (23.1)	
			Years of experience as paediatric radiologist	$n=16$ (%)
			Less than 5	2 (12.5)
			5–10	10 (62.5)
			11–15	2 (12.5)
			More than 15	2 (12.5)

CT computed tomography, DEXA dual-energy X-ray absorptiometry, MRI magnetic resonance imaging

53.0%) compared to 34.0% (77/224) of radiologic technologists. Similarly, 65.0% (59/91) of radiologists compared to 46.0% (102/224) of radiologic technologists believed that having a parent or caregiver younger than 16 years is a risk factor for child abuse. Radiologists had a greater knowledge of these risk factors compared to radiologic technologists, with median scores of 4.0 and 3.5, respectively ($P<0.001$).

With regard to the understanding of the term *child physical abuse* and its synonyms (inflicted injury and non-accidental injury), radiologic technologists and radiologists demonstrated good and excellent understanding of

the term, respectively (154/224, 68.8% for technologists and 85/91, 93.4% for radiologists), with radiologists having a higher median score compared to radiologic technologists (5.0 and 4.0, respectively; $P<0.001$; Online Supplementary Material 3).

The radiologic practice of imaging children with suspected physical abuse

Of the 335 participants, 92.0% (206/224) of radiologic technologists and 83.5% (76/91) of radiologists reported that

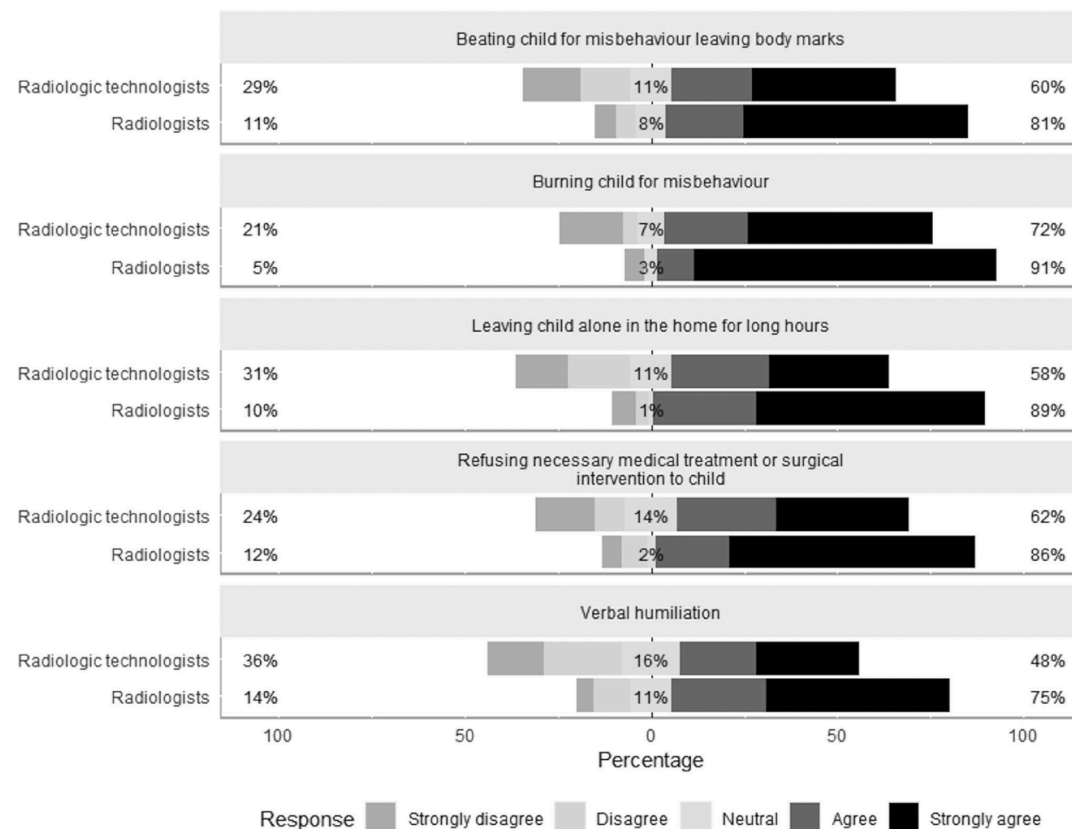


Fig. 1 Level of agreement regarding five proposed forms of child abuse. The percentage of neutral responses is indicated on each bar with the total percentage of disagreement (strongly disagree or dis-

