






ORIGINAL ARTICLE

Comparison of typical radiation doses and risks using an anthropomorphic 'bone fracture' phantom for commonly performed X-ray projections in a 5-year-old

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Abstract

Introduction: Diagnostic reference levels (DRLs) are typical dose levels for medical imaging examinations for groups of standard-sized patients or standard phantoms for broadly defined types of equipment used as a tool to aid optimisation of protection for medical exposures. Currently, there are no paediatric DRLs for conventional radiography (i.e. general X-rays) published in Australia. The aim of this study was to establish typical radiation doses and risks that are representative of those delivered for commonly performed X-ray projections for a 5-year-old/20 kg child using a 5-year-old anthropomorphic 'bone fracture' phantom in three dedicated paediatric radiology departments in Victoria. **Methods:** A total of 20 projection images were acquired for a standard 5-year-old/20 kg phantom using digital radiography X-ray equipment. The air kerma-area product (KAP) measured at each centre by a KAP metre, which was calibrated to a national primary standard, was considered to represent the median value for that centre for each X-ray projection. Organ doses and effective dose were estimated using PCXMC software, and risks of radiation-induced cancer and radiation-induced death were calculated based on the BEIR VII report. **Results:** The typical doses for the individual X-ray projections ranged from 3 mGy•cm² to 86 mGy•cm², whilst the effective doses ranged from 0.00004 to 0.07 mSv. The radiation risks were 'minimal' to 'negligible'. **Conclusion:** The estimation of typical radiation doses and associated risks for a 5-year-old/20 kg phantom study provides reference values for guidance and is a first step in assisting optimisation at other institutions until national DRLs, based on patient data from the clinical setting, are published.

Introduction

Diagnostic reference levels (DRLs) are not dose limits; they were first introduced in European legislation in 1997 where the definition in Article 2 of 97/43/Euratom defines DRLs as meaning 'dose levels in medical radiodiagnostic...practices...for typical examinations for groups of standard-sized patients or standard phantoms for broadly defined types of equipment. These levels are

not expected to be exceeded for standard procedures when good and normal practice regarding diagnostic and technical performance is applied'.¹ ICRP Publication 135 outlines the considerations when conducting DRL surveys, how to collect data for radiography examinations including a separate section dedicated to paediatric DRLs, as well as how to apply DRLs in clinical practice.² It is recommended that individual centres calculate the median dose level and that a national DRL is then

calculated as the 75th percentile of the medians from each centre.²

DRLs are not mentioned in the Australian Radiation Protection And Nuclear Safety Act.³ Although the Australian Radiation Protection And Nuclear Safety Agency (ARPANSA) now collects DRL data for CT, nuclear medicine and interventional radiology, there are no Australian DRLs for conventional radiography. Therefore, a phantom study provides a convenient first step for evaluating the performance of radiography equipment.² New South Wales is the first state to introduce a compliance requirement (section 3.4 of Radiation Standard 6, Part 2), which states that 'Dosimetric evaluation of diagnostic procedures should be conducted as part of the QA program. Practice DRLs for common X-ray examinations should be established'.⁴ Whilst it provides the UK adult DRLs from 2010 as the reference standard, there are no recommended DRLs for paediatric X-rays. ICRP Publication 135 recommends that paediatric X-ray DRLs are calculated according to weight, rather than age.² A Scandinavian group compared regional DRLs to European, French and Irish DRLs with limited success due to insufficient numbers in the weight bands.⁵ As the 5-year-old phantom used in this study is a standard-sized phantom weighing 20 kg, it falls within the middle weight band of 15–30 kg recommended by the ICRP.

The ARPANSA Code for Radiation Protection in Medical Exposure (Code 5) requires imaging facilities to determine typical doses to patients for common imaging procedures and to ensure that the patient, or their representative, is informed of the benefits and risks of procedures.⁶ Establishing typical levels of dose and assessing the radiation risks assists staff in discussing benefit and risk with patients and their care-givers.

