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FULL PAPER

Comparison and optimization of imaging techniques in suspected physical abuse paediatric radiography

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Objective: This study compares protocols in clinical use for paediatric suspected physical abuse (SPA) radiographic imaging across four National Health Service Trusts in the UK. The patient dose delivered from a SPA skeletal survey was compared between two sites using different imaging technology. Additionally, the technique in use for the abdomen anteroposterior (AP) radiographic projection was optimized at one of the participant sites.

Methods: Retrospective data collection was performed to compare SPA protocols. Exposure details and patient dose data for SPA skeletal surveys were collected and compared. SPA skeletal surveys were performed on two anthropomorphic paediatric phantoms using two digital imaging systems. Effective dose (ED) was calculated using a dose calculator software (PCXMC v. 2.0, STUK, Helsinki, Finland) and used as a quantification of the radiation risk. For the optimization study, abdomen AP radiographs of the phantoms were acquired over a range of tube potentials (40–117 kV) for constant ED

on a digital radiography (DR) system. The contrast-to-noise ratio (CNR) between “bone” and “soft tissue” in the images was measured and used as an indicator of image quality.

Results: This study showed that there is a variation in the protocols and a range of techniques in use for SPA imaging across the four participant sites. The skeletal surveys undertaken on the newborn phantom at two sites resulted in an ED of $57 \pm 3 \mu\text{Sv}$ and $90 \pm 4 \mu\text{Sv}$, on the DR unit and digital radiography/fluoroscopy (dRF) unit, respectively. Measurements of the abdomen AP projection achieved an improved CNR (4%) at a lower tube potential (55 kV) without increasing ED, compared with the current clinical setting (64 kV).

Advances in knowledge: This study showed that an improved CNR can be achieved for newborn and 1-year-old abdomen AP radiographs using 0.1 mm copper filtration and a reduced kV (55 kV) without increasing ED.

BACKGROUND

In suspected physical abuse (SPA), skeletal surveys are performed because bone fractures are the most common presentation of SPA, after soft tissue bruising and burns.¹ The current national guidelines [Royal College of Radiologists/Society and College of Radiologists (RCR/SCoR)] recommend a full skeletal survey with 25 projections for small children and 34 for large children.² The mean age of patients presenting with SPA is typically very low (<1-year-old).¹³ It is essential that a diagnosis of abuse is not missed, as evidence shows that in 50–80% of fatal or near-fatal abuse cases there was evidence of prior abusive injuries.¹ Therefore, ensuring that images with optimal image quality for the diagnosis are produced is essential.

The 2008 RCR/RCPC guidelines have recently been updated and replaced by new 2017 RCR/SCoR SPA guidelines, which recommend an increased number of radiographic projections as part of the skeletal survey.^{3–5} The 2008 RCR/RCPC guidelines recommend that optimized digital systems or high-resolution computed radiography systems should be used for SPA imaging and that all imaging systems should be part of a rigorous routine quality assurance programme.⁵ The new 2017 guidance does not provide any additional advice on imaging modality or technique.² The current European Union (EU) guidelines for paediatric radiography have not been updated since 1996 and do not reflect the advances in X-ray technology over the past 20 years.⁶ Therefore, it is important to undertake optimization studies on digital X-ray systems to

identify the most suitable technique for each type of examination and explore technology to their full potential.

There are currently global campaigns to support studies to reduce paediatric dose whilst ensuring the optimal image quality is achieved. Two major campaigns are “Image Gently” promoted by the Society of Paediatric Radiology, and the European Society of Radiology Paediatric Diagnostic Reference Level (DRL) project, “PiDRL”.^{7,8} The PiDRL project has been tasked since December 2013, with developing European DRLs for paediatric imaging; the availability of this resource will help to harmonize and optimize paediatric dose and imaging techniques across different hospitals. There are currently no paediatric national (UK) DRLs for SPA skeletal survey examinations or for individual radiographs.

Other authors have shown that using a lower kV can give better image quality for paediatric imaging. Jones et al reported that an improved clinical image quality can be achieved for paediatric ankle radiographs by using 40 kV instead of 55 kV, and removing any additional filtration.⁹ This finding was contrary to current EU guidelines on paediatric imaging which were established for screen-film technology, and state that filtration and tube voltages greater than 60 kV should be used.⁶

The purpose of this study was two-fold; firstly, to assess the current practice in place for SPA imaging, and compare protocols in use between sites, and with national guidance; secondly, to explore the potential to optimize tube voltage and X-ray beam filtration combination to improve image quality without detrimental impact on radiation dose to paediatric patients.