agree) noted at left and the total percentage of agreement (strongly agree or agree) noted at right

their practice covers paediatric patients (Online Supplementary Material 3). Of those, 66.9% (138/206) of radiologic technologists and 56.6% (43/76) of radiologists estimated that they image/report on 1–10 cases of SPA annually (Online Supplementary Material 3).

With regard to protocols, 93.8% (210/224) of radiologic technologists and 67.0% (61/91) of radiologists reported that no skeletal survey protocols existed at their hospital for imaging children for SPA (Table 2). We found great variation in the protocols for imaging children for SPA in Saudi Arabia (Online Supplementary Material 3). Most radiologic technologists (193/224, 86.2%) and more than half of radiologists (55/91, 60.4%) had no awareness of the published international guidelines for imaging children with SPA (Table 2).

Availability of paediatric radiologists was lacking in many hospitals: more than half of radiologists (51/91,

56.0%) reported having no paediatric radiologist at their workplace. Most radiologists said that no radiologist was assigned to report radiologic imaging performed for SPA (79/91, 86.8%) and that there was no double reporting (by at least two radiologists) of such imaging studies at their hospitals (80/91, 87.9%) (Table 2).

On the question of training, most radiologic technologists (165/224, 73.7%) had no training in paediatric radiology (Table 2). Of those radiologic technologists who had received training in paediatric radiology, only 32.2% (19/59) stated that their training discussed injuries relating to SPA (Online Supplementary Material 3). Furthermore, it was much more common for radiologic technologists to attend the national training format in Saudi Arabia (i.e. courses, workshops or conferences) related to paediatric radiology (37/59, 62.7%) as opposed to the international training format (4/59, 6.8%; Online Supplementary

