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SCATTER DOSE VALUES IN LOWER EXTREMITIES FOR STAFF DURING PAEDIATRIC INTERVENTIONAL CARDIOLOGY PROCEDURES: AN EXPERIMENTAL APPROACH

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The aim of this study was to determine experimentally the scatter dose at the cardiologist's lower extremities in 10 common types of paediatric interventional cardiology procedures and categorised in four age groups of simulated patients, on the basis of measurements taken from characterisation of X-ray systems together with average fluoroscopy time values and the number of cine frames used as references. The highest scattered dose rates recorded during the simulations were 700 and 4000 μSv h^{-1} for the low fluoroscopy and cine modes, respectively. Scattered dose at cardiologist's lower extremities for the four age groups of simulated patients and procedures ranged from 1 to 28 μSv (aged below 1 y), 6 to 58 μSv (below 5 y), 13 to 155 μSv (below 10 y) and 29 to 375 μSv (below 15 y). The present study showed a maximum annual dose that may reach the cardiologist's lower extremities of 90 mSv.

INTRODUCTION

In general, physicians who perform interventional procedures often have to stand close to the X-ray beam in order to carry out manipulations. As a result, their lower extremities, which will not be protected by a conventional lead apron, may receive significant radiation doses from scattered X-rays(1).

During paediatric interventional cardiology procedures, interventional physicians need to remain closer to the patient than in adult procedures(2). Procedural complexity may require lengthy fluoroscopy times and multiple numbers of cine frames. Contributing factors include the higher heart rates, smaller cardiovascular structures, smaller body size and wider variety of anatomical variants seen in children(3). As such, a careful evaluation of scatter dose levels for staff involved in these procedures is appropriate(2).

In any event, the evaluation of staff radiation dose levels should be considered an important part of quality assurance programmes for interventional cardiology procedures(4, 5) and can, in part, be estimated from the experimental measurements performed in the context of the characterisation of an X-ray system(2, 6, 7).

Several studies have been published reporting scatter dose levels to the lower extremities of physicians during interventional radiology and cardiology procedures in adults(1, 8–15), but similar data are scarce for paediatric cardiology(2). Papers providing scatter dose level values for the lower extremities of interventional cardiologists for different kinds of procedures and age groups of patients are practically non-existent for paediatric cardiology.

Therefore, the goal of this study was to determine experimentally scatter dose at the cardiologist's lower extremities in 10 common types of paediatric interventional cardiology procedures and categorised in 4 age groups of patients.

MATERIALS AND METHODS

Six X-ray systems were characterised using DIMOND and SENTINEL protocols in terms of dose and image quality and adapted in the present case to paediatric procedures(16–18). These X-ray systems belong to four paediatric interventional cardiology services, representing all the paediatric cardiac angiography laboratories in Chile. Three systems used flat-panel detectors, and three used image intensifiers. The systems were numbered from 1 to 6 (numbers 1–3 with flat-panel detector and numbers 4–6 with image intensifier; see Table 1).

Polymethyl methacrylate (PMMA) plates of 25 cm × 25 cm × 0.5 cm were used as phantoms in thicknesses from 4 to 16 cm, simulating the full range of

Table 1. X-ray systems evaluated in the survey.

ID no.	Manufacturer	Model	Image detector	Name of protocols used	Year of installation
1	Siemens	Axiom Artis dBC, Biplane	Flat Detector	Paediatric 20 kg	2008
2	Philips	Allura Xper FD20, monoplane	Flat Detector	5 kg, child 5–15 kg and child 15–40 kg	2005
3	Philips	Allura Xper FD20, biplane	Flat Detector	5 kg, child 5–15 kg and child 15–40 kg	2012
4	General Electric	Advantx, biplane	Image Intensifier	Cardio Ped	2009
5	Siemens	Axiom Artis BC, biplane	Image Intensifier	Newborn, infant and child	2005
6	General Electric	Advantx, monoplane	Image Intensifier	Cine A, B, C and D	1994

equivalent paediatric patients. A test object (Leeds TOR 18-FG)[19] was positioned at the isocentre and in the middle of the PMMA thickness during all measurements to evaluate image quality. According to Rassow *et al.*[20], the ratio between PMMA and patient chest thickness can be considered to be ~1.5. It was assumed that 4 cm of PMMA represents patients aged below 1 y, 8 cm of PMMA represents patients aged below 5 y, 12 cm of PMMA represents patients aged below 10 y and 16 cm of PMMA represents patients aged below 15 y.

Measurements taken during the experiments used the default settings to simulate the most common paediatric examination protocols used in each X-ray system (see Table 1). No extra collimation was applied to the radiation field during these simulations, its size being automatically collimated according to the image intensifier or flat-panel detector field-of-view format.