This phantom study aims to establish typical radiation doses at three dedicated paediatric centres who do not have this information already available. Centre A is a tertiary paediatric hospital and in the period from January to December 2022, performed a total of 8500 radiographs. In the period January to December 2022, Centre B's medical imaging department imaged approximately 15,500 patients in X-ray and CT, and acquired over 15,000 radiographs. In the period January to December 2022, the medical Imaging department of Centre C imaged 10,330 patients of which 8265 were X-rays.

A phantom study is a first step to establish typical radiation doses prior to patient-based DRLs in Australia. The aim of this study was to establish typical radiation doses and risks that are representative of those delivered for commonly performed X-ray projections for a 5-year-old/20-kg child using the Kyoto Kagaku bone fracture paediatric phantom (PBU-70B) in three dedicated paediatric radiology departments in Victoria using their

pre-programmed exposure factors for a 5-year-old/20-kg child.⁷

Materials and methods

Ethical considerations

As this was a phantom study, the Human Research Ethics Committees at Centres A, B and C confirmed that no ethical approval was required. Permission was granted by the Chief Radiographer at each of the three dedicated paediatric centres to perform imaging using the only commercially available 5-year-old anthropomorphic 'bone fracture' phantom, which measures 109 cm and weighs 20 kg.⁷ A Research Collaboration Agreement was signed for Centre B.

Data collection

A radiographer with 17 years of postgraduate experience attended each centre in 2021 and acquired the projections listed in Table 2 to ensure that the radiographic technique was consistent. At each centre, the pre-programmed exposure factors for each projection including peak tube kilovoltage (kV_p), tube current-time product (mAs), source to image distance (SID) and air kerma-area product (KAP) measurements were recorded for each X-ray projection acquired on the phantom. The KAP measurements represent the output emitted by the X-ray tube before entering the phantom and are a standardised metric to determine radiation dose in general radiography when establishing DRLs (i.e. typical doses).⁸ The KAP values were divided by the irradiated area to calculate the air kerma at the image receptor in the absence of the patient, which is another standardised metric used to measure radiation dose.

Dose standardisation

Inter-site KAP measurements can vary by as much as $\pm 35\%$.⁹ As recommended by ICRP Publication 135, the KAP measured at each centre was calibrated to a national standard using a PTW Diamantor CD-R KAP metre (PTW Freiburg GmbH, Germany).² This approach enabled the true KAP to be calculated using the substitution method so that the radiation doses between the three centres could be compared.¹⁰

The calibrated mobile KAP metre (PTW Diamantor) was brought to each of the three dedicated paediatric centres and used to acquire readings with a standardised irradiated field. This established the calibration factor for each site-specific KAP metre, which was applied to the KAP readings for each of the individual X-ray projections,

thereby minimising the error associated with variability of the KAP metre measurements between the three centres.

X-ray equipment and dose calculation software

The X-ray equipment used at each of the three dedicated paediatric centres is listed in Table 1. All X-ray equipment at the three centres was digital radiography (DR) units. The radiographer collimated to include the relevant anatomical information for each X-ray projection according to local protocol using the 5-year-old/20-kg phantom and the local pre-programmed exposure factors for a 5-year-old child (Table 2).

The KAP values measured in $\mu\text{Gy}\cdot\text{m}^2$ or $\text{dGy}\cdot\text{cm}^2$ at each centre were converted to 'true' KAP values in $\text{mGy}\cdot\text{cm}^2$ and rounded to the nearest whole number. This was performed using the substitution method, as described in a previous publication.¹¹

PCXMC software (STUK, Vantaa, Finland) is routinely used to calculate organ doses and effective doses by medical physicists.¹² The doses can be calculated in 29 organs and tissues, and the software can estimate the effective dose with the current tissue weighting factors of ICRP Publication 103.¹³ The kV_p , SID, height and width of each X-ray image were entered into PCXMC, along with the KAP to estimate the effective dose (mSv) for each individual projection at each of the three dedicated paediatric centres. The software calculations were based on the Monte Carlo method to estimate organ absorbed doses for each projection, using the height and weight of a 5-year-old child, 109 cm and 20 kg.¹⁴

Radiation risks for 5-year-old males and females for each X-ray projection at each of the three dedicated paediatric centres were estimated using data published in the BEIR VII report, Table 12D-1 for radiation-induced cancer and Table 12D-2 for radiation-induced death.¹⁵

Table 1. Specifications of the X-ray equipment used in each of the dedicated paediatric imaging centres.