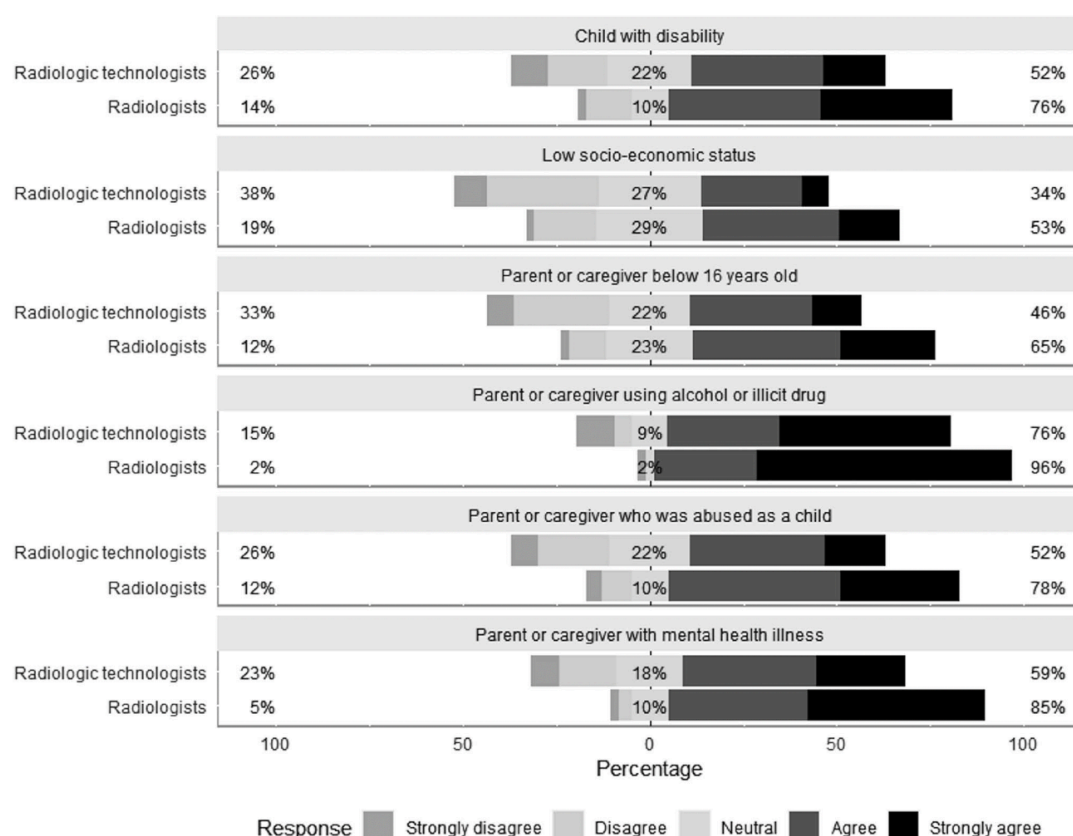


Fig. 2 Level of agreement regarding six proposed risk factors for child abuse. The percentage of neutral responses is indicated on each bar with the total percentage of disagreement (strongly disagree or

disagree) noted at left and the total percentage of agreement (strongly agree or agree) noted at right

Material 3). Finally, 33.5% (75/224) of radiologic technologists responded that they thought they were not competent to be involved with cases of SPA, with most indicating that they required training for such cases (179/224, 80.0%) (Fig. 3).

Among radiologists, most had received no training in evaluating radiologic imaging in children performed for SPA (73/91, 80.2%). Of those radiologists who had received such training, it was slightly more common that they had undertaken the international training format (i.e. courses, workshops or conferences; 8/18, 44.4%) as opposed to the national training format (6/18, 33.3%; Online Supplementary Material 3). Most radiologists were aware of the radiologic patterns of inflicted injury in children (71/91, 78.0%) and more than half of radiologists stated that they were confident to report radiologic imaging performed for SPA

(49/91, 54.0%). However, most radiologists indicated that they required (further) training (67/91, 74.0%) (Fig. 4).

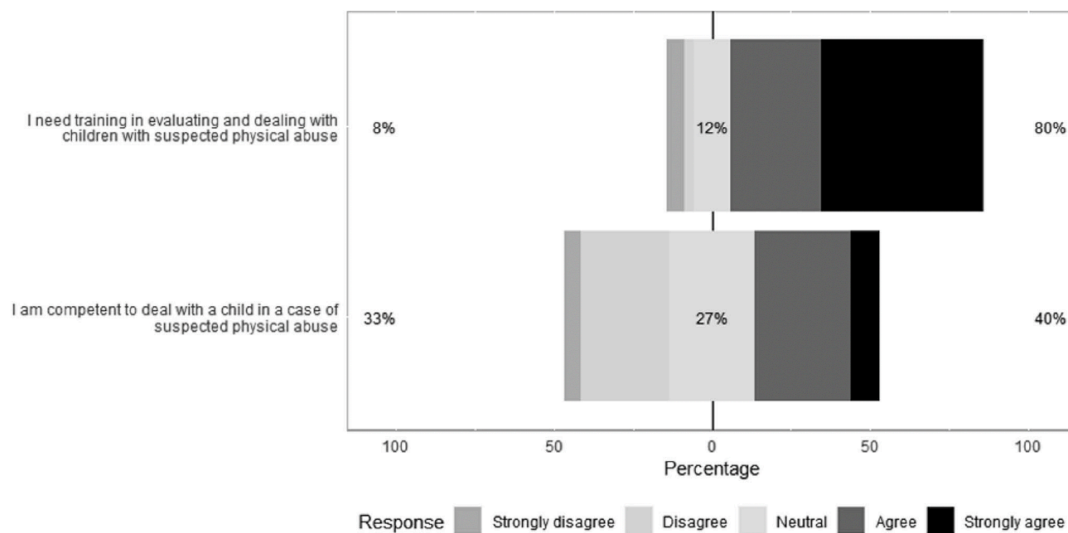
Knowledge of national legislation and reporting and acting procedures in child abuse