METHODS AND MATERIALS

Assessment of current practice for SPA radiographic imaging

Prior to this study, an ethics approval questionnaire from the National Health Service (NHS) Health Research Authority was completed. The result of the questionnaire deemed that this study would not require ethical approval from the NHS Research Ethics Committees according to the criteria of the NHS Health Research Authority.¹⁰

Four London-based hospitals participated in the study; radiographic SPA standard operating procedures, including exposure factors and equipment set up, were collected for comparison. The details listed in these local documents were compared with each other and with national guidance, and the similarities and differences summarized. This work was led by clinical scientists and had input from a consultant paediatric radiologist and a radiographer with experience in paediatric imaging.

All SPA skeletal survey examinations undertaken between September 2012 and June 2015 were considered for analysis. Dose–area product (DAP) values for each SPA examination were extracted from the Digital Imaging and Communications in Medicine headers of images where possible (Sites A and B), and from the Radiology Information System (RIS) otherwise (Site C). No DAP data could be extracted from Site D as SPA skeletal surveys were not uniquely coded.

Dose comparison between sites

A phantom study was performed to assess and compare the dose and image quality for SPA skeletal surveys at two participant sites (Sites C and D). A newborn CIRS ATOM phantom (Computerized Imaging Reference Systems, Inc., Norfolk, VA) was used.¹¹

Radiographers employed at each site positioned the phantom and carried out the SPA skeletal survey following the local protocol.

An Ysio digital X-ray system (digital radiography, DR), and an Axiom Luminos dRF X-ray system (dRF) (both from Siemens Medical Solutions, Erlangen, Germany) operating in digital acquisition mode were used. Both units are currently used to perform SPA skeletal surveys.

Exposure factors (kV, mAs) and geometry used (focus-to-image plane distance, radiation field size) were recorded for all exposures undertaken. Additional details of the X-ray systems used, and key quality control metrics were also collected (model, X-ray tube filtration, anode angle, image receptor technology).

An estimate of ED was calculated using PCXMC v. 2.0 software package (the Finnish Radiation and Nuclear Safety Authority, Helsinki, Finland) for the SPA skeletal survey performed at each site.¹² The entrance surface air kerma was used as the input dosimetric quantity. Figure 1 shows the digital X-ray image acquired of the newborn CIRS ATOM phantom, and Figure 2 shows the corresponding PCXMC phantom used for dose calculation for the newborn phantom's right femur.

Optimization study

The optimization study was carried out using an Ysio digital X-ray system, with a direct digital flat panel detector (Siemens Medical Solutions, Erlangen, Germany). This system has an image receptor composed of a Caesium Iodide scintillator layer coupled to a thin film transistor matrix with amorphous silicon technology.¹³ The pixel pitch is 144 µm, and the active detector area is approximately 34 × 43 cm. The maximum spatial resolution of the system is mainly limited by its pixel pitch.

From the retrospective assessment of current practice, the radiographic views with the highest dose (DAP) were identified: anteroposterior (AP) skull, lateral skull, lateral spine, AP abdomen.

The AP abdomen projection was selected for optimization. It is an important view as it includes part of the ribs, the spine, the pelvis and hips, all of which could show occult fractures unavailable in other views.⁵ Fractures in the spine can be easily overlooked due to the soft tissue overlay, hence, the AP abdomen projection must be of excellent image quality to enable small low contrast details to be observed; this may incur a relatively high radiation dose compared with the other projections.

For this part of the study, a full SPA skeletal survey was performed by local radiographers on both the newborn and 1-year-old phantoms, following the current clinical protocol. The entrance

Figure 1. Digital X-ray image acquired using a Siemens Ysio X-ray unit. It shows the right femur of the CIRS ATOM newborn phantom. The CIRS ATOM anthropomorphic dosimetry phantoms are constructed from tissue-equivalent epoxy resins, and homogenous material that represents age appropriate average bone composition. The phantoms have 25 mm thick slices, and TLD locations specific to inner organs to allow dosimetry. TLD, thermoluminescent dosimeter.

surface air kerma values measured were used to calculate the effective dose (ED) in PCXMC.

The current technique for abdomen AP radiographs for patients under 2-years-old at the paediatric specialist site is to use 64 kV, 3.2 mAs, with additional 0.1 mm copper (Cu) and using fine focal spot.

