RADIATION DOSE SURVEY IN A PAEDIATRIC CARDIAC CATHETERISATION LABORATORY EQUIPPED WITH FLAT-PANEL DETECTORS

O. Dragusin1,*, M. Gewillig2, W. Desmet2, K. Smans1,3, L. Struelens3 and H. Bosmans1
1Department of Radiology, University Hospital Gasthuisberg, 49 Herestraat, B-3000 Leuven, Belgium
2Department of Cardiology, University Hospital Gasthuisberg, 49 Herestraat, B-3000 Leuven, Belgium
3SCK.CEN, 200 Boeretang, 2400 Mol, Belgium

Flat-panel X-ray detectors for fluoroscopy represent a modern imaging equipment that is being implemented in paediatric cardiac catheterisation laboratories. Infants and children represent a group of patients with a high radiosensitivity. A survey of 273 (126 diagnostic and 147 therapeutic) paediatric catheterisations was performed to investigate the radiation doses delivered by the new X-ray system. Statistical parameters (75th, 50th and 25th percentiles) of dose-area product (DAP) and fluoroscopy time are reported for patients divided into six age groups: 0–30 d, >1–12 m, >1–3, >3–5, >5–10 and >10–15 y. For accurate risk estimation, effective dose (E) has been determined for all patients using the PCXMC software. For diagnostic procedures, the third quartile of E ranges from 11.3 mSv for newborns to 7 mSv for children of 10–15 y. Therapeutic procedures are more complex than diagnostic. Consequently, the third quartile of E is 22.6 mSv (0–30 d), 18.6 (>1–12 m), 13.3 (>1–3 y), 21.5 (>3–5 y), 17.8 (>5–10 y) and 34.1 mSv (>10–15 y). Dose conversion factors, which relate the DAP and E, have been estimated for each age group. The results of this study may serve as a first step in the optimisation process, in order to make full use of the dose reduction potential of flat-panel systems.

INTRODUCTION

Medical exposures are the most important source of man-made ionising radiation. According to the Euratom Directive 97/43 of the European Communities, exposures of children and procedures involving high doses to the patient, such as interventional radiology, should be given special attention (1). Both criteria apply to the paediatric cardiac catheterisation laboratories (Cath Labs) and quality assurance programmes and patient dose evaluations should thus be established with priority. The practical implementation is however difficult due to the complexity of the procedures. Flat-panel detector (FPD) for fluoroscopy is a new technology that is an alternative for the image intensifier (II) system in the Cath Labs. These FPDs provide an image quality and a dose efficiency that are in general superior to the II systems, except at the lowest fluoroscopic dose levels (2). A limited number of published articles have provided typical paediatric radiation doses for older imaging equipment with II. Information is expressed in terms of dose-area product (DAP) values, skin doses (using thermoluminiscent dosimeters) or effective doses (E). As far as we know, there are no studies reporting paediatric cardiac catheterisation radiation doses using flat-panel technology. Consequently, the aims of this study are:

(a) investigate the radiation exposure parameters: DAP for fluoroscopy and cineangiography, fluoroscopy time (FT), number of cineangiographic images;
(b) to calculate the E as a quantity to estimate stochastic effects of the radiation exposure;
(c) to establish baseline operation values and further strategies to optimise image quality at all radiation exposure levels.

METHODS

Patients and procedures

Two hundred and seventy-three consecutive paediatric patients with congenital heart disease were studied. Patients were subdivided into six age bands: Group A (0–30 days), B (>1–12 months), C (>1–3 years), D (>3–5 years), E (>5–10 years) and F (>10–15 years). Patients underwent cardiac catheterisation procedures for diagnostic and/or therapeutic purposes. Diagnostic catheterisation examinations study complex congenital heart diseases. Therapeutic procedures mainly involve dilatation of stenotic vessels or valves and occlusion of abnormal communications. The therapeutic procedures included in this study were balloon dilatation of pulmonary valve, balloon dilatation of peripheral pulmonary stenosis, balloon dilatation for coarctation of the aorta, stent implantation, occlusion of patent ductus arteriosus, closure of atrial septal defect and closure of ventricular septal defect.

*Corresponding author: odragusin@yahoo.com

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X-ray system: acquisition of exposure parameters

The paediatric Cath Lab is equipped with a biplane Siemens Artis dBC system (Siemens, Erlangen, Germany) installed in August 2005. X-rays are produced by a multipulse generator with tube load computer and fully automatic exposure control. Tube voltage (kV), tube current (mA), pulse width, additional Copper (Cu) filters and iris diaphragm are preset for acquisition. The