Imaging centre	X-ray Tube	Filtration	Detector
A	Siemens Multitom Rax (Erlangen, Germany)	Total filtration ≥ 2.5 mm Al	MAX wi-D
B	GE Optima XR656 (USA) with Siemens X-ray tube (Erlangen, Germany)	Inherent filtration of not less than 2.7 mm Al at 70 kV_p	'Flash-Pad' flat-panel wireless digital detector
C	GE Discovery XR656 (USA) with Siemens X-ray tube (Erlangen, Germany)	2 mm Al at 70 kV	GE wireless detector

Absorbed doses in organs were multiplied by the organ-specific lifetime attributable risks (LAR) and then summed to compute the overall risk. A weighted average dose was computed for all organs that did not have an organ-specific risk listed in the BEIR VII report, and this weighted average dose was used to calculate the contribution of 'other solid cancers' to the overall risk.¹² The table of weighting factors used is provided as Supporting Information. Separate calculations were made for both incidence and mortality, and for males and females. Average risks for each projection were calculated by averaging the results for both sexes at each centre and then averaging across the three centres. The spreadsheet containing the formulae for the risk calculations is available on request from the corresponding author.

Results

Exposure factors and radiation dose

The pre-programmed exposure factors (kV_p , mAs and SID) used to acquire each projection at each dedicated paediatric centre, along with the air kerma, KAP and effective dose, are presented in Table 2. There was variation in the kV_p and mAs used at each of the three centres, whilst the SID ranged from 100 to 180 cm with 115 cm used consistently in Centre A and 100 cm used consistently in Centre B, except for the PA chest projections where an increased SID was utilised in all three centres.

The KAP recorded for the individual X-ray projections at each centre is presented in Tables 2 and 3, and was found to vary from 2.5 $\text{mGy}\cdot\text{cm}^2$ for a lateral wrist X-ray projection in Centre B to 86.2 $\text{mGy}\cdot\text{cm}^2$ for an oblique projection of the ribs in Centre B. The effective doses presented in Table 2 for the individual X-ray projections ranged from 0.00004 mSv for a lateral projection of the wrist in Centre B to 0.07 mSv for an oblique projection of the ribs in Centre B.

The typical KAP for the individual X-ray projections of the axial skeleton at each centre presented in Table 3 ranged from 34 $\text{mGy}\cdot\text{cm}^2$ for a lateral projection of the lumbar spine in Centre B to 86 $\text{mGy}\cdot\text{cm}^2$ for an oblique projection of the ribs in Centre B. The typical KAP for the individual X-ray projections of the appendicular skeleton at each centre ranged from 3 $\text{mGy}\cdot\text{cm}^2$ for lateral elbow and wrist X-ray projections in Centre B to 64 $\text{mGy}\cdot\text{cm}^2$ for an antero-posterior (AP) humerus X-ray projection in Centre A.

ICRP Publication 135 recommends that for paediatric radiography, at least two DRL quantities are reported in order to simplify the assessment of proper use of collimation.² Both the air kerma and the KAP values are presented in Table 2. The air kerma was calculated by

Table 2. The exposure factors (kV_p, mAs and SID) used to acquire each X-ray projection for a 5-year-old/20-kg phantom.

