UCC

University College Cork, Ireland

Coláiste na hOllscoile Corcaigh

Computed Tomography versus Radiography for the detection of rib and skull fractures in Paediatric Suspected Physical Abuse: A Systematic Review

Authors

Ahmed Mohammed[1,4], Eimear Mahon[1], Niamh Moore[1], Lorna Sweetman[3], Michael Maher[1,2], Patrick O'Regan[1], Andrew England[1] and Mark F. McEntee[1,5,6].

Affiliation

1. Discipline of Medical Imaging and Radiation Therapy, School of Medicine, University College Cork, Cork, Ireland.
2. Department of Radiology, Cork University Hospital, Cork, Ireland.
3. Department of Medical Physics, Cork University Hospital, Cork, Ireland.
4. Radiological Sciences Department, College of Applied Medical Sciences, Taif University, Taif, Saudi Arabia.
5. Institute of Regional Health Research, University of Southern Denmark, Denmark
6. Faculty of Medicine, University of Sydney, Australia

Corresponding author

Ahmed Mohammed

e-mails: 121129186@umail.ucc.ie

a.abdulahad@tu.edu.sa

Telephone: +966553032987

+353 852697240

Abstract

Purpose: The diagnosis of suspected physical abuse (SPA) remains a continuous challenge to paediatric healthcare. Several studies have reported that computed tomography (CT) improves the evaluation of SPA. This study aims to systematically review the diagnostic performance of CT compared to radiography in investigating skull and chest fractures for SPA.

Materials and methods: Multiple databases were searched, using PRISMA methods, from 2008 to August 2024 for relevant studies in English. Two reviewers independently screened and selected relevant studies using Covidence software. The QUADAS-2 tool was used for the quality assessment of the included papers. Sensitivity, specificity and the effective radiation dose of CT and radiography from the included studies were extracted. Pooled sensitivity and specificity were calculated with their respective 95% confidence intervals (CI). GRADE criteria were used to appraise the overall quality of the synthesis.

Results: Of the 4057 identified papers, 10 met the inclusion criteria; all 10 included skull and/or chest. The overall sensitivity and specificity of CT were 96.5% (95%CI: 94.9–97.7%) and 99.5% (95%CI: 99.1–99.8%), respectively. Compared to the sensitivity and specificity of radiography, 59.8% (95%CI: 56.2–63.3%) and 99.7% (95%CI: 99.3–99.8%), respectively.

Conclusion: CT sensitivity is significantly higher than radiography in detecting rib and skull fractures for SPA. The effective dose for chest LDCT is comparable to that of radiography. Therefore, LDCT should be considered as a potential replacement to radiography in SPA investigations for the chest and skull.

What is known?
• CT shows higher diagnostic performance than radiography in detecting skull and rib fractures in the diagnosis of SPA.
What is new?
• When a head CT scan is acquired for SPA diagnosis at any age, the two-view skull radiograph can be safely eliminated from the Skeletal Survey protocol. • With respect to rib fracture diagnosis, Chest CT can replace chest radiography for SPA diagnosis. • The effective dose and image quality of low-dose chest CT is comparable to that of two-view chest radiography for SPA diagnosis.

Keywords

Non-accidental injury; head; chest; diagnosis; skeletal survey

Abbreviations

3D	Three-dimensional
AP	Anteroposterior
AUC	Area under the curve
BEIR	Biological Effects of Ionizing Radiation
CCJ	Costochondral junction
CI	Confidence intervals
CT	Computed tomography
CXR	Chest radiography
ESPR	European Society of Paediatric Radiology
FN	False negative
FP	False positive
k-factor	Effective dose conversion factor
LDCT	Low-dose computed tomography
MeSH	Medical subject headings
mGy	Milligray
mSv	Millisievert
SPA	Suspected physical abuse
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-analyses
QUADAS-2	Quality Assessment of Diagnostic Accuracy Studies-2
SS	Skeletal surveys
SXR	Skull radiography
TN	True negative
TP	True positive

Introduction

Suspected physical abuse (SPA) is any form of harm or injury to a child that is intentionally inflicted by a caregiver or other person responsible for the child's welfare [1; 2]. SPA is a significant cause of childhood morbidity and mortality and remains a continuous challenge to healthcare and society [1-5]. Hence, accurate diagnostic evaluation and management of these injuries are crucial for ensuring the well-being and safety of the child. However, detecting injuries in neonates, infants and young children should be balanced against concerns regarding the radiation dose from diagnostic imaging [5].

For decades, radiography has been utilised for SPA due to its availability, high spatial resolution, and low effective radiation dose [1]. Guidelines for skeletal surveys (SS) have been established by multiple governing bodies to optimise and standardise the detection of injuries associated with SPA [6-8]. SS refers to high-quality radiographic projections investigating the entire skeleton and typically consists of 25 to 32 projections depending on the age and size of the child and also the imaging guidelines being followed [1; 2; 5; 9]. The utility of diagnostic imaging in addition to clinical assessment are supported by research, especially for children under the age of three [7; 10-12]. However, recent studies have highlighted concerns about the ability of radiography to detect certain fractures in the acute stage [1; 9; 13].

It is recommended to undertake a follow-up SS approximately two weeks after the initial SS to identify additional fractures as well as an assessment of the age of the injury of the abused child [1; 14]. Several studies reported that follow-up SS can detect between 9% and 46% more fractures than the initial projections, especially within the ribs and bone metaphases [15-18]. Furthermore, many cases were reported where suspected fractures detected on initial radiography were identified as negative in follow-up studies [1; 15]. Significant challenges exist regarding the child’s return for follow-up, and reports suggest that between 23-60% of abused children do not return for follow-up imaging [15]. Radiation doses associated with the initial and the follow-up SS are relatively low, with the effective dose ranging from 0.09 to 0.52 mSv and 0.07 to 0.11 mSv respectively [14; 19; 20]. However, fractures, including ribs, scapula, skull and some long bones, have been diagnosed more accurately when using computed tomography (CT) [5; 21-26].

In 2018, The European Society of Paediatric Radiology (ESPR) updated guidelines for radiological diagnosis of suspected SPA to include a head CT with three-dimensional (3D) reconstruction as a part of the routine SS in all children younger than one year [27]. The guidelines also suggest that 3D head CT should be routinely performed to better diagnose skull fractures and related soft tissue injuries. Several studies have reported a greater diagnostic accuracy of head CT compared to conventional radiography for SPA [14; 25; 28].