In this article, the dosimetric quantities proposed by the International Commission on Radiation Units and Measurements were used. For patient or phantom dosimetry, incident air kerma (IAK) or entrance surface air kerma (ESAK) (with backscatter) was used[21]. For staff, the dosimetric quantity expressed as personal dose equivalent $H_p(0.07)$ was used to estimate lower extremity dose[22].

IAK was measured using an Unfors Xi (model 8201010-A) system with a solid-state detector (model 82020030-AXi)[23] in contact with the PMMA slabs. The backscatter factor used to estimate ESAK from IAK values was 1.3[21]. The Unfors Xi detector was positioned inside the radiation field, out of the automatic exposure control area. To simulate clinical conditions, the image detectors of the evaluated X-ray systems were always in anterior–posterior projection and positioned at 5 cm from the phantom. Although other projections could be used, the evaluation of different C-arm angulations has been overlooked because in paediatric IC procedures using biplane systems, anterior–posterior projections were used in around 85–90 % of cases[6]. The focus-to-detector distances ranged from ~74 to ~68 cm for the PMMA thicknesses studied (4, 8, 12 and 16 cm). In order to measure dose at the cardiologist's lower extremities position (~113 cm from isocentre and ~10 cm from floor), a model 8131010-C Unfors EED-30 detector[23] was used, consisting of a solid-state sensor and an independent display. Dosimetric systems were duly calibrated, traceable to official calibration laboratories.

From the experimental measurements for all PMMA thicknesses during the characterisation of each X-ray system (see Figure 1), ESAK rates for low-rate fluoroscopy mode and ESAK per frame for cine acquisition and their respective scatter dose rates at simulated lower extremities position were selected (details of the settings used are shown in Table 2). The average values for fluoroscopy time (FT) and the number of cine frames (CF) obtained in one of the authors' previous papers were also used[24]. The scattered dose at cardiologist's lower extremities position was estimated using the operational data (fluoroscopy time, number of cine frames and so on) collected for 10 different types of paediatric interventional cardiology procedures (see Table 3).

Though several of the measurements for the ESAK and $H_p(0.07)$ values were not taken in this study, it has been done in previous experiments. Reproducibility has always been good, with the geometric conditions being most critical if altered during experiments. The highest intrinsic 'uncertainties' were those of the solid-state detectors (Unfors Xi 10 % and Unfors EDD 6 %), which were assumed as the uncertainties for the single measurements of the present study. The significant figures in our Tables 4 and 5 have been adjusted accordingly. However, as regards global results with several fluoroscopy and cine series and as highlighted in the present conclusions, the total error estimate for these figures should be increased by a factor of about three, depending on the age of X-ray system, geometric factors and automatic exposure control.

RESULTS

Table 4 presents ESAK and scattered dose rate values for all X-ray systems and PMMA thicknesses, evaluated in low-rate fluoroscopy and cine acquisition modes.

Table 5 shows staff scattered dose values at cardiologist's lower extremities position [personal