X-ray projection	Imaging centre A						Imaging centre B						Imaging centre C					
	kV _p	mAs	SID (cm)	'True' KAP (mGy•cm ²)	Air kerma (mGy)	Eff.dose (mSv)	kV _p	mAs	SID (cm)	'True' KAP (mGy•cm ²)	Air kerma (mGy)	Eff.dose (mSv)	kV _p	mAs	SID (cm)	'True' KAP (mGy•cm ²)	Air kerma (mGy)	Eff.dose (mSv)
SXR – AP	68	2.8	115	35.1	.08	.005	70	8	100	79.0	.3	.01	60	4	120	60.8	.1	.008
SXR – Lat	68	2.8	115	53.3	.08	.006	70	8	100	84.0	.2	.008	60	4	120	70.1	.1	.004
CXR – AP	70	1.6	115	38.1	.05	.02	70	2	100	45.0	.08	.03	70	2.5	120	66.7	.09	.04
CXR-PA	70	1.6	180	38.1	.05	.01	70	2	150	45.0	.08	.02	70	2.5	120	66.7	.09	.02
Ribs – Obl	70	1.6	115	40.3	.05	.02	70	5	100	86.2	.2	.07	65	2.5	120	26.7	.08	.02
CXR – Lat	73	2.5	115	56.7	.05	.02	70	2.5	100	60.2	.1	.03	70	2.5	120	55.4	.09	.03
AXR – AP	64.5	2.8	115	76.4	.07	.03	70	2.5	100	63.7	.09	.04	65	3.2	100	68.8	.1	.03
L sp – Lat	70	4	115	52.2	.1	.01	65	3.2	100	34.3	.08	.01	65	6.3	120	46.5	.2	.01
Humerus – AP	60	2.8	115	64.5	.06	.006	65	2	100	17.9	.07	.001	57	2.5	100	15.3	.06	.001
Elbow – Lat	52	2.5	115	9.2	.04	.0007	60	1	100	2.8	.04	.0001	57	2.5	100	10.9	.06	.0004
Forearm – AP	55	2	115	7.5	.04	.0003	60	1	100	7.5	.03	.0004	57	2.5	100	13.1	.06	.0007
Wrist – Lat	50	2	115	6.3	.03	.0001	60	1	100	2.5	.03	.00004	55	2.5	100	6.6	.06	.0001
Hand – DP	50	1	115	5.2	.01	.0001	60	1	100	7.9	.03	.0001	55	1.25	100	6.8	.03	.0001
Femur – AP	55	1.8	115	22.0	.03	.003	65	3.2	100	47.7	.1	.005	65	4	100	61.3	.1	.01
Knee – AP	60	1.8	115	9.5	.04	.0002	60	2.5	100	10.1	.07	.0002	57	2.5	100	16.1	.06	.0002
Knee – Lat	60	1.8	115	15.7	.04	.0002	60	2.5	100	13.2	.07	.0003	57	2.5	100	17.7	.06	.0003
Tibia and Fibula – AP	57	1.8	115	21.4	.03	.0003	60	2	100	15.7	.05	.0003	55	3.2	100	20.8	.07	.0004
Ankle – AP	52	2	115	5.0	.03	.0001	60	1.6	100	4.9	.04	.0001	55	2.5	100	8.2	.05	.0001
Ankle – Lat	52	2	115	10.1	.03	.0001	60	1.6	100	7.3	.05	.0001	55	2.5	100	10.7	.05	.0002
Foot – DP	50	2	115	6.3	.03	.0001	60	1.6	100	6.7	.04	.0001	55	1.25	100	6.2	.03	.0001

The air kerma, KAP and effective radiation doses for each imaging centre are also presented. Note: The air kerma is calculated at the image receptor in the absence of the patient by dividing the KAP by the area of the image field.

AP, antero-n kerma-area product; kV_p, kilovoltage peak; L sp, lumbar spine.; Lat, lateral; mAs, milliampere second; mGy, milligray; mSv, millisievert; obl, oblique; PA, postero-anterior; SID, source to image distance; SXR, skull X-ray.

Table 3. Typical KAP for each X-ray projection at each dedicated paediatric centre for a 5-year-old/20-kg phantom.