Modern imaging technologies, including CT, have become a primary investigation tool for various medical disorders [29]. Several studies have indicated a rise in the use of CT, including its increased use within the paediatric population [30-33]. This awareness has led to radiation safety campaigns such as Image Gently which aims to optimise radiation dose when imaging paediatric patients [34]. To minimise the radiation risks to the paediatric patient, the use of low-dose CT (LDCT) has been recommended [1; 35]. Previous studies assessing CT skull and chest for SPA indicated improvements in CT technology enabled a significant reduction in radiation dose during CT scanning for SPA [1; 35; 36].

Interpretation of SPA on plain radiographs can be challenging. CT can improve visualisation of complex anatomical regions [28; 37]. False-positive interpretations of skull radiographs, for example, can happen because of the superimposition of suture lines, vascular grooves, fissures or other normal variants [28; 38; 39]. This may result in unnecessary medical assessment and social work investigation [28; 38; 39]. On the contrary, false-negative interpretation may result in a patient being returned to an unsafe environment [38]. Similar interpretation difficulties are found with chest radiographs [21; 40]. Incomplete and non-displaced rib fractures are difficult to diagnose using radiography [41]. Additionally, it is difficult to detect posterior rib fractures using radiography due to the superimposition of the transverse process of the spine on the rib [42; 43]. Unlike radiography, CT can separate anatomical structures and allows more accurate detection of fractures. A further benefit of using CT for SPA is its ability to detect additional clinical injuries including, but not limited to, intracranial injuries, soft-tissue lung issues, small pneumothoraxes, intra-abdominal perforation and lacerations from blunt trauma to solid organs [24; 44]. However, disadvantages of using CT technology for SPA include: access to CT, time required, potential requirement for sedation, cost of the procedure, dose to the carers, increasing demands on CT, specialised training for the radiographers, more time needed to review the images, increased potential for incidental findings, should be considered[1; 5]. Additionally, there has been no meta-analysis comparing radiography with CT in the diagnosis of SPA, this current work aims to fill that gap.

This systematic review and meta-analysis aims to compare radiography and CT in the evaluation of skull and chest fractures for SPA to determine whether CT provides superior sensitivity and specificity to radiography. A secondary aim is to identify the range of radiation doses and protocol variations when utilising CT for SPA.

Methods

This systematic review was registered with PROSPERO (CRD42023439354) and conducted in line with the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines [45]. As all information was in the published domain, no ethical waiver was necessary.

Literature search

Keywords

Relevant keywords were identified using a PIRO approach, from which appropriate medical subject headings (MeSH terms) were generated. The MeSH terms used for this systematic review are summarised in **Fig. 1**.

Search strategy

The chosen MeSH terms were then linked and used in different databases, including PUBMED (including Medline), SCOPUS, EMBASE, Web of Science, CINHAL and Cochrane, to find all relevant studies that compared the use of CT and radiography for SPA. These databases were chosen because they are the largest English language, systematically searchable, biomedical and health sciences literature databases that are either open-access or subscribed to by the study institution library. Further searching was performed using Google Scholar to ensure as much grey literature as possible was included.

PIRO

P — Child abuse or Child neglect or Child mistreatment, or Pediatric Emergency Medicine or Non-accidental injury or Suspected physical abuse.

I — Computed x-ray tomography or Transmission computed tomography or CT or CAT scan or Spiral CT or Helical CT or Tomography or Computed Tomography or CT x-ray.

R — Skeletal survey or SS or CXR or SXR or Radiography or X-ray or Digital Radiography.

O — Detection of fractures.

Fig. 1Summary of the terms used in the systematic review. P, Population; I, Index test; R, Reference standard; O, Outcome.

Inclusion criteria

(1) Publications, including randomised control trials, cohort studies, case-control trials and experimental studies published between 2008 and August 2024. 2008 was chosen as our scoping review indicated that the first paper comparing CT to radiography in the diagnosis of SPA was in 2008 by Wootton-Gorges et al. [21]. (2) Studies should include a comparison between CT and radiography in identifying fractures in cases of SPA. (3) The age of participants was ideally restricted to children under the age of five years because older patients can identify the cause of harm therefore, imaging is not the main source of information (4) Included studies were restricted to those in the English language (5) papers are to have sample sizes sufficient for appropriate power.

Exclusion criteria

(1) Phantom and/ or animal studies are excluded; (2) reviews, conference abstracts and letters were excluded; (3) papers not in English language; (4) patients with accidental injuries; (5) studies where the majority of patients were aged over 5 years. Our rationale being that Patients over 5 years typically can communicate the cause of their injuries and as such would be imaged slightly differently. (6) commercially funded studies.

Data extraction

All papers collected from different databases were uploaded to the Covidence software (Covidence, Melbourne, Australia) for screening and review. Duplicated articles were automatically removed by the software. Two reviewers independently reviewed records and applied the review inclusion and exclusion criteria. The following characteristics were extracted, including year of publication, study design, sample size, average patient age and fracture location. For comparison, average radiation doses and imaging protocols for CT and radiography were also extracted. Controversies between the two reviewers were resolved by consensus discussion.

Quality assessment and risk of bias

The validity of the included studies was assessed using the Quality Assessment of Diagnostic Accuracy Studies-2 tool (QUADAS-2) [46]. QUADAS-2 tool evaluates the risk of bias across four key domains: patient selection, index test, reference test, and flow and timing. To determine the level of bias, each domain was evaluated using a three-point scale: low risk (green), high risk (red) or unclear risk (yellow). Each domain has questions to help authors reach the appropriate judgments of bias level.

Data analysis

The pooled sensitivity and specificity of CT and radiography were calculated and reported together with their 95% confidence intervals (CIs) for each included study. The pooled diagnostic performance across all these studies was represented by identifying the sensitivity and specificity of the total number of participants. Then, these sensitivity and specificity figures were compared graphically using a forest plot. Heterogeneity between included studies was estimated using I^2 statistics performed using the MetaDisc 1.4 software (Hospital Universitario Ramon y Cajal, Madrid, Spain). Heterogeneity is categorised as follows: (≤40%) low heterogeneity, (41-75%) moderate heterogeneity and (>75%) high heterogeneity.

Result

Literature Search

The PRISMA flowchart (**Fig.** 2) illustrates the selection process for the included studies. From the databases previously mentioned, a total of 4057 non-duplicate records were identified. The titles and abstracts of these studies were screened, and 131 studies were deemed relevant and underwent full-text review. Of these 131 papers, 121 did not meet the required inclusion criteria for several reasons, including that the study did not include a comparison between radiography and CT, most patients in the study were older than five years and the study objective was not relevant to this review. Ten studies were considered eligible for inclusion.