The survey asked participants about the NFSP and the local reporting procedures at their hospitals in cases of SPA in children. More than half of radiologic technologists and radiologists were unfamiliar with the NFSP (134/224, 60.0%, and 55/91, 60.0%, respectively), and 58.5% (131/224) of radiologic technologists and 48.4% (44/91) of radiologists were also unfamiliar with the reporting and action procedures at their hospitals in cases of SPA (Fig. 5). Radiologists were more familiar with the legal mandate to report child abuse in Saudi Arabia (69/91,

Table 2 Participants' responses to professional practice regarding imaging children with suspected physical abuse

Questions	Radiologic technologists (<i>n</i> = 224)		Radiologists (<i>n</i> = 91)	
	Yes	No	Yes	No
	<i>n</i> (%)	<i>n</i> (%)	<i>n</i> (%)	<i>n</i> (%)
Is there an imaging protocol (i.e. skeletal survey) at your hospital for children younger than 2 years with suspected physical abuse?	14 (6.3)	210 (93.8)	30 (33.0)	61 (67.0)
Are you aware of the international guidelines for imaging children with suspected physical abuse?	31 (13.8)	193 (86.2)	36 (39.6)	55 (60.4)
Have you received training (i.e. courses, workshops, workplace mentoring, etc.) in paediatric radiology?	59 (26.3)	165 (73.7)	N/A	
Have you received training (i.e. courses, workshops, etc.) in evaluating injury in children related to suspected physical abuse?	N/A		18 (19.8)	73 (80.2)
Is there a paediatric radiologist at your hospital?	N/A		40 (44.0)	51 (56.0)
Is there a named radiologist at your hospital to report cases with suspected abuse?	N/A		12 (13.2)	79 (86.8)
Are the radiologic images of suspected child abuse reported by at least 2 radiologists at your hospital?	N/A		11 (12.1)	80 (87.9)

N/A not applicable

**Fig. 3** Radiologic technologists' opinions regarding their training needs and their confidence in evaluating and dealing with cases of suspected physical abuse. The percentage of neutral responses is indi-

cated on each bar with the total percentage of disagreement (strongly disagree or disagree) noted at left and the total percentage of agreement (strongly agree or agree) noted at right

76.0%) than were radiologic technologists (105/224, 47.0%). Both groups had little knowledge regarding the reporting procedures and actions in cases of child abuse (all forms); however, radiologists demonstrated a slightly higher score than radiologic technologists regarding reporting procedures in cases of SPA (median scores 3.0 compared to 2.7, respectively; $P < 0.002$).

Discussion

This cross-sectional survey assessed the current practice, knowledge and awareness of child abuse amongst radiologists and radiologic technologists in Saudi Arabia. Overall, most survey respondents had a good knowledge of the various forms and risk factors for child abuse. However,

