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Original Paper

Patient and staff doses in paediatric interventional cardiology derived from experimental measurements with phantoms

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ABSTRACT

The aim of this paper was to determine experimentally the entrance surface air kerma (ESAK) and kerma-area product (KAP) levels to patients and scatter doses at the cardiologist's eyes during paediatric interventional cardiology (IC) procedures for Chile, on the basis of measurements taken from X-ray systems characterization for different thicknesses of polymethyl methacrylate, together with the average values of fluoroscopy time and number of cine frames for ten paediatric IC procedures. The range of cumulative ESAK values when the different clinical procedures were simulated was from 2 to 1100 mGy. KAP values ranged from 0.30 to 150 Gy cm^2. Scatter doses at cardiologist's eyes for the simulated procedures ranged from 0.20 to 116 μSv per procedure. Large differences between the X-ray systems were found in our study. Standardized guidelines in terms of X-ray system setting and protocols should be developed for hospitals that perform paediatric IC procedures in Chile.

Introduction

It is known that interventional cardiology (IC) procedures may produce high doses of radiation for both patients and staff [1–3].

Radiation dose is particularly important for paediatric patients because, according to a recent UNSCEAR report, estimates of lifetime cancer risk for exposed children were uncertain but might be a factor of 2–3 times as high as estimates for a population exposed at all ages [4].

Moreover, during paediatric IC procedures interventional cardiologists need to remain closer to the patient than in adult procedures. Sometimes procedural complexity requires lengthy fluoroscopy time and multiple numbers of cine frames. As such, a careful evaluation of scatter dose levels for staff involved in these procedures is appropriate [5]. Evaluating the dose to the eye lens holds particular significance due to both cataract or opacity being one of the major deterministic effects for staff [6] and the ICRP having reduced the dose limit for workers from 150 to 20 mSv year^{-1}, averaged over a defined period of 5 years [7].

Evaluation of radiation doses received by patients and staff should be considered an important part of quality assurance programmes for IC procedures [8,9] and can, in part, be estimated from the experimental measurements performed within characterization of an X-ray systems [5,10].

This paper aims to determine experimentally some dosimetric parameters related with dose levels to patients and scatter doses at cardiologist's eyes in ten common types of paediatric IC procedures.

Materials and methods

The X-ray systems of four paediatric interventional cardiology services were characterized using modified DIMOND and SENTINEL protocols in terms of dose and image quality [11–13]. Six X-ray systems were evaluated, representing 100% of the paediatric cardiac angiography laboratories in Chile (a country with 18 million inhabitants) [14]. Three systems used image intensifiers and three used flat panel detectors. 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) slabs of 25 cm × 25 cm × 0.5 cm were used as phantoms in thicknesses from 4 cm to 16 cm, equivalent to paediatric patient chest thicknesses of around 6 cm and 24 cm thick, respectively, according to Rassow et al. [15]. These

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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

thicknesses may be considered as the range of the typical sizes of paediatric chest patients in antero-posterior X-ray beam direction. We assumed that 4 cm of PMMA represent patients aged below 1 year, 8 cm of PMMA represent patients aged below 5 year, 12 cm of PMMA represent patients aged below 10 year and 16 cm of PMMA represent patients aged below 15 years. A test object (Leeds TOR 18-FG) [16] was positioned at the isocentre and in the middle of the PMMA thickness during all measurements to evaluate image quality.

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). During these simulations, no extra collimation was applied to the radiation field, its size being automatically collimated according to the image intensifier or flat panel detector field-of-view (FOV) format.

In accordance with the International Commission on Radiological Units (ICRU) Report 74 [17], the dosimetric quantities for patient dosimetry used were incident air kerma (IAK) or entrance surface air kerma (ESAK) (with backscatter) and kerma-area product (KAP) or dose-area product. For staff, the dosimetric quantity expressed as personal dose-equivalent Hp(0.07) was used to estimate eye doses. ICRP Publication 103 suggests that the monitoring of eye lens exposure is sufficiently reliable using Hp(0.07) [18]. Other studies show that to assess the equivalent dose to the eye lens of Hp(3) in IC, a passive whole-body dosimeter calibrated at Hp(10) or Hp(0.07) can be used satisfactorily. Numerically, Hp(10) is close to Hp(0.07) in IC and both can be used to assess Hp(3) [19].

IAK was measured using an Unfors Xi (model 8201010-A) system with a solid-state detector (model 82020030-AXi) [20] in contact with the PMMA slabs. The backscatter factor used to estimate ESAK from IAK values was 1.3 [17]. 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 antero-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, antero-posterior projections were used in around 85%–90% of the cases [10]. The focus-to-detector distances were ~74 cm to ~68 cm for the PMMA thicknesses studied (4 cm, 8 cm, 12 cm and 16 cm). In order to measure the dose at the cardiologist's eye lens position (~77 cm from isocentre and ~170 cm from floor), an Unfors EED-30 detector, model 8131010-C [20] was used, consisting of a solid-state sensor and an independent display. Dosimetric systems were duly calibrated, traceable to official calibration laboratories (RaySafe laboratory).

From the experimental measurements for all PMMA thicknesses during the characterization of each X-ray system, we selected ESAK rates for low rate fluoroscopy mode and ESAK per frame for cine acquisition and their respective scatter dose rates at simulated eye position (details of settings used are shown in Table 2). We also used the average values for fluoroscopy time (FT) and number of cine frames (CF) obtained in one of our previous papers [21]. Different dosimetric quantities such as ESAK, KAP (using the PMMA phantom) and scattered dose at cardiologist's eye lens position were estimated using the operational data (fluoroscopy time, number of cine frames, etc) collected for ten different types of paediatric IC procedures (see Table 3).

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

We have not made several measurements of each of the values (ESAK and scatter dose), but this has been done in previous experiments and the reproducibility was always good, with the geometry conditions being most critical if changed during the experiments. The intrinsic "uncertainty" of the used solid-state detectors (Unfors Xi 10% and Unfors EDD 6%) was the highest and was assumed as the uncertainties for our single measurements. The significant figures in our table haves been adjusted accordingly. However, when referring to global results with several fluoroscopy and cine series, and as highlighted in the conclusions section, the total error estimation of these figures should be increased by a factor of about 3, depending of the age of the X-ray system, the geometry factors, and the automatic exposure control.

Results

Table 5 shows ESAK values for all X-ray systems and estimated for the ten procedures simulated with 4, 8, 12 and 16 cm of PMMA, respectively. Each value refers to a single procedure.

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

Table 3
Average fluoroscopy time and average number of cine frames for each type of procedure simulated [21].

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