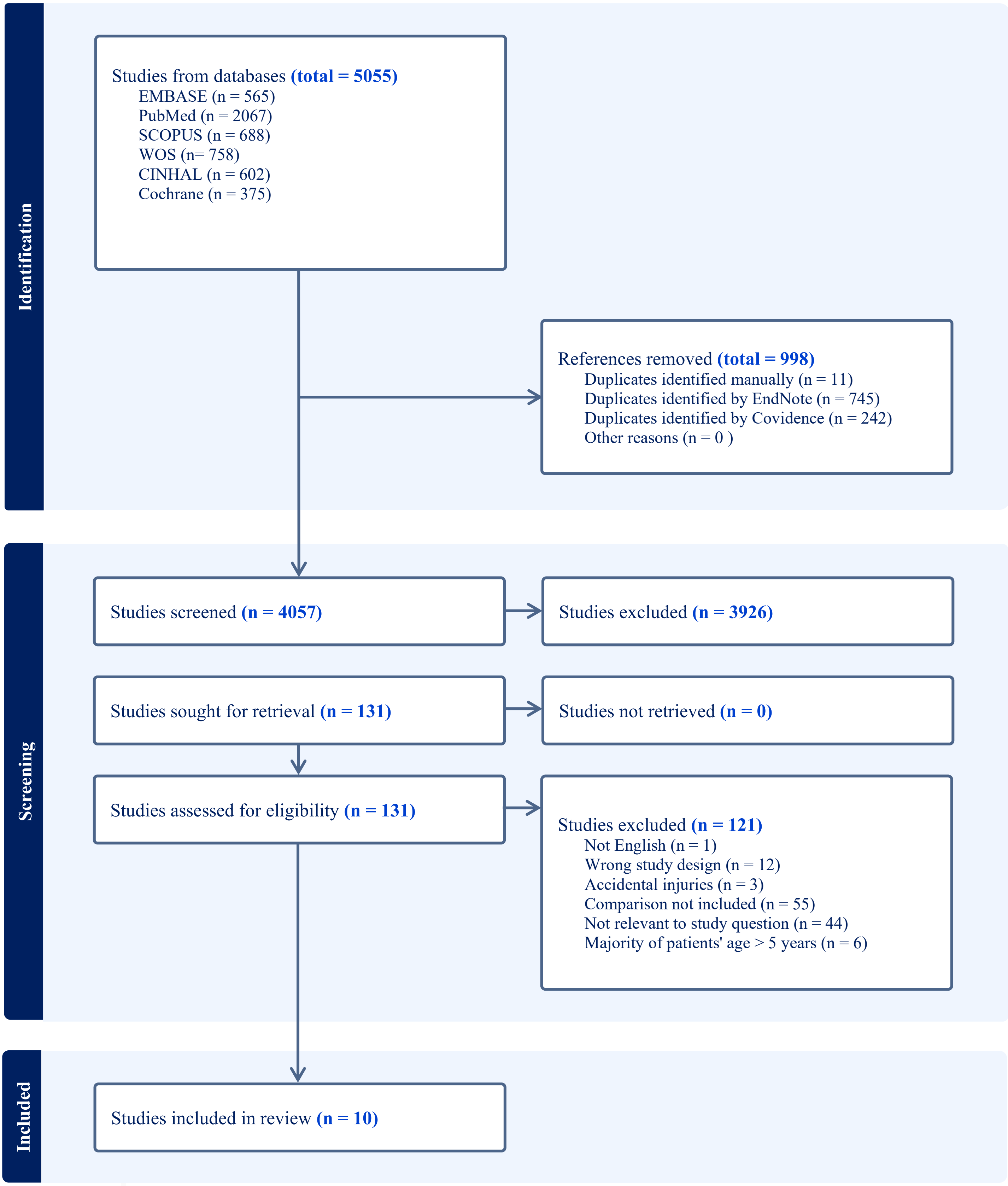

Fig. 2 A PRISMA flow chart summarising the selection process for the included papers. n, number of studies

Quality Assessment

Table 1 summarises the quality assessment for each included paper. All included studies were regarded as a low risk of concern in the patient selection domain. Four studies were considered as having a low risk of concern in all four domains [25; 38; 47; 48]. The paper by Sanchez and colleagues (2018) was graded as an unclear risk for the index test and reference standard domains because the interpretation processes for both the index test and reference standard were not reported [22]. For the flow and timing domains, three papers were regarded as an unclear risk because the interval times between the index test and reference standard were not represented in their studies [28; 44; 49]. Therefore, none of the selected papers were eliminated at this stage, because they had an overall low risk of bias.

Data extraction

All ten included studies compared the use of radiography and CT for SPA investigation. Table 2 summarises the number, gender and age of patients in each study and the number of fractures detected by radiography and CT for SPA. Five studies focused on chest injuries, while the other five studies investigated skull fractures. The mean age of the participants across all studies was 9.6 months (range 0 to 7 years old). Of the total number of fractures identified through CT; 512 were rib fractures, and 210 were skull fractures. When compared, to the number of fractures identified by radiography, 273 were rib fractures and 175 were skull fractures.

Table 3 highlights the number of fractures detected by radiography and CT based on their anatomical position. For chest imaging, fractures in all parts of the rib except in the lateral portion were detected more by CT than by chest radiography (CXR). Two studies reported that fractures of the lateral part of the rib were better visualised by CXR than by CT with the total number of fractures detected by CXR being 53 compared to 48 detected by CT [21; 37]. For skull imaging, only one study presented the fractures based on their anatomical position [44]. All parts of the skull were better visualised with CT rather than skull radiography, except for the frontal bone, one fracture was detected by skull XR compared to zero by CT.

Table 4 illustrates the performance and the effective dose of CT and radiography for SPA diagnosis. All included studies reported superior diagnostic sensitivity of CT in the detection of fractures for SPA when compared to radiography. Imaging protocols used in each included paper were different; consequently, different radiation doses were recorded. Karmazyn et al. [48] recorded an estimated effective dose of 0.06 mSv for three radiographs of ribs, while they used three different protocols for the chest CT. In the first group, for patients with a suspicion of intrathoracic trauma, chest CT was performed with intravenous contrast media with an average dose of 0.45 mSv.

The other two groups used LDCT, with and without tin filtration, with average estimated doses of 0.14 and 0.17 mSv, respectively [48]. Forbes-Amrhein et al. [47] and Sanchez et al. [22] compared the effective radiation dose for chest CT with the four view images of the CXR (AP, lateral and bilateral oblique ribs). For CXR, they recorded a radiation dose of 0.15-0.29 mSv in the Forbes-Amrhein et al. [47] study and an average of 0.35 mSv in the Sanchez et al. [22] study. Whereas, for chest CT average doses of 0.77 mSv [47] and 0.48 mSv [22] were recorded, respectively. Martin et al. [25], Sharp et al. [28] and Culotta et al. [38] recorded an effective radiation dose ranging from 0.006 to 0.112 mSv associated with two views of the skull (AP and lateral). For skull CT, an effective radiation dose of 0.9-5.8 mSv was recorded [25; 28; 38].