X-ray projection	Imaging centre		
	A (mGy•cm ²)	B (mGy•cm ²)	C (mGy•cm ²)
SXR – AP	35	79	61
SXR – Lat	53	84	70
CXR – AP	38	45	67
CXR – PA	38	45	67
Ribs – Obl	40	86	27
CXR – Lat	57	60	55
AXR – AP	76	64	69
L sp – Lat	52	34	47
Humerus – AP	64	18	15
Elbow – Lat	9	3	11
Forearm – AP	7	7	13
Wrist – Lat	6	3	7
Hand – DP	5	8	7
Femur – AP	22	48	61
Knee – AP	9	10	16
Knee – Lat	16	13	18
Tibia and Fibula – AP	21	16	21
Ankle – AP	5	5	8
Ankle – Lat	10	7	11
Foot – DP	6	7	6

AP, antero-posterior; AXR, abdomen X-ray; C sp, cervical spine; cm, centimetre; CXR, chest X-ray; DP, dorsi-palmar/plantar; DRL, diagnostic reference level; KAP, kerma-area product; L sp, lumbar spine; Lat, lateral; mGy, milliGray; obl, oblique; PA, postero-anterior; SXR, skull X-ray.

dividing the KAP by the irradiated area at the image receptor. The KAP measurements recorded for the individual X-ray projections of the 5-year-old phantom at each centre are considered to be the typical radiation doses for that centre. These doses were presented for each projection in Table 3 and were compared to international patient-based DRLs published by Almen *et al.* in Table 4.⁵

Calculation of radiation-induced cancer and death risks

A summary of the estimated risk of radiation-induced cancer and death calculated for each X-ray projection using the BEIR VII model are presented in Tables 5 and 6.¹⁵ The

LAR of radiation-induced cancer averaged across the three centres ranged from 1 in 280,000,000 (i.e. 1 in 280 million) for a DP hand X-ray projection for both males and females to 1 in 160,000 for an AP abdominal X-ray projection in males and from 1 in 67,000 for an AP chest X-ray projection in females with a gender-averaged highest risk of 1 in 160,000 for an AP abdominal X-ray projection, whereas the risk of radiation-induced death averaged across the three centres ranged from 1 in 800,000,000 (i.e. 1 in 800 million) in males and 1 in 790,000,000 in females for a DP projection of the hand to 1 in 390,000 for an AP abdominal X-ray projection in males and from 1 in 180,000 for an AP chest X-ray projection in females with a gender-averaged highest risk of 1 in 380,000 for an AP abdominal X-ray projection.

Discussion

Whilst radiation dose and image quality are inextricably linked, this study focused on demonstrating the range of effective doses and associated radiation risks for individual X-ray projections for 5-year-old/20-kg children across three dedicated paediatric centres. As the X-ray exposure factors used at each centre were those pre-programmed by senior radiographers locally to image children who present for clinically indicated and justified radiographic examinations, it is assumed that they have been optimised locally to produce diagnostic quality images meeting radiologists' requirements. Whilst the irradiated fields for the projections differ slightly between individual radiographers, the irradiated field should always be collimated to the anatomical regions of interest in accordance with local protocols to keep the dose as low as reasonably achievable (ALARA), so, therefore, it is reflective of clinical practice. The reporting of air kerma in addition to the KAP values demonstrates any significant differences due to collimation and KAP metre accuracy. The KAP readings were those produced locally, which would be the values utilised in a calculation of radiation dose by that dedicated paediatric centre. It is appreciated that radiation doses may be optimised more effectively in specialist paediatric radiology departments compared to non-dedicated paediatric centres. When considering the effect of SID on the radiation doses, this

Table 4. Comparison of results of this phantom study to international DRLs for chest X-ray and abdomen X-rays.⁵

X-ray projection	(Gy•cm ²)				
	Phantom study (Centre A/B/C)	Scandinavian DRL (2022)	Irish DRL (2021)	French DRL (2020)	European DRL (2018)
CXR – AP	.038/.045/.067	.028	.022	.035	.050
AXR – AP	.076/.064/.069	.237	.100	.220	.250

AP, antero-posterior; AXR, abdomen X-ray; CXR, chest X-ray.

Table 5. The estimated radiation risks (1 in...) for radiation-induced cancer for each X-ray projection for a 5-year-old child (average for male/female and gender-averaged across each of the three centres), as calculated from the LAR for cancer incidence in the BEIR VII report.