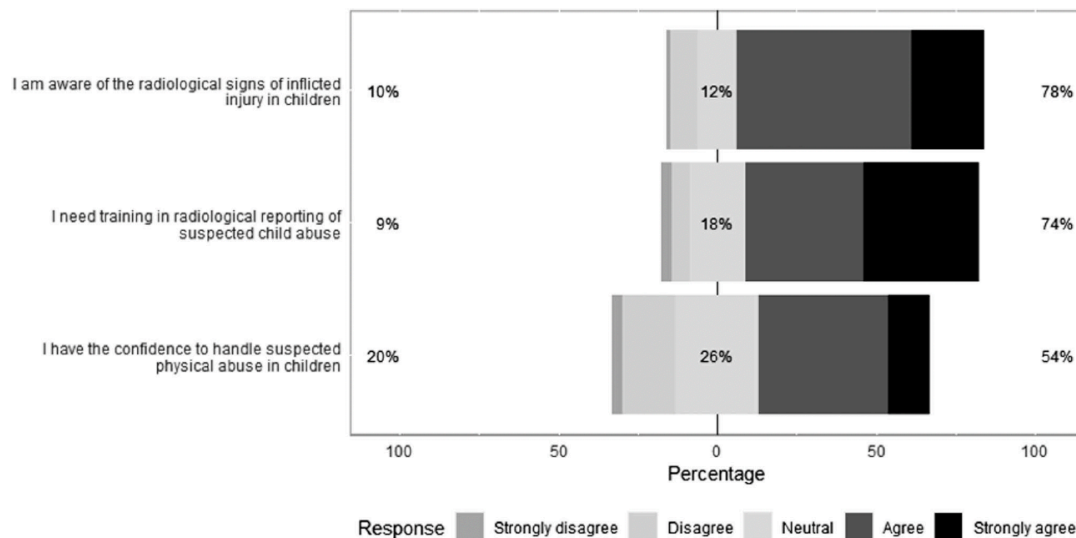


Fig. 4 Radiologists' opinions regarding recognising the radiologic signs, their training needs and confidence in the radiologic reporting of cases of suspected physical abuse. The percentage of neutral

responses is indicated on each bar with the total percentage of disagreement (strongly disagree or disagree) noted at left and the total percentage of agreement (strongly agree or agree) noted at right

48.4% of radiologists and more than half of radiologic technologists (58.5%) lacked knowledge regarding the reporting procedures in cases of child abuse. Moreover, most radiologic technologists (93.8%) and many radiologists (67.0%) reported no imaging protocols (e.g., radiographic skeletal survey) at their hospital for imaging children with SPA.

Child abuse is a serious global problem with severe consequences for victims, their families and society. In Saudi Arabia, the number of child abuse cases is reported to be increasing annually [6, 17]. The NFSP's national record for child abuse and neglect reported that 428 and 1,253 children were physically abused in 2020 and 2021, respectively [6, 18]. A comprehensive understanding of the various forms of child abuse and the factors that increase the risk of child abuse is vital for health care professionals to facilitate increased detection and reporting of suspected cases.

The definition of abuse (in general) varies among societies. For example, in the Arab culture, corporal punishment and verbal discipline are likely to be considered societal norms [14]. Several risk factors have been established for child abuse and maltreatment, including but not limited to low socioeconomic status/economic disadvantage, caregivers with mental health or drug issues, young parents, and children with disabilities [15, 19, 20]. Although it is well reported that socioeconomic status is an important risk factor for child abuse in the literature [15], more than one-third

(36.0%) of radiologic technologists in this study did not recognise this as a risk factor.

Although child abuse takes various forms (emotional abuse, sexual abuse and neglect), physical abuse might be more well-known given the media attention surrounding high-profile cases. However, the diagnosis of physical child abuse is challenging; children require a thorough physical examination, radiologic imaging, laboratory tests and a social evaluation [20, 21]. Given that children who are physically abused are more likely to have negative lifelong consequences such as behavioural problems and neurological disabilities [22], an early and accurate diagnosis of physical child abuse is paramount to improving child health outcomes and preventing potential future harm.

Medical imaging is a crucial tool in the diagnosis and management of children with SPA. Published guidelines for imaging SPA in children include those from the American College of Radiology and the Society for Pediatric Radiology (ACR-SPR) [23], the Royal College of Radiologists (RCR) and the Society and College of Radiographers (SCoR). The last has been endorsed by the Royal College of Paediatrics and Child Health (RCPCH) in the UK [24] and recognised by the European Society of Paediatric Radiology (ESPR) as the gold standard guidance for imaging children with SPA across Europe [25].

The radiographic skeletal survey, which comprises a series of radiographic images of the entire skeleton [23, 24], is a well-established radiologic examination in the