Diagnostic performance of CT and Radiography for SPA

The pooled sensitivity and specificity for CT were 96.5% (95% CI: 94.9–97.7%) and 99.5% (95% CI: 99.1–99.8%) with heterogeneity (I2) of 82% and 59.3%, respectively. Radiography showed a sensitivity of 59.8% (95% CI: 56.2–63.3%) and a specificity of 99.7% (95% CI: 99.3–99.8%) with a high heterogeneity of 94.2% and a moderate heterogeneity of 49.9%, respectively. **Fig. 3** illustrates the forest plot of the overall sensitivity of CT in comparison with the forest plot of the overall sensitivity of radiography. Forest plots for pooled specificity of CT and radiography are illustrated in **Fig. 4**. Additionally, the area under the curve (AUC) for the combined diagnostic performance of CT and SS across all ten papers is represented with a high overall performance of CT (AUC=0.99) compared to the overall performance of radiography (AUC=0.89). Only 4 articles included a definition of the gold standard, these details have been included in Table 2. Other studies did not include a definition or identification of the 'gold standard' for their comparison and they relied solely on radiological reports, so the gold standard could be a combination between the two modalities.

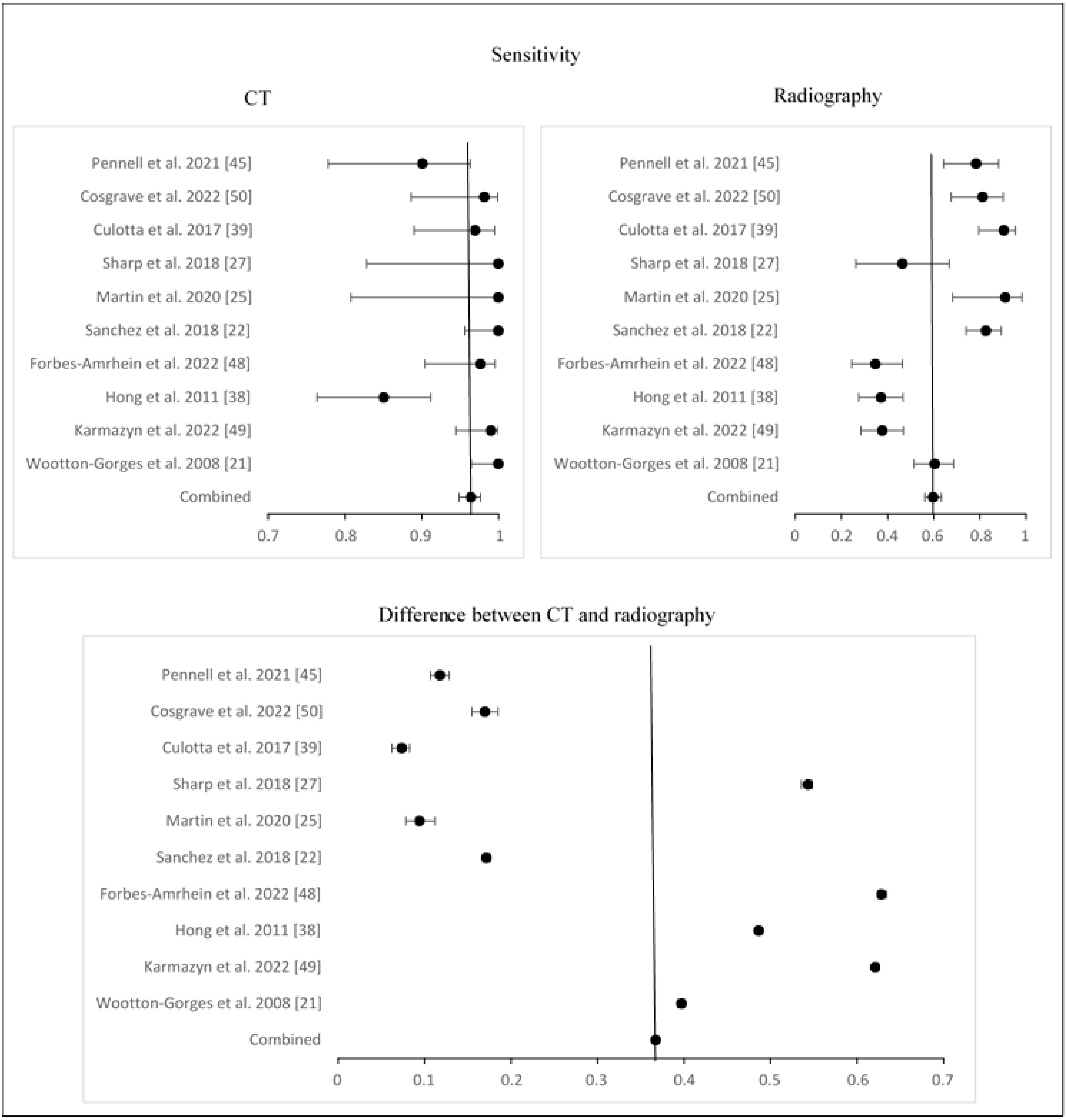

Fig. 3 Top left indicates the sensitivity of CT, top right, sensitivity of radiography and the bottom forest plot of the difference in sensitivity of CT and radiographic SS in the diagnosis of SPA, indicating CT has a higher sensitivity of 0.37 on average.