X-ray projection	Average		Gender-averaged	Risk ¹⁹
	Male	Female		
SXR – AP	640,000	270,000	460,000	Minimal
SXR – Lat	790,000	380,000	590,000	Minimal
CXR – AP	340,000	67,000	210,000	Minimal
CXR – PA	400,000	180,000	290,000	Minimal
Ribs – Obl	420,000	70,000	250,000	Minimal
CXR – Lat	330,000	110,000	220,000	Minimal
AXR – AP	160,000	170,000	160,000	Minimal
L sp – Lat	710,000	540,000	620,000	Minimal
Humerus – AP	15,000,000	8,600,000	12,000,000	Negligible
Elbow – Lat	93,000,000	89,000,000	91,000,000	Negligible
Forearm – AP	48,000,000	46,000,000	47,000,000	Negligible
Wrist – Lat	190,000,000	180,000,000	190,000,000	Negligible
Hand – DP	280,000,000	280,000,000	280,000,000	Negligible
Femur – AP	570,000	1000,000	800,000	Minimal
Knee – AP	20,000,000	19,000,000	19,000,000	Negligible
Knee – Lat	19,000,000	17,000,000	18,000,000	Negligible
Tibia and Fibula – AP	16,000,000	14,000,000	15,000,000	Negligible
Ankle – AP	60,000,000	55,000,000	57,000,000	Negligible
Ankle – Lat	49,000,000	45,000,000	47,000,000	Negligible
Foot – DP	51,000,000	47,000,000	49,000,000	Negligible

The figures have been rounded to two significant figures.

AP, antero-posterior; AXR, abdomen X-ray; CXR, chest X-ray; DP, dorsi-palmar/plantar; L sp, lumbar spine; Lat, lateral; obl, oblique; PA, postero-anterior; SXR, skull X-ray.

Table 6. The estimated radiation risks (1 in...) for radiation-induced death (REID) for each X-ray projection for a 5-year-old child (average for male/female and gender-averaged across each of the three centres), as calculated from the LAR of Cancer Mortality in the BEIR VII report.

X-ray projection	Average		Gender-averaged	Risk ¹⁹
	Male	Female		
SXR – AP	1,600,000	1000,000	1,400,000	Negligible
SXR – Lat	2,000,000	1,600,000	1,800,000	Negligible
CXR – AP	530,000	180,000	360,000	Minimal
CXR – PA	590,000	310,000	450,000	Minimal
Ribs – Obl	700,000	215,000	460,000	Minimal
CXR – Lat	550,000	260,000	410,000	Minimal
AXR – AP	390,000	380,000	380,000	Minimal
L sp – Lat	1,600,000	1000,000	1,400,000	Negligible
Humerus – AP	27,000,000	17,000,000	22,000,000	Negligible
Elbow – Lat	220,000,000	220,000,000	220,000,000	Negligible
Forearm – AP	110,000,000	110,000,000	110,000,000	Negligible
Wrist – Lat	540,000,000	503,000,000	520,000,000	Negligible
Hand – DP	800,000,000	790,000,000	790,000,000	Negligible
Femur – AP	1,800,000	3,000,000	2,400,000	Negligible
Knee – AP	54,000,000	52,000,000	53,000,000	Negligible
Knee – Lat	50,000,000	47,000,000	48,000,000	Negligible
Tibia and Fibula – AP	42,000,000	40,000,000	41,000,000	Negligible
Ankle – AP	160,000,000	150,000,000	150,000,000	Negligible
Ankle – Lat	130,000,000	120,000,000	130,000,000	Negligible
Foot – DP	130,000,000	130,000,000	130,000,000	Negligible

The figures have been rounded to two significant figures.