The CIRS ATOM anthropomorphic dosimetry phantoms are constructed from tissue-equivalent epoxy resins and

Figure 2. The right femur being simulated in PCXMC v. 2 for the newborn phantom. The clinical image is used to align the beam with the anatomy to ensure that the dose calculation is as representative of the clinical situation as possible.

homogenous material that represent age appropriate average bone composition.¹¹ The phantoms are composed of 25 mm thick slabs, and contain thermoluminescent dosimeter locations specific to inner organs to enable internal organ dosimetry.

Abdomen AP exposures were performed on both the newborn and 1-year-old phantoms over a range of tube voltages (40–117 kV) with and without additional 0.1 mm copper filtration at constant ED. A focus-to-image distance (FID) of 115 cm was set and no antiscatter grid was used.

The PCXMC software was used to determine the appropriate tube current–time product (mAs) to deliver an ED that matched the current clinical ED, at each tube voltage investigated.

10 images were acquired for the newborn phantom over the tube voltage range stated above, with and without phantom copper

filtration. 10 images were also acquired over the same exposure conditions for the 1-year-old phantom.

To calculate the contrast-to-noise ratio (CNR), the mean pixel value and standard deviation were measured and recorded for regions of interest (ROIs) drawn in the “spinal vertebra” and the surrounding “soft tissue” background of the phantom images. Six

pairs of measurements (in the anatomy and surrounding background) were undertaken on each phantom image to improve statistical accuracy.

The CNR was calculated using the mean pixel value measured within the “bone” (μ_{ct}) and surrounding soft tissue (μ_{bg}), and the standard deviation (σ_{bg}) as shown in Equation 1. The system

Table 1. Summary of the radiographic views included in the protocols for paediatric patients (<16 years) undergoing an SPA skeletal survey at the four participant hospitals

	Site A	Site B	Site C	Site D (<6 months)	Site D (>6 months)
Imaging technology	DR & CR	DR	Digital R/F	DR	DR
Views obtained as standard protocol	Views in protocol	Views in protocol	Views in protocol	Views in protocol	Views in protocol
AP skull	X	X	X	X	X
Lat skull	X	X	X	X	X
AP chest (including clavicles)	X	X	X	X	X
Rt obl chest	X	X	X	X	X
Lt obl chest	X	X	X	X	X
C. spine	X	X	–	–	–
Lat spine (up to 3 views—AP c. spine should not be standard)	X	X	X	X	X
AP of abdomen including the pelvis and hips.	X	X	X	X	X
AP Rt humerus	X	X	X	X ^a	X
AP Rt forearm	X	X	X		X
AP Lt humerus	X	X	X	X ^a	X
AP Lt forearm	X	X	X		X
Rt elbow	X	–	–	–	–
Lt elbow	X	–	–	–	–
Rt hand PA	X	X	X	X	X
Lt hand PA	X	X	X	X	X
Rt femur AP	X	X	X	X ^a	X
Rt tibia/fibular AP	X	X	X		X
Lt femur AP	X	X	X	X ^a	X
Lt tibia/fibular AP	X	X	X		X
Rt knee	X	–	–	–	–
Lt knee	X	–	–	–	–
Rt ankle lat	X	X	–	X	X
Lt ankle lat	X	X	–	X	X
Rt DP foot	X	X	X	X	X
Lt DP foot	X	X	X	X	X
Rt oblique foot	X	–	–	–	–
Lt oblique foot	X	–	–	–	–
Total	28	22	19	17	21

AP, anteroposterior; CR, computed radiography; SPA, suspected physical abuse.

^aLimbs are not split into upper and lower regions; whole limbs are acquired in one image.

Figure 3. The mean DAP for each SPA skeletal survey view at Sites A and B. The four highest dose views from both sites are abdomen, lateral spine, AP and lateral skull. The uncertainty bars show the standard error in the mean. DAP, dose-area product; SPA, suspected physical abuse.

transfer properties of the digital system were used to linearize the pixel values measured on the images.^{14, 15}

$$CNR = \frac{(\mu_{ct} - \mu_{bg})}{\sigma_{bg}} \quad (1)$$

Equation 1 describes the CNR.^{14, 15}

The CNR measurements obtained using different exposure settings were compared statistically. Using SPSS v. 23.0 statistical analysis software (International Business Machines Corp., Armonk, NY) the Shapiro–Wilk test was performed to assess the normality of the data and the Mann–Whitney test was used to compare non-parametric data samples.¹⁶

RESULTS

Assessment of current practice

There was a large variation in the number of views included in SPA skeletal survey; a range of 17–28 views was found in the protocols analysed (Table 1).