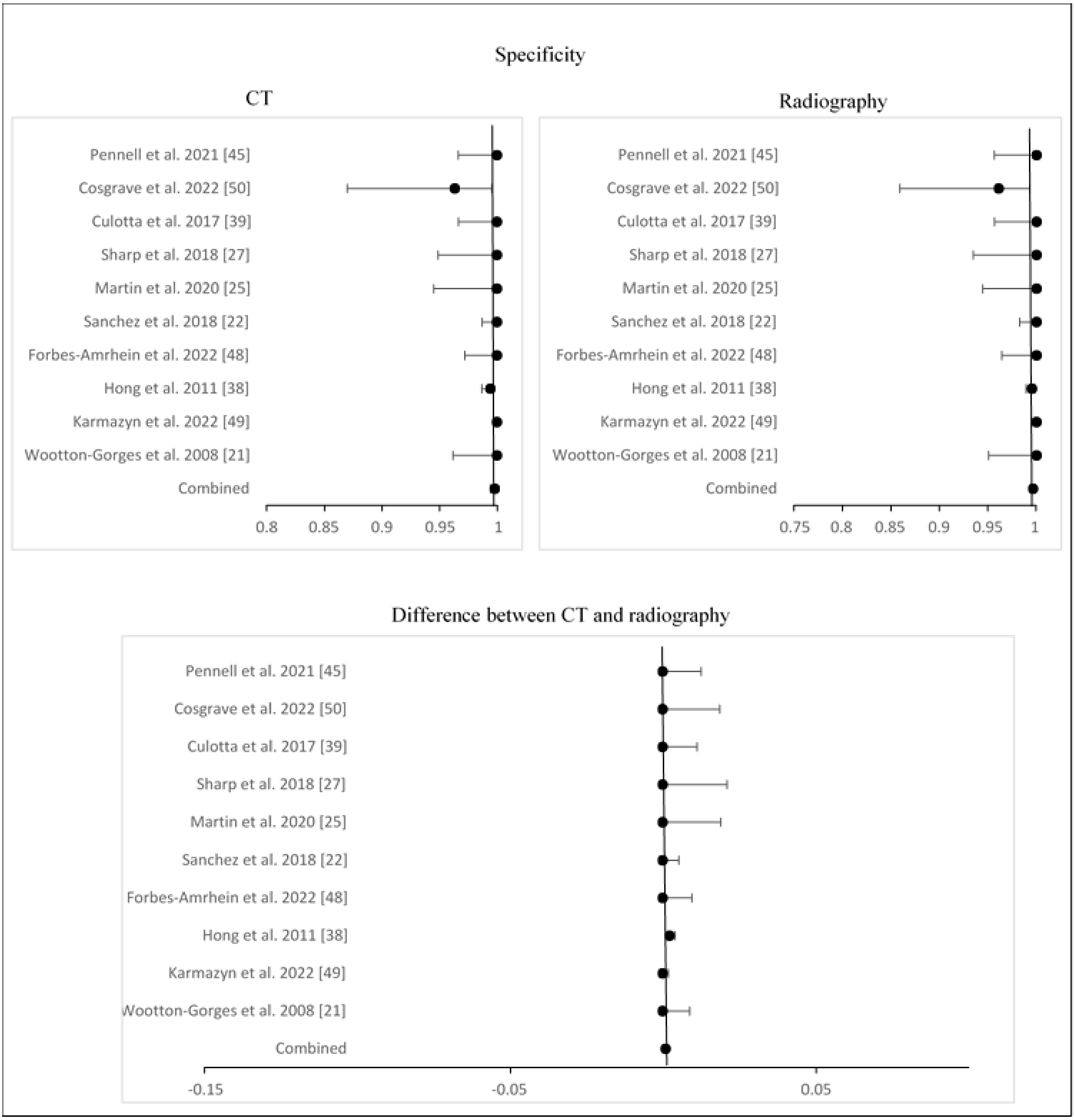

Fig. 4 The top left indicates the specificity of CT, the top right, the specificity of radiography, and the bottom is a forest plot of the difference between CT and radiographic SS in the diagnosis of NAI, indicating CT and radiographic SS has about similar specificity.

Discussion

This systematic review identified ten papers eligible for inclusion; five focused on the detection of rib fractures, while the remainder focused on skull fractures associated with SPA. Rib and skull fractures are the most common skeletal injuries associated with SPA [21; 25]. Furthermore, non-accidental brain injuries are a leading cause of fatal injury in young children, accounting for 80% of deaths from all head trauma in young children [50]. Due to the associated increased radiation dose used in diagnostic CT imaging, optimising CT protocols for SPA is important. This is particularly so for paediatric patients, who are more vulnerable to the effects of radiation compared to adults [51].

Four of the included studies compared the diagnostic performance of CT with radiography in detecting fractures at specific locations of ribs [21; 37; 47; 48]. Forbes-Amrhein et al. [47] investigated the performance of different imaging modalities in the diagnosis of costochondral junction fractures. CT was reported to be more sensitive than CXR for detecting Costochondral junction fractures. CXR identified only 34.6% of Costochondral junction fractures detected on CT, while CT missed two fractures identified by CXR. The other three studies reported the number of fractures identified by radiography and CT in different positions of ribs, including anterior, anterolateral, lateral, posterolateral, and posterior locations. CT was more sensitive than CXR in detecting fractures in all locations, except for in lateral locations [21; 48]. Such trends could have resulted where abdominal CT scans were evaluated in some cases, these may have only image part of the rib and thus could have impacted on sensitivity [21]. Based on the included studies, CT scans detected more rib fractures than radiography. CT detected a total of 512 and missed 18 fractures with a sensitivity of 96.6% and specificity of 99.7%, while CXR identified 273 and missed 258 fractures with a sensitivity of 51.4% and specificity of 99.8%. The severity of rib fractures are often underestimated, however, rib fractures are a sign of a severe injury which may result in fatal harm [52]. Karmazyn et al. [48] used LDCT in their study and reached an effective dose of 0.14 mSv, comparable to the dose of the standard three views rib radiography (0.06 mSv). LDCT imaging protocols help alleviate concern regarding the perceived high radiation dose for CT imaging. Thus, CXR could be replaced by CT for investigating SPA when protocols have been optimised accordingly.

Although the results show a wide range of doses for CT (0.14-0.48 mSv) and radiography (0.06-0.35 mSv), these ranges overlap, indicating a somewhat comparable dose. An overlap between the highest CXR radiation doses and the lowest CT chest doses indicates just how much dose optimisation there has been in CT over the years. However, there are limitations as different studies used different effective dose conversion factors (*k*-factors) to calculate the estimated effective dose. There were no significant differences observed in the estimated radiation dose between radiography and CT ($p=0.059$). Karmazyn et al. [48] and Forbes-Amrhein et al. [47] used body-size-specific k-factors to estimate radiation dose in their studies. Karmazyn et al. [48] used a *k*-factor of 0.026 mSv mGy $^{-1}$ cm $^{-1}$ while Forbes-Amrhein et al. [47] used a *k*-factor of 0.032 mSv mGy^{-1} cm^{-1} depending on the patents' sizes included in their studies. On the other hand, Sanchez et al. [22] used an age-specific *k*-factor which is found to overestimate effective dose when compared to size-specific *k*-factors [53]. This makes direct comparison of doses challenging.

In the current study, one paper describes the accuracy of CT and radiography in detecting skull fractures based on their anatomical position. Pennell et al. [44] found that CT identified more fractures in parietal and occipital bones than radiography, 35 on CT and three on skull XR compared to 33 on CT and one on skull XR, respectively. Overall, the diagnostic performance of skull CT was greater than skull XR, with 210 skull fractures (96.3% sensitivity) detected by CT compared with 175 skull fractures detected by radiography (80.3% sensitivity). Additionally, 3D reconstruction of the CT skull provides additional information on soft tissue injuries, which may be overlooked on skull XR [25; 38; 44; 54]. As the current guideline for investigating suspected SPA involving head CT as a part of the SS, these results suggest that when there is a head CT then two-view skull radiography can be safely eliminated from the SS protocol. Further work is needed to investigate whether CT is equal to SS for dating old fractures.