AP, antero-posterior; AXR, abdomen X-ray; CXR, chest X-ray; DP, dorsi-palmar/plantar; L sp, lumbar spine; Lat, lateral; obl, oblique; PA, postero-anterior; SXR, skull X-ray.

will not change the KAP values as KAP values are constant along the beam axis, and the PCXMC software requires the SID to be entered when calculating the effective radiation dose. The PCXMC software also takes into consideration the proximity of the irradiated field to radiosensitive organs to estimate the effective radiation doses. When trying to put the effective radiation doses into perspective when explaining radiation risks to care-givers or the patient, it should be borne in mind that 30 g of Brazil nuts is associated with emitting 0.001 mSv of ionising radiation which we are unlikely to take into consideration before eating.¹⁶

Table 3 presents the proposed typical radiation doses for each projection from this phantom study, noting that the facility's typical median values range from 3 mGy•cm² to 86 mGy•cm² for individual projections across the three centres. It would be expected that the radiation dose associated with X-ray projections is reducing over time. However, comparison of the results from this phantom study against published international DRLs as shown in Table 4 does not appear to fully support this hypothesis. The typical radiation doses proposed in this phantom study for an AP chest X-ray (CXR) at each centre (0.038/0.045/0.067 Gy•cm²) are all higher than the Scandinavian DRL (0.028 Gy•cm²), the Irish DRL (0.022 Gy•cm²) and the French DRL (0.035 Gy•cm²), whereas Centre A and B's typical radiation dose is lower than the European DRL that was proposed in 2018 (0.050 Gy•cm²). This may be linked to the fact that the phantom was imaged in a supine position compared to a 5-year-old child who would be imaged erect; however, the SID for the CXR in the international DRLs has not been published. It is also quite likely that optimisation is not performed as well in Australia compared to Europe where the legislative requirement to establish DRLs has been in place since 1997. A grid was not used in the AXR AP procedure in this study, which may explain why the dose is lower than the international comparisons. With the exception of the Scandinavian DRL, the DRLs for abdominal X-rays (AXRs) have been decreasing over time. This demonstrates the importance of reporting the exposure factors, including the use of a grid, and the air kerma, so the area of the collimated field can be taken into consideration when comparing a local protocol to national or international DRLs. As the results of this study do not follow the expected trend, this supports the need for clinical DRLs to be collected, so they can be compared directly to the international studies.

A recent Australian study from a specialist paediatric hospital published that their estimated effective dose for an AP chest X-ray for a child weighing 16–25 kg (kg) was 0.014 mSv compared to 0.02/0.03/0.04 mSv for Centre A/B/C in this study.¹⁷ For an abdomen X-ray, their typical

effective dose for a 16–25 kg child was 0.03 mSv, which is very similar to this study (0.03/0.04/0.03 mSv). These estimates were calculated using the same software as this study from the pre-programmed exposure factors at that specialist paediatric hospital and did not include patient data nor a phantom study, so there is no air kerma or KAP values to compare against. Whilst the KAP is the easiest parameter for radiographers to use in clinical practice as it is displayed on each X-ray image as it is acquired, it must be borne in mind that DRLs are not to be applied to individual patients, nor are they dose limits. However, the KAP should be easily exported from the Picture Archiving and Communication System (PACS) for the calculation of local DRLs that can be compared to international, national or regional DRLs.

When obtaining informed consent from care-givers, they may ask what are the risks associated with their child having the X-ray taken. This is very difficult to answer if DRLs are not updated regularly, and particularly, when new equipment is installed. Table 5 presents the estimated additional radiation risks of radiation-induced cancer for each X-ray projection for male and female 5-year-olds at each of the three dedicated paediatric centres, as calculated from the LAR in the BEIR VII report. The LAR is the probability of a person acquiring a pre-mature cancer that is attributable to radiation exposure. For a given radiation dose, LAR is the additional cumulated probability of having a specific cancer over the expected lifetime, that is up to age of 120 years. It is known to be higher in females than males. When we put these risks into perspective, we must bear in mind that children under the age of 5 years in Australia have a 1 in 1000 baseline risk of naturally developing cancer before the age of 15.¹⁸ The additional risk of radiation-induced cancer range can be described as 'minimal' (i.e. 1 in 100,000 to 1 in 1,000,000) for X-ray projections of the axial skeleton and AP projections of the femur or 'negligible' (i.e. less than 1 in 1,000,000) for the remaining X-ray projections of the appendicular skeleton.¹⁹ It must be explained to the care-givers that the larger the number, the lower the risk. The theoretical risks have been presented in Table 5 in their raw numerical form to demonstrate that the risks from many of the body parts are so low that they are almost inconsequential.