A total of 79 SPA examinations were analysed across sites A and B (64 cases from Site A and 15 cases from Site B). The four views with the highest dose (recorded DAP) (AP abdomen, lateral spine, AP and lateral skull) were the same at both sites (as shown in Figure 3), although they ranked differently.

These views were expected to have the highest DAP because they involve the most attenuating parts of the body, and require

a larger radiation field to cover the intended anatomy, than most other views.

Dose comparison between sites

The estimated ED for the SPA skeletal survey with the DR system was $57 \pm 3 \mu\text{Sv}$; a higher ED, $90 \pm 4 \mu\text{Sv}$, was obtained for the dRF system. The expressed uncertainties originate from the uncertainties of the risk models used by PCXMC dose calculator.

Optimization study

The abdomen AP view had the highest calculated ED to the newborn phantom, and the second highest dose to the 1-year-old phantom, on the Siemens Ysio unit.

10 AP abdomen exposures were performed over a tube voltage range (40–117 kV) for both newborn and 1-year-old phantoms. The nearest available mAs setting that matched the intended ED calculated by PCXMC was used.

The relationships between CNR and kV for each phantom are shown in Figures 4 and 5.

An improved CNR was observed at 55 kV for both phantoms compared with the 64 kV in current clinical use (Table 2). This difference was found to be statistically significant ($p < 0.05$). There are two atypical results in Figures 4 and 5 at 45 kV and 117 kV, where higher than expected CNRs have been measured.

Figure 4. The calculated CNR to the newborn phantom. These results are for CNR measured on the spine, for exposures of a newborn phantom using 0.1 mm Cu additional filtration. The clinical CNR data point represents the CNR for current clinical settings. The error bars represent the standard deviation. CNR, contrast-to-noise ratio.

The CNR is higher at 117 kV due to the image acquisition at a higher than intended dose. Although the intended mAs was 0.36 mAs and 0.43 mAs for the newborn and 1-year-old respectively, the value set for the acquisition was 0.5 mAs, the minimum available on the unit. This resulted in a dose almost 40% greater than intended and subsequently an increased CNR. Further investigation is needed to determine the cause of the unexpectedly high CNR measured at 45 kV. Although it is not certain why this peak occurs, it is possible that a k-edge in the detector material (Caesium Iodide) could have caused this result.¹⁷

DISCUSSION

Cross-site data collection

This study has shown a great variation (17–28 views) in the standard protocols in clinical use for SPA skeletal survey. Only one site had specific protocols for different size children. The recent updates in the national RCR/SCoR guidance recommend 25 and 34 views as standard for small and large children, respectively.² A clinical audit should be carried out at the site performing larger number of views as standard practice to determine the clinical value brought in by the additional views to the diagnosis. Similarly, an audit would be beneficial at the remaining three sites to determine whether the images being acquired provide sufficient clinical information to make a diagnosis, or whether further views could add value to the diagnosis in line with the current guidance.¹⁸

Dose values were collected across the four NHS sites; data collected from the Digital Imaging and Communications in Medicine header are more robust than that obtained from RIS, because they are automatically recorded by the imaging system. Data available on RIS are entered manually, and therefore, more prone to transcription errors. All data included in the study were screened for accuracy prior to analysis. Missing values were excluded and outliers were individually analysed; data points that differed by more than a factor of 10 from the mean DAP were considered to be incorrect entries and were excluded from the analysis. Some outliers were identified as being recorded in the wrong units and these were converted accordingly.

Another disadvantage of collecting dose data from RIS is that frequently, only the total exam DAP is available, and not the DAP from each individual exposure. This still allows the estimation of ED, but does not allow estimation of the individual organ doses.

At one site, it was not possible to identify the SPA skeletal surveys, as all skeletal survey examinations were assigned the same RIS code, regardless of the clinical indication. The number of projections, the imaging technique used as well as the average age of the patient varies depending on the clinical purpose of the skeletal survey.¹⁹ Skeletal surveys can be used as a diagnostic tool for a number of different indications including skeletal dysplasia; metabolic and metastatic bone disease; and

Figure 5. The calculated CNR to the 1-year-old phantom. These results are for CNR measured on the spine, for exposures of a 1-year-old phantom using 0.1 mm Cu additional filtration. The clinical CNR data point represents the CNR for current clinical settings. The error bars represent the standard deviation. CNR, contrast-to-noise ratio.

osteogenesis imperfecta, all of which will have different protocols with different views required.¹⁹ Therefore, it is not advisable to group all skeletal survey examinations in this way, as it can make dose audits difficult and of limited value.