Based on the ten included studies, the overall diagnostic performance of CT for SPA is higher than radiography. These findings suggest CT has greater performance in fracture diagnosis of SPA in the chest and skull. The risk of the high radiation dose associated with CT should be balanced with the risk of missed diagnosis of fractures in the initial SS for SPA. Due to the high percentage of non-return children for the follow-up SS, patients may remain in an abusive environment which may lead to a fatal injury. This review found a higher sensitivity of CT in the detection of rib and skull fractures for SPA. Furthermore, using LDCT protocols allows a reduction in the effective radiation dose and facilitates the prompt and appropriate management of SPA diagnosis.

CT should be considered as a replacement for radiography SPA diagnosis, particularly for the skull and chest. This recommendation is made at the cost of a higher dose, but the benefit of improved sensitivity. However, further research and possibly clinical trials are needed before replacing SS with whole-body CT when contributing to SPA diagnosis.

This review has several limitations. An estimate of bias using Eggers test was not possible as no papers reported a sample mean and standard deviation. Only ribs and skull fractures are included when comparing CT and radiography for SPA. For a more accurate comparison, whole-body CT should be included. Furthermore, the various CT and SS radiography protocols and gold standards used in the included studies will affect the accuracy of the pooled sensitivity and specificity values. Wootton-Gorges et al. [21] included patients who were scanned for either abdomen or chest CT which resulted in missing some parts of ribs. Also, one paper, by Hong et al. [37], calculated the diagnostic accuracy of CT in post-mortem cases, which may increase the diagnostic performance as radiation dose levels were not a consideration. Another limitation, although SPA is not common over the age of 5 years, one study, Hong et al. [37], has included less than 10 participants aged up to 8 years with a percentage of less than 1.5% of the total participants, this study was included to ensure that all relevant studies were captured. Moreover, all the included papers were retrospective. Finally, this review is restricted to English language studies only which may have further limited the review.

Conclusion

CT sensitivity is significantly higher than radiography in detecting rib and skull fractures for SPA. The effective dose for chest LDCT is comparable to that of radiography. Therefore, LDCT should be considered as a potential replacement to radiography in SPA investigations for the chest and skull.

References

1. Lawson M, Tully J, Ditchfield M, Metcalfe P, Qi Y, Kuganesan A, Badawy MK (2022) A review of current imaging techniques used for the detection of occult bony fractures in young children suspected of sustaining non-accidental injury. J Med Imaging Radiat Oncol 66:68-78
2. Nguyen A, Hart R (2018) Imaging of non-accidental injury; what is clinical best practice? J Med Radiat Sci 65:123-130
3. Waller AE, Baker SP, Szocka A (1989) Childhood injury deaths: national analysis and geographic variations. American journal of public health 79:310-315
4. Weldon J, Price R (2016) Skeletal survey quality in non-accidental injury–A single site evaluation of the effects of imaging checklists. Radiography 22:e159-e165
5. Lawson M, Tully J, Ditchfield M, Kuganesan A, Badawy MK (2022) Using Computed Tomography skeletal surveys to evaluate for occult bony injury in suspected non-accidental injury cases - A preliminary experience. J Med Imaging Radiat Oncol 66:41-48
6. American College of Radiology (2016) ACR–SPR practice parameter for the performance and interpretation of skeletal surveys in children. American College of Radiology ACR standards American College of Radiology, Reston:1-9
7. Lindberg DM, Berger RP, Reynolds MS, Alwan RM, Harper NS, Examining Siblings To Recognize Abuse I (2014) Yield of skeletal survey by age in children referred to abuse specialists. J Pediatr 164:1268-1273 e1261
8. Royal College of Radiologists (2017) The radiological investigation of suspected physical abuse in children. The Royal College of Radiologists and The Society and College of Radiographers
9. Hulson OS, van Rijn RR, Offiah AC (2014) European survey of imaging in non-accidental injury demonstrates a need for a consensus protocol. Pediatr Radiol 44:1557-1563
10. Jain N (2015) The role of diagnostic imaging in the evaluation of child abuse. BC Med J 57:336-340
11. Ellerstein NS, Norris KJ (1984) Value of radiologic skeletal survey in assessment of abused children. Pediatrics 74:1075-1078
12. Belfer RA, Klein BL, Orr L (2001) Use of the skeletal survey in the evaluation of child maltreatment. The American journal of emergency medicine 19:122-124
13. Spies AJ, Steyn M, Brits D (2021) A comparison of computed tomography, X-ray and Lodox((R)) scans in assessing pediatric skull fractures using piglets. J Forensic Sci 66:470-478
14. Rao R, Browne D, Lunt B, Perry D, Reed P, Kelly P (2019) Radiation doses in diagnostic imaging for suspected physical abuse. Archives of Disease in Childhood 104:863-868
15. Zimmerman S, Makoroff K, Care M, Thomas A, Shapiro R (2005) Utility of follow-up skeletal surveys in suspected child physical abuse evaluations. Child abuse & neglect 29:1075-1083
16. Bennett BL, Chua MS, Care M, Kachelmeyer A, Mahabee-Gittens M (2011) Retrospective review to determine the utility of follow-up skeletal surveys in child abuse evaluations when the initial skeletal survey is normal. BMC Research Notes 4:1-4
17. Harper NS, Eddleman S, Lindberg DM, Investigators E (2013) The utility of follow-up skeletal surveys in child abuse. Pediatrics 131:e672-e678
18. Harper NS, Lewis T, Eddleman S, Lindberg DM, Investigators E (2016) Follow-up skeletal survey use by child abuse pediatricians. Child Abuse & Neglect 51:336-342
19. Berger RP, Panigrahy A, Gottschalk S, Sheetz M (2016) Effective radiation dose in a skeletal survey performed for suspected child abuse. The Journal of pediatrics 171:310-312