Table 6 presents the risk estimates of radiation-induced death or fatal cancer, which can be described as 'negligible' for all extremity X-ray projections and skull X-rays, or 'minimal' for AP or PA chest X-ray, oblique projection of the ribs, AP abdomen X-ray or lateral projection of the lumbar spine. It is noted that these computed risks are based on the linear no-threshold (LNT) model for radiation risks since epidemiological demonstration of such low risks is intractable.¹⁶ Explaining that there is a 1 in 100,000 chance of dying from being struck by lightning

may help a care-giver put the risks of radiation-induced death into perspective.¹⁹ The theoretical risks have been presented in Table 6 in their raw numerical form to demonstrate that the risks from many of the body parts are so low that they are almost inconsequential, thereby tipping the risk : benefit analysis in favour of the medical benefit of the child having the X-ray examination.

The BEIR VII model used to estimate the risks presented in Tables 5 and 6 is based upon a United States of America population, and it is important to acknowledge the advice of the BEIR VII committee that 'the risk estimates should be regarded with a healthy scepticism, placing more emphasis on the magnitude of the risk'.¹²

Limitations of the research include the fact that the KAP measurements recorded at each of the three dedicated paediatric centres were for a 5-year-old/20 kg only as this was the age of the 'bone fracture' phantom available.⁷ It is also acknowledged that the irradiated area for the upper limb X-ray projections is limited by the external boundary of the PCXMC software phantom. However, this is thought to be mitigated by the fact that when X-raying the arm, it will always be extended away (i.e. abducted) from the body. Therefore, the fact that the width of the X-ray image is limited to 3 cm by the PCXMC software is not thought to significantly influence the software calculation, which is based on the arm being alongside the torso. Earl *et al.* acknowledged the same limitations when using the PCXMC software so they did not publish their typical effective radiation doses for the upper extremities despite describing how they had normalised published data for the exposure parameters.¹⁷ It is also appreciated that when performing a lateral X-ray projection, the opposing limb would not be positioned within the primary X-ray beam. Therefore, lateral projections of the knee and ankle were calculated using the AP position.

Ideally, DRLs should be calculated based upon the 75th percentile of the spread of median patient doses across a number of imaging centres and X-ray equipment. It is acknowledged that this is a small sample size of only three centres, and therefore, the typical doses for each centre were published. To the knowledge of the authors, this is the first effort to propose local typical radiation doses for commonly performed X-rays for children of any age across multiple centres in Australia, thereby addressing a gap in knowledge, rather than proposing a national DRL.

As identified by Erskine *et al.*, these reference values can be used for guidance in radiology departments who do not have their own facility reference levels established.²⁰ However, these should not be interpreted as national DRLs, and therefore, comparison is not a regulatory requirement. It is hoped that the Environment Protection

Authority of New South Wales collates the DRLs collected and publishes them for both adults and children within the Australian context. At this stage, ARPANSA does not have any processes in place to collect data to establish Australian national DRLs in conventional radiography. This phantom study has prompted the authors to recruit X-ray departments across Australia to collect DRL data for commonly performed paediatric X-rays as part of a pilot study to establish weight-based paediatric DRLs in Australia. Ethical approval and a Waiver of Consent have been granted for this next research study.

Conclusion

The estimation of local typical radiation doses based on measurements from a 5-year-old/20-kg (paediatric) anthropomorphic phantom provides reference values for guidance, but does not trigger a regulatory requirement to undertake a comparison and optimisation process. The values reported here are the first step in providing guidance to other institutions until national DRLs are published, based on patient data from the clinical setting. The risks of radiation-induced cancer or death in 5-year-old/20-kg children can be described as 'minimal' or 'negligible', depending on the body part being irradiated. The results have been presented in their raw numerical form to show the 'real' risk and help put that in perspective when compared to the potential medical benefit of having the X-ray.

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Conflict of Interest

The authors declare that they have no conflict of interest.

Data Availability Statement

The spreadsheets used for risk calculations are available from the corresponding author upon request.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table S1. Organ weighting factors.