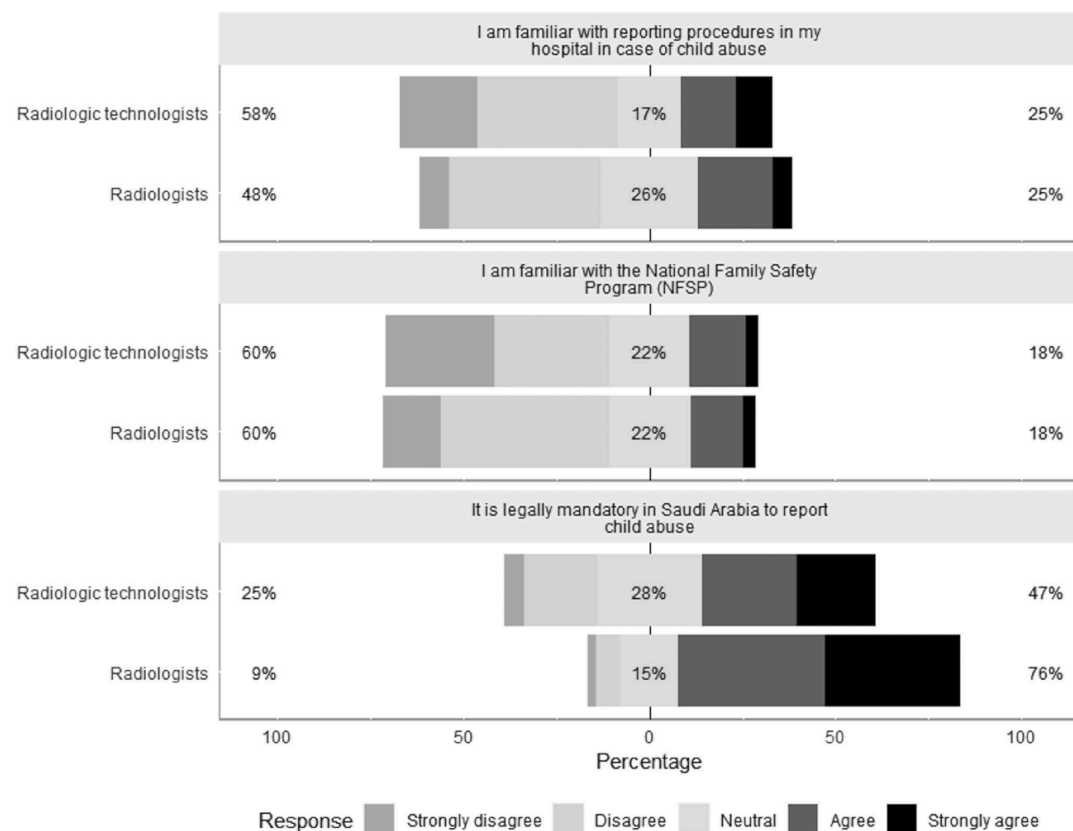


Fig. 5 Level of agreement among responders regarding their knowledge of the national law and programs for child abuse and reporting procedures and actions at their hospitals in suspected child abuse cases. The percentage of neutral responses is indicated on each bar

with the total percentage of disagreement (strongly disagree or disagree) noted at left and the total percentage of agreement (strongly agree or agree) noted at right

investigation of SPA in children. In our study, 93.8% of radiologic technologists and 67.0% of radiologists reported having no SPA skeletal survey protocol at their place of work. Additionally, 86.2% of radiologic technologists and 60.4% of radiologists were unfamiliar with any published guidelines for SPA imaging. It is important that radiology departments have a clear imaging protocol in place for imaging children with SPA; the previously mentioned guidelines [23, 24] serve as exemplar practice and our findings indicate that radiology departments in Saudi Arabia should endorse and utilise one of these imaging guidelines as evidence-based best practice.

Radiologists have a pivotal role in assessing children investigated for SPA by differentiating traumatic injuries from normal variants or other pathologies, recognising features that might indicate underlying metabolic and inherited

conditions, and suggesting the most likely time frame and mechanisms for injuries; further, radiologists sometimes play a key role in subsequent legal proceedings [10, 11, 26]. The role of radiologists in SPA is rendered less effective if suspicions regarding physical abuse are not promptly and appropriately communicated to the relevant clinical team. In Saudi Arabia, the child protection team includes a paediatric physician, a psychologist and professionals from social services and a legal department [3]. We recommend that a radiologist also be considered as a key member of the child protection team to facilitate communication of important radiologic findings to aid in clinical and child-protection decision-making.