20. Sait S, Havariyoun G, Newman H, Das S, Haque S (2023) Effective radiation dose of skeletal surveys performed for suspected physical abuse. Pediatric Radiology 53:69-77
21. Wootton-Gorges SL, Stein-Wexler R, Walton JW, Rosas AJ, Coulter KP, Rogers KK (2008) Comparison of computed tomography and chest radiography in the detection of rib fractures in abused infants. Child abuse & neglect 32:659-663
22. Sanchez TR, Grasparil AD, Chaudhari R, Coulter KP, Wootton-Gorges SL (2018) Characteristics of rib fractures in child abuse—the role of low-dose chest computed tomography. Pediatric emergency care 34:81-83
23. Shelmerdine SC, Langan D, Hutchinson JC, Hickson M, Pawley K, Suich J, Palm L, Sebire NJ, Wade A, Arthurs OJ (2018) Chest radiographs versus CT for the detection of rib fractures in children (DRIFT): a diagnostic accuracy observational study. The Lancet Child & Adolescent Health 2:802-811
24. Sanchez TR, Lee JS, Coulter KP, Seibert JA, Stein-Wexler R (2015) CT of the chest in suspected child abuse using submillisievert radiation dose. Pediatric radiology 45:1072-1076
25. Martin A, Paddock M, Johns CS, Smith J, Raghavan A, Connolly DJ, Offiah AC (2020) Avoiding skull radiographs in infants with suspected inflicted injury who also undergo head CT:"a no-brainer?". European radiology 30:1480-1487
26. Horn BD, Crisci K, Krug M, Pizzutillo PD, MacEwen GD (2001) Radiologic evaluation of juvenile tillaux fractures of the distal tibia. Journal of Pediatric Orthopaedics 21:162-164
27. European Commission Directorate-General for Energy (2018) European guidelines on diagnostic reference levels for paediatric imaging. Publications Office
28. Sharp S, Patel S, Brown R, Landes C (2018) Head imaging in suspected non accidental injury in the paediatric population. In the advent of volumetric CT imaging, has the skull X-ray become redundant? Clinical Radiology 73:449-453
29. Renton J, Kincaid S, Ehrlich P (2003) Should helical CT scanning of the thoracic cavity replace the conventional chest x-ray as a primary assessment tool in pediatric trauma? An efficacy and cost analysis. Journal of pediatric surgery 38:793-797
30. Brenner DJ, Elliston CD, Hall EJ, Berdon WE (2001) Estimated risks of radiation-induced fatal cancer from pediatric CT. American journal of roentgenology 176:289-296
31. Wiest PW, Locken JA, Heintz PH, Mettler Jr FA (2002) CT scanning: a major source of radiation exposure. Seminars in Ultrasound, CT and MRI. Elsevier, pp 402-410
32. Blackwell CD, Gorelick M, Holmes JF, Bandyopadhyay S, Kuppermann N (2007) Pediatric head trauma: changes in use of computed tomography in emergency departments in the United States over time. Annals of emergency medicine 49:320-324
33. Brady Z, Cain TM, Johnston PN (2011) Paediatric CT imaging trends in Australia. Journal of medical imaging and radiation oncology 55:132-142
34. Strauss KJ, Goske MJ, Kaste SC, Bulas D, Frush DP, Butler P, Morrison G, Callahan MJ, Applegate KE (2010) Image gently: ten steps you can take to optimize image quality and lower CT dose for pediatric patients. American Journal of Roentgenology 194:868-873
35. Pomeranz CB, Barrera CA, Servaes SE (2022) Value of chest CT over skeletal surveys in detection of rib fractures in pediatric patients. Clinical Imaging 82:103-109
36. Joyce S, O'Connor OJ, Maher MM, McEntee MF (2020) Strategies for dose reduction with specific clinical indications during computed tomography. Radiography (Lond) 26 Suppl 2:S62-S68

37. Hong TS, Reyes JA, Moineddin R, Chiasson DA, Berdon WE, Babyn PS (2011) Value of postmortem thoracic CT over radiography in imaging of pediatric rib fractures. Pediatric radiology 41:736-748
38. Culotta PA, Crowe JE, Tran Q-A, Jones JY, Mehollin-Ray AR, Tran HB, Donaruma-Kwoh M, Dodge CT, Camp EA, Cruz AT (2017) Performance of computed tomography of the head to evaluate for skull fractures in infants with suspected non-accidental trauma. Pediatric radiology 47:74-81
39. Sanchez T, Stewart D, Walvick M, Swischuk L (2010) Skull fracture vs. accessory sutures: how can we tell the difference? Emergency radiology 17:413-418
40. Alzahrani NM, Jeanes A, Paddock M, Shuweihdi F, Offiah AC (2021) 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
41. Lonergan GJ, Baker AM, Morey MK, Boos SC (2003) From the archives of the AFIP: child abuse: radiologic-pathologic correlation. Radiographics 23:811-845
42. Kleinman PK, Marks SC, Adams VI, Blackbourne BD (1988) Factors affecting visualization of posterior rib fractures in abused infants. American Journal of Roentgenology 150:635-638
43. Kleinman PK, Marks SC, Spevak MR, Richmond JM (1992) Fractures of the rib head in abused infants. Radiology 185:119-123
44. Pennell C, Aundhia M, Malik A, Poletto E, Grewal H, Atkinson N (2021) Utility of skull radiographs in infants undergoing 3D head CT during evaluation for physical abuse. Journal of pediatric surgery 56:1180-1184
45. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, Shamseer L, Tetzlaff JM, Akl EA, Brennan SE (2021) The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. International journal of surgery 88:105906
46. Whiting PF, Rutjes AW, Westwood ME, Mallett S, Deeks JJ, Reitsma JB, Leeflang MM, Sterne JA, Bossuyt PM, Group* Q- (2011) QUADAS-2: a revised tool for the quality assessment of diagnostic accuracy studies. Annals of internal medicine 155:529-536
47. Forbes-Amrhein MM, Gensel AJ, Cooper ML, Karmazyn B (2022) Multi-modality imaging characteristics of costochondral fractures, a highly specific rib fracture for child abuse. Pediatric radiology 52:910-923
48. Karmazyn B, Marine MB, Wanner MR, Cooper ML, Delaney LR, Jennings SG, Eckert GJ, Hibbard RA (2022) Chest CT in the evaluation of child abuse–When is it useful? Child Abuse & Neglect 133:105823
49. Cosgrave L, Bowie S, Walker C, Bird H, Bastin S (2022) Abusive head trauma in children: radiographs of the skull do not provide additional information in the diagnosis of skull fracture when multiplanar computed tomography with three-dimensional reconstructions is available. Pediatric Radiology 52:924-931
50. Niederkrotenthaler T, Xu L, Parks SE, Sugerman DE (2013) Descriptive factors of abusive head trauma in young children—United States, 2000–2009. Child abuse & neglect 37:446-455
51. Brady Z, Ramanauskas F, Cain TM, Johnston PN (2012) Assessment of paediatric CT dose indicators for the purpose of optimisation. Br J Radiol 85:1488-1498
52. Cho S, Sung Y, Kim M (2012) Missed rib fractures on evaluation of initial chest CT for trauma patients: pattern analysis and diagnostic value of coronal multiplanar reconstruction images with multidetector row CT. The British journal of radiology 85:e845-e850

53. Romanyukha A, Folio L, Lamart S, Simon SL, Lee C (2016) Body size-specific effective dose conversion coefficients for CT scans. Radiation protection dosimetry 172:428-437
54. Orman G, Wagner MW, Seeburg D, Zamora CA, Oshmyansky A, Tekes A, Poretti A, Jallo GI, Huisman TA, Bosemani T (2015) Pediatric skull fracture diagnosis: should 3D CT reconstructions be added as routine imaging? Journal of Neurosurgery: Pediatrics 16:426-431

Statements and Declarations

1. ***Funding***

This study has received funding from Taif University

Compliance with Ethical Standards

2. ***Guarantor:***

The scientific guarantor of this publication is Professor Mark McEntee

3. ***Conflict of Interest:***

The authors of this manuscript declare no relationships with any companies, whose products or services may be related to the subject matter of the article.