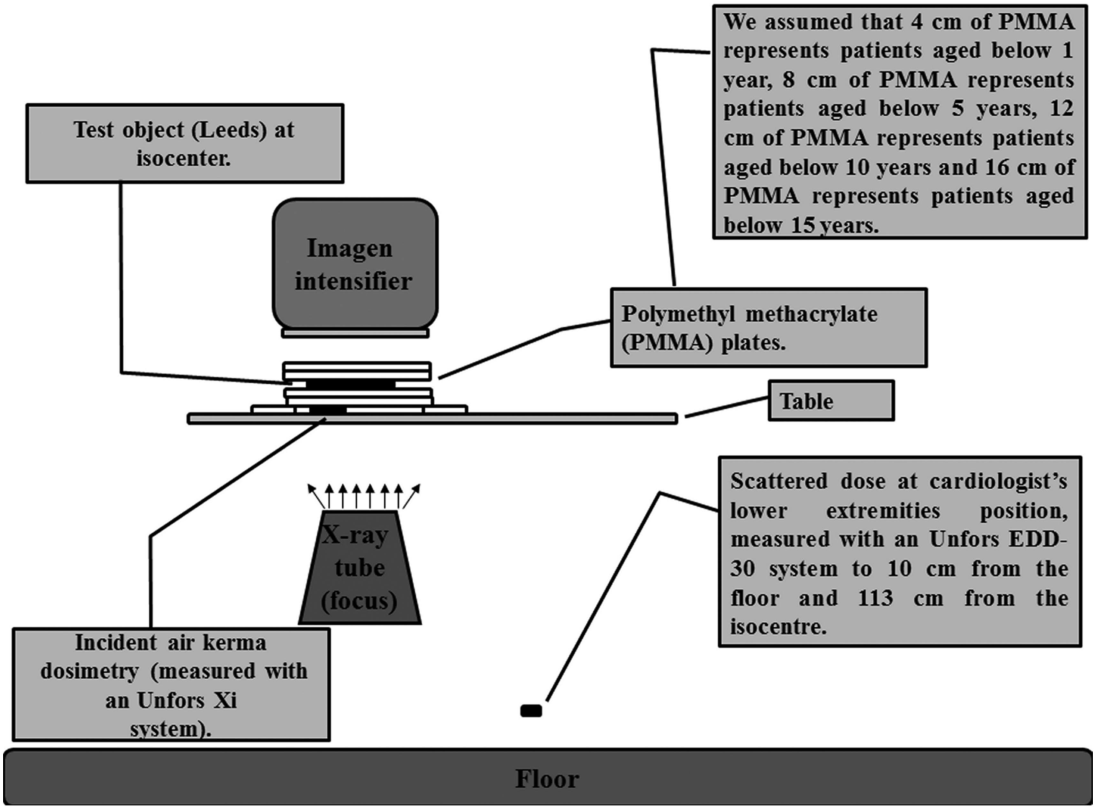

Figure 1. Experimental setup.

Table 2. Selected configurations in each X-ray systems (ID no.) for low-rate fluoroscopy and cine modes and field of view (FOV) used.

ID no.	Manufacturer	Low-rate fluoroscopy (pulses s^{-1})	Cine (frame s^{-1})	FOV (cm)
1	Siemens	8	15	25
2	Philips	8	15	22
3	Philips	13	15	22
4	General Electric	15	30	17
5	Siemens	10	15	22
6	General Electric	25	25	23

dose equivalent, $H_p(0.07)$] for all X-ray systems, estimated for the 10 procedures simulated from 4 to 16 cm of PMMA. Each value refers to a single procedure.

DISCUSSION

In this article, the ESAK rate values in other papers have been reported and discussed[18]. However, those

Table 3. Average fluoroscopy time and the average number of cine frames for each type of procedure simulated[24].

ID	Procedure	Fluoroscopy time (min)	Number of cine frames
A	Diagnostic normal	7.3	770
B	Diagnostic complex	17.9	1114
C	Aortic angioplasty	13.7	1053
D	Pulmonary angioplasty	23.4	979
E	Pulmonary angioplasty with stent	29.4	1333
F	Atrial septal defect closure	21	479
G	Aortic valvuloplasty	11.5	563
H	Pulmonary valvuloplasty	14.2	507
I	Patent ductus arteriosus closure with coil	9	337
J	Patent ductus arteriosus closure with device	11.7	605

Table 4. ESAK (uncertainty ±10 %) and scatter dose (uncertainty ±6 %) for all X-ray systems (ID no.) evaluated with 4, 8, 12 and 16 cm of PMMA in low-rate fluoroscopy (LF) and cine acquisition (CI) modes.

ID no.	Acquisition mode	4 cm of PMMA (0 to <1 y)		8 cm of PMMA (1 to <5 y)		12 cm of PMMA (5 to <10 y)		16 cm of PMMA (10 to <15 y)	
		ESAK (mGy min^{-1})	Scatter dose (μSv h^{-1})	ESAK (mGy min^{-1})	Scatter dose (μSv h^{-1})	ESAK (mGy min^{-1})	Scatter dose (μSv h^{-1})	ESAK (mGy min^{-1})	Scatter dose (μSv h^{-1})
1	LF	0.43	25	1.0	60	2.3	135	6.9	330
	CI	2.7	125	7.3	330	28	900	70	2000
2	LF	0.62	45	1.4	100	2.5	170	5.3	320
	CI	2.4	150	8.8	450	15.2	750	56	2400
3	LF	0.62	40	1.4	85	2.9	175	5.5	280
	CI	2.2	125	8.8	430	28	1200	54	2000
4	LF	0.37	30	0.9	60	2.0	130	6.2	320
	CI	0.90	250	6.6	480	28	1600	93	4000
5	LF	0.11	<0.2	0.24	25	0.58	60	1.4	120
	CI	5.3	270	14	900	20	1400	58	3400
6	LF	2.0	40	3.8	100	11.5	300	33	700
	CI	8.0	660	9.3	260	21	670	104	2200

Table 5. Scatter dose ($H_p(0.07)$) values (uncertainty ±6 %) estimated for the ten procedures (A–J) simulated with 4, 8, 12 and 16 cm of PMMA for all evaluated X-ray systems (ID no.).