In the context of evaluating children with SPA, radiology departments should have at least one dedicated paediatric radiologist (or radiologist trained in paediatric

imaging) who is designated (and trained) to report skeletal survey imaging; ideally two experienced reporters are required to facilitate independent double reporting [24]. Paediatric-trained radiologists could support and train colleagues in their department to increase the number of available radiologists to double-report such examinations. In the UK, 61.0% of radiology departments have a designated radiologist to report the skeletal survey, and 62.0% of radiology departments reported that the skeletal survey is double-reported by radiologists [26]. In this study, 51.0%, 79.0% and 80.0% of radiologists reported no paediatric radiologist, no designated radiologist to report the skeletal survey, and no double reporting of skeletal surveys, respectively, at their centres.

Unlike general radiologists, paediatric radiologists have more experience and a greater familiarity with normal paediatric bone development, normal variants in children and the radiographic appearance of fracture patterns in inflicted injury. However, paediatric radiology is a relatively small radiologic subspecialty, and there is an international shortage of paediatric radiologists [27–29]. As a consequence, not all hospitals have direct access to a trained paediatric radiologist. We advise that such centres forge links/networks with paediatric radiologists to facilitate access to timely reports on SPA imaging, which in turn could facilitate quicker decision-making. Such a system would also promote continuing professional development in paediatric radiology and SPA imaging. We also recommend involving experienced musculoskeletal radiologists and neuroradiologists to report brain and spine imaging performed for SPA.

In Saudi Arabia, it is necessary to improve not only the practice of paediatric radiography and radiology, particularly in the evaluation of SPA in children, but also the education of relevant professionals on this topic. In Saudi Arabia, the clinical radiology speciality training curriculum includes only a 4-month rotation in paediatric radiology out of the 4-year training program, with a single lecture on fracture patterns in abused children [30]. Trainees enrolled in a UK clinical radiology speciality program usually complete at least a 3-month rotation in paediatric radiology during their 5-year training program [31]. The RCR speciality training curriculum states that trainees are expected to have appropriate skills in interpreting images of inflicted injuries in children and that “examples of” imaging procedures in which all radiology trainees will develop skills to level 4 (fully independent practice) ... include accidental and non-accidental injury in children” [31]. Although didactic lectures are important in training programs, the practice of interpreting cases at the workstation with an experienced paediatric radiologist is essential to training. Additionally, discussion with the clinical teams regarding the proffered history and mechanism of injury is of critical importance to contextualising any radiologic findings.

In clinical practice, double reporting is recommended for radiologic studies with elevated risk [32, 33], with the second read improving confidence for less experienced radiologists and offering an improvement in diagnostic accuracy and consistency [32, 34]. Arguably, the skeletal survey performed in cases of SPA could be considered one of the highest-risk examinations performed given the impact of any positive (or negative) findings on the accurate and timely diagnosis of SPA. Moreover, the radiologic report can be critical to legal proceedings, further signifying not only its clinical importance but its utility in the forensic and medico-legal arena.

As health care professionals in Saudi Arabia, radiologic technologists are mandated to alert the relevant authorities to cases of SPA whilst maintaining patient confidentiality and professionalism. In cases of SPA, the role of the radiologic technologist is to produce high-quality diagnostic images using an evidence-based (and reproducible) skeletal survey protocol with careful documentation of the examination, including the time; who was present; and the type, number and dose of projections obtained [24, 35]. The aforementioned guidelines [23, 24] for imaging children with SPA recommend that radiologic technologists who are trained in paediatric imaging perform the skeletal survey. In our study, fewer than half of radiologic technologists (40.0%) reported that they were competent in imaging children in cases of SPA, which might reflect a lack of education and training.

There is a national reporting centre in Saudi Arabia [6] and health care professionals are mandated by law to report suspected abuse to child protective services [3]. In this study, 76.0% of radiologists and 47.0% of radiologic technologists were aware of the existing law in Saudi Arabia relating to the mandated reporting of all types of child abuse. However, few participants (25.0% in each group) were familiar with their workplace’s reporting *procedures* for suspected child abuse. This result is consistent with the results of other surveys conducted among health professionals in Saudi Arabia concerning suspected child abuse [12, 13]. The reason for the lack of knowledge regarding reporting procedures, which we found in up to 60.0% of radiologists and radiologic technologists in our study, could be a lack of training and awareness of the NFSP. We hope the survey increased knowledge of the NFSP among radiologic technologists and radiologists who participated and that any lack of knowledge could be further remedied with ongoing promotion of the program on a national scale.