Optimization

Paediatric phantoms that appear anatomically realistic on an X-ray image are extremely difficult to source and much less common than adult phantoms. In this study, an appropriate clinically accurate phantom could not be sourced.

The phantoms used in this study are tissue equivalent and provide radiographic characteristics similar to those offered by human tissue. However, the anatomical structures contained within the phantoms are not clinically realistic; and do not enable a qualitative visual image quality assessment.

The current EU guidelines for paediatric radiography have not been updated since 1996 and do not reflect the advances in X-ray technology over the past 20 years. Therefore, it is important to undertake optimization on X-ray equipment, to determine whether these changes in technology have impacted the validity of the advice in the EU guidelines, such as in the study at Evelina Children's Hospital.^{6,9}

The guidelines currently advise the following settings for an abdomen AP exposure:⁶

- 100–115 cm FID
- 0.1 or 0.2 mm Cu additional filtration
- No antiscatter grid, for children <6 months
- Tube voltage 65–85 kV
- Manual exposure (mA) technique

Table 2. Exposures were performed over a range of tube voltages (kV) to determine at which kV the highest CNR could be achieved

Phantom	CNR		Statistical significance between values using SPSS Mann–Whitney test (<i>p</i> -values)
	55 kV 6 mAs	64 kV 3.2 mAs	
Newborn	13.4	13.0	0.011
1-year-old	11.8	11.1	0.039

CNR, contrast-to-noise ratio.

The peak CNR was measured at 55 kV, which can be compared with the current clinical CNR for both the newborn and 1-year-old phantom. These exposures were performed using 0.1 mm additional copper filtration in the beam.

The results of this study showed that an improved CNR can be achieved by altering the EU recommended settings for abdomen AP exposure as follows:

- 115 cm FID
- 0.1 mm Cu additional filtration
- No grid for all children <2 years
- Tube voltage 55 kV
- Manual exposure (mA) technique

This study has shown that using 55 kV and 0.1 mm Cu for abdomen imaging on both newborn and 1-year-old patients resulted in a statistically significant improvement of CNR without impact on ED. The proposed changes in the X-ray settings cause a small increase in skin dose (5.1% for newborn; 9% for 1-year-old), which remains well below the threshold for deterministic effects.²⁰

This is contradictory to the current EU guidance, which recommends a tube voltage of 65–85 kV.⁶ However, this guidance pre-dates the introduction of digital systems, which have been in use since the early 1990s and have been extensively validated since. DR systems can produce adequate radiographic image quality at lower tube voltages when compared with screen-film systems, as they exhibit wider dynamic range and higher detective quantum efficiency.²¹

CNR is an important metric of image quality as it impacts on the visibility of subtle contrast variations and anatomical details. However, other image quality descriptors such as spatial resolution are also important, particularly when trying to determine small, subtle fractures. One of the limitations of this study was that it has not assessed the effect of the reduction of tube voltage on spatial resolution and overall clinical image quality. This was due to the limitations posed by the paediatric phantoms used.

CONCLUSIONS

This study showed that there is noticeable variation in SPA skeletal survey protocols across sites and this has an impact on patient dose.

The SPA skeletal survey performed on the paediatric anthropomorphic phantoms at two sites (C & D) using the local protocols

showed that lower dose was achieved with the DR imaging system compared with the DRF system.

DR systems, where available, should be preferred for paediatrics examinations as they offer improved potential for dose reduction compared with other technologies. However, optimization of each individual system is still required and the conclusions of this study should not be transferred on to other imaging systems without prior validation.

Further investigation on the potential to optimize abdominal AP radiographs with the DR system showed that improved CNR could be achieved for both newborn and 1-year-old phantom when the kV was reduced from the current 64 kV to 55 kV, maintaining 0.1 mm Cu filtration.

This finding would benefit from clinical validation to ascertain if a similar improvement trend is observed in clinical image quality. This could be achieved by using a paediatric phantom with suitable features for assessment of clinically relevant image quality criteria. If a realistic phantom cannot be sourced, a pilot study could be implemented using the proposed reduced exposure settings. This should include close observation of image quality by paediatric radiologists to ensure it is deemed appropriate for the intended clinical task.

Further to the recent updates in the RCR/SCoR guidance for SPA imaging, advice on preferred imaging technology, recommended exposure technique and factors, and optimized protocols possibly adapted according to patient age, weight, or other suitable size metric would be very useful.² This would also help to promote harmonization in SPA radiographic imaging across centres.

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