		$H_p(0.07)$ procedures (μSv)									
ID no.	PMMA (cm)	A	B	C	D	E	F	G	H	I	J
1	4	5	10	8	12	15	10	6	7	5	6
	8	12	25	20	29	37	24	15	17	11	15
	12	29	59	49	69	88	55	35	40	26	36
	16	68	138	113	163	209	132	83	96	61	86
2	4	8	16	13	20	26	17	10	12	8	10
	8	18	38	31	46	58	38	23	27	17	24
	12	31	66	54	80	102	66	40	47	30	42
	16	74	146	120	169	217	133	87	98	63	90
3	4	6	14	11	17	22	14	9	10	6	9
	8	16	34	28	41	52	33	21	24	15	21
	12	38	76	63	89	115	71	46	52	34	47
	16	63	125	103	146	187	116	75	85	55	77
4	4	6	12	10	15	19	12	7	9	6	8
	8	10	21	17	26	33	22	13	15	10	14
	12	27	55	45	65	83	52	33	38	24	34
	16	67	136	112	160	205	129	82	94	60	84
5	4	2	3	3	2	3	1	1	1	1	1
	8	9	16	14	17	23	12	9	10	6	10
	12	17	32	27	35	45	26	18	20	13	19
	16	39	71	61	78	101	57	41	44	29	43
6	4	10	19	16	22	28	16	11	12	8	12
	8	15	36	28	45	57	39	22	27	17	23
	12	42	97	76	123	155	108	61	74	47	62
	16	104	236	185	297	375	257	148	178	113	151

were repeated for different X-ray systems, phantom thicknesses and acquisition modes used in Table 4. Differences found between the various PMMA thicknesses for ESAK and Hp(0.07) quantities are derived from the wide range of operating points, different protocols and locally used X-ray system settings, including automatic exposure control, kilovolts, added copper filtration, number of pulses per second, pre-selection of tube potential, pulse time and tube current, and so on[17, 25].

Table 4 also shows an increase in scatter dose by factors ranging from 7 to 600 during a move from low to high fluoroscopy modes and during a change in phantom thickness from 4 to 16 cm for all X-ray systems. For 'thick' patients (PMMA of 16 cm), the highest scattered dose rate at lower extremities in fluoroscopy mode reached values of 700 μSv h^{-1}. However, during cine acquisition, dose rates of 4000 μSv h^{-1} (i.e. six times higher than in low fluoroscopy mode) were measured for different X-ray systems at a PMMA thickness of 16 cm.

Comparing the results with a previous national evaluation conducted in 2009[2] (see Table 4), current scatter doses at cardiologist's lower extremities were found to be lower, particularly for values in CI modes. These differences are explained mainly due to the Siemens Axiom Artis dBC biplane (ID No. 1), Philips Allura Xper FD 20 monoplane (ID No. 2) and Siemens Axiom Artis BC biplane (ID No. 5) X-ray systems having been previously evaluated and optimised as a part of Chile's active participation in the following International Atomic Energy Agency (IAEA) technical cooperation projects: 'Strengthening Radiological Protection of Patients in Medical Exposures (TSA3), RLA/9/057', 'Ensuring Radiological Protection of Patients during Medical Exposures (TSA3), RLA/9/067' and 'Strengthening National Infrastructure for End-Users to Comply with Regulations and Radiological Protection Requirements, RLA/9/075'[17, 18, 26–28].

Table 5 shows scattered dose values at cardiologist's lower extremities position. These reported values allow an estimation of staff dose received in paediatric cardiac laboratories if a ceiling-suspended screen is not used. For example, the procedures that irradiated the most and the least on average were pulmonary angioplasty with stent (ID E) with 94 ± 90 μSv and patent ductus arteriosus closure with coil (ID I) 28 ± 27 μSv, respectively. Scattered doses at cardiologist's lower extremities for the 4 age groups of patients and 10 kinds of simulated procedure ranged from 1 to 28 μSv (factor 28, aged below 1 y), 6 to 58 μSv (factor 10, aged below 5 y), 13 to 155 μSv (factor 12, aged below 10 y) and 29 to 375 μSv (factor 13, aged below 15 y). If a typical workload of 20 procedures per month is assumed, exclusively examining patients aged between below 15 y of age could mean a scattered dose from 580 to 7500 μSv per month. Therefore, the maximum annual dose that may reach the cardiologist's lower extremities would be ~90 mSv, which represents 18 % of the limit for extremities established by the International Commission on Radiological Protection[22].

STUDY LIMITATIONS

The limitations affecting this study related to the use of fluoroscopy time and the number of cine frames from one hospital and assumption that the other services worked with the same parameters. The impact of using both C-arms simultaneously and other angulations should be taken into account in future research. However, this would require the access to patient dose reports for all centres, which is impossible for most of the X-ray systems currently in use in Chile.

CONCLUSIONS

The aim of this study was to determine experimentally scatter dose at the cardiologist's lower extremities in 10 common types of paediatric interventional cardiology procedures and categorised in four selected patient age groups. For the 4 age groups of patients and 10 kinds of simulated procedure selected, scattered doses at cardiologist's lower extremities ranged from 1 to 375 μSv per procedure. The present study found that the maximum annual dose that may reach the cardiologist's lower extremities was 90 mSv.

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