4. ***Statistics and Biometry:***

No complex statistical methods were necessary for this paper.

5. ***Informed Consent:***

Written informed consent was not required for this systematic review.

6. ***Ethical Approval:***

Institutional Review Board approval was not required for this systematic review.

7. ***Methodology***

Methodology:

- Systematic review

Tables

Table 1: Summary of the Risk of Bias Assessment for the included publications.

Study	RISK OF BIAS			
	PATIENT SELECTION	INDEX TEST	REFERENCE STANDARD	FLOW AND TIMING
Wootton-Gorges et al. 2008 [21]	🟢	🟡	🟢	🟢
Karmazyn et al. 2022 [49]	🟢	🟢	🟢	🟢
Hong et al. 2011 [38]	🟢	🟢	🟡	🟢
Forbes-Amrhein et al. 2022 [48]	🟢	🟢	🟢	🟢
Sanchez et al. 2018 [22]	🟢	🟡	🟡	🟢
Martin et al. 2020 [25]	🟢	🟢	🟢	🟢
Sharp et al. 2018 [27]	🟢	🟡	🟡	🟡
Culotta et al. 2017 [39]	🟢	🟢	🟢	🟢
Cosgrave et al. 2022 [50]	🟢	🟢	🟢	🟡
Pennell et al. 2021[45]	🟢	🟢	🟢	🟡

🟢 Low Risk 🔴 High Risk 🟡 Unclear Risk

Table 2: Data extraction – general information

Study	Fracture location	Sample size	Gender		Mean Age	Gold standard	Radiography				CT			
			M	F			TP	TN	FP	FN	TP	TN	FP	FN
Wootton-Gorges et al. 2008 [21]		12 (225 ribs)	5	7	2.5 mo	NR	79	94	0	52	131	94	0	0
Karmazyn et al. 2022 [49]		50 (1200 ribs)	29	21	9.7 mo	NR	42	1087	0	71	112	1087	0	1
Hong et al. 2011 [38]	Chest	56 (1318 ribs)	27	29	1 y	Autopsy	38	1195	5	66	86	1209	8	15
Forbes-Amrhein et al. 2022 [48]		15 (210 CCJ)	NR		2.5 mo	CT	27	132	0	51	78	130	0	2
Sanchez et al. 2018 [22]		16 (384 ribs)	7	9	6 mo	NR	87	279	0	18	105	279	0	0
Martin et al. 2020 [25]		21	NR		6.8 mo	CT	19	83	0	2	21	83	0	0
Sharp et al. 2018 [27]		94	NR		11 mo	Radiography	11	70	0	13	24	70	0	0
Culotta et al. 2017 [39]	Skull	177	93	84	5 mo	NR	62	108	0	7	67	108	0	2
Cosgrave et al. 2022 [50]		106	NR		10.6 mo	NR	43	51	2	10	52	51	2	1
Pennell et al. 2021 [49]		158	NR		5 mo	NR	40	107	0	11	46	107	0	5

FN, false negative; FP, false positive; TN, true negative; TP, true positive; sz, sample size; mo, months; y, year; CCJ, costochondral junction; NR, not reported.

Table 3: Location of the fractures

Study	Body part	Fractures, n		
		Position	**X-ray**	**CT**
Wootton-Gorges et al. 2008 [21]	Chest	Posterior	24	39
		Posterolateral	3	9
		Lateral	26	16
		Anterolateral	12	21
		Anterior	11	42
Karmazyn et al. 2022 [49]		Posterior	11	27
		Posterolateral	4	5
		Lateral	23	31
		Anterior	2	12
		Costochondral	1	38
Hong et al. 2011 [38]		Posterior	19	37
		Posterolateral	0	1
		Lateral	4	1
		Anterolateral	1	4
		Anterior	14	40
Forbes-Amrhein et al. 2022 [48]		Costochondral	27	78
Sanchez et al. 2018 [22]		Not reported		
Martin et al. 2020 [25]	Skull			
Sharp et al. 2018 [27]				
Culotta et al. 2017 [39]				
Cosgrave et al. 2022 [50]				
Pennell et al. 2021 [45]		Frontal	1	0
		Parietal	33	35
		Occipital	1	3
		Multiple	4	8
		Indeterminate	1	0

Table 4: Diagnostic performance and radiation dose for x-ray and CT

Study	%				AUC		Radiation dose mSv	
	Sensitivity		Specificity					
	X-ray	CT	X-ray	CT	X-ray	CT	X-ray	CT
Wootton-Gorges et al. 2008 [21]	60.3	100	100	100	0.9 (0.8 - 1)	1	NR	
Karmazyn et al. 2022 [49]	37.2	99	100	100	0.84 (0.69 - 1)	0.998 (0.99 -1)	0.06	G1: 0.45 G2: 0.17 G3: 0.14
Hong et al. 2011 [38]	36.5	85.1	99.6	95.6	0.84 (0.68 - 0.99)	0.96 (0.92 - 0.99)	NR	
Forbes-Amrhein et al. 2022 [48]	34.6	97.5	99.2	100	0.84 (0.67 -1)	0.99 (0.98 - 1)	0.22	0.77
Sanchez et al. 2018 [22]	82.9	100	100	100	0.96 (0.91 - 1)	1	0.35	0.48
Martin et al. 2020 [25]	90.5	100	90	100	0.98 (0.95 - 1)	1	0.009	2.15
Sharp et al. 2018 [27]	45.8	100	100	100	0.86 (0.73 - 1)	1	0.04	1.6
Culotta et al. 2017 [39]	89.6	97	98.2	93.9	0.97 (0.95 - 1)	0.99 (0.98 - 1)	0.059	4.2
Cosgrave et al. 2022 [50]	81	98	98	96	0.94 (0.89 - 0.98)	0.99 (0.97 - 0.998)	Not reported	1.6
Pennell et al. 2021 [45]	78.4	90.2	100	100	0.95 (0.98 - 1)	0.98 (95 – 1)	NR	

G, group; AUC, area under the curve; mSv, millisievert; NR, not reported.