Training health care professionals in recognising, evaluating and reporting child abuse is central for improving and promoting the health and welfare of children. In this study, most participants had not received training to deal with or evaluate cases of SPA, with many respondents reporting the need for (further) training in such cases. About 73% of radiologic technologists in this study had not received training in

paediatric radiology and 64% of radiologic technologists had not received training related to imaging children with SPA. The results of our study correlate with a study conducted in Nigeria, which demonstrated that 49% and 65% of radiologic technologists had not received training in paediatric radiology and imaging children with SPA, respectively [9]. Improving the education system and establishing training courses in paediatric radiology, with specific reference to SPA, are necessary to enable radiologic technologists and radiologists to engage in this important facet of their practice whilst working alongside other health care professionals to protect vulnerable children. Furthermore, a dedicated training program for health care professionals in Saudi Arabia is needed to help them recognise cases of SPA and to outline the steps of reporting to the appropriate authorities within the workplace.

This study has several limitations. First, although we distributed the survey via various channels, and included reminders, the findings must be interpreted with caution because of the small number of responders (the overall number of members in the national radiology/radiography societies was not known at the time of the study). The small number of participants could be the result of a lack of interest in research in general, or more specifically in paediatric radiology, where it is well recognised that there is a significant clinical workforce shortage [27, 29, 36]. In addition, email-based contact might have been labelled “junk” by mail servers, increasing the possibility that intended emails were not received or read by recipients. The number of radiologic technologists and radiologists in Saudi Arabia is not small but, unfortunately, we are not able to ascertain the exact number because of the lack of statistical data provided by the Ministry of Health in Saudi Arabia. Second, there is sampling bias caused by the online design of the survey whereby access might have been restricted to only those with email or social media accounts (i.e. Twitter, WhatsApp and Telegram) and those working in Saudi Arabia radiology departments. Furthermore, there might be a response bias, with responses potentially being biased by personal experience or opinions regarding child abuse, or by cultural background/understanding of child abuse from the non-Saudi radiologic technologists and radiologists, who represented 13.8% and 38.5% of respondents, respectively. Additionally, although most participating radiologic technologists were primarily working with modalities commonly used for imaging children with SPA, such as general radiography (59.4%), CT (15.2%) and MRI (8.5%), a few technologists were more involved with other modalities that are far less likely (US, 9.4%; nuclear medicine, 3.1%; and dental radiography, 0.9%) or never (e.g., interventional radiology, 2.2%; and mammography, 0.9% of respondents) used in imaging children with SPA. However, the results of this study still provide a valuable insight into the current

practice, knowledge and awareness of child abuse amongst radiologists and radiologic technologists in Saudi Arabia. The final limitation is that the study was restricted to Saudi Arabia and might therefore be of limited relevance to readers from other countries. However, it could represent a similar lack of awareness of child physical abuse in other lower-income countries in Africa and the Middle East. Our results serve as a baseline to which other countries can compare their findings, and with which Saudi Arabia can compare itself in future studies. The ESPR and SPR are significantly involved in outreach work through the World Federation of Pediatric Imaging, and perhaps through them future international studies can be conducted. Importantly, child abuse is a worldwide problem and therefore dissemination of such a study in internationally recognised journals should lead to the sharing of knowledge on a wider international scale, increasing the awareness of health care professionals of child protection and reminding them of the role of medical imaging in diagnosing SPA.

Conclusion

Radiologic technologists and radiologists, alongside all health care professionals who work with or alongside children, play an integral role in the diagnosis and management of children suspected of having been physically abused. This study has demonstrated that overall knowledge and awareness of child abuse amongst radiologists and radiologic technologists in Saudi Arabia is good; however, they lack specific knowledge regarding the reporting and acting procedures at their hospitals in cases of suspected child abuse. Moreover, there is a lack of standardised protocols and radiologic reporting expertise for cases of suspected child abuse. This study highlights a clear need for national imaging guidelines and training programs relating to the imaging and radiologic reporting of suspected physical abuse in infants and young children in Saudi Arabia.

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Declarations

Conflicts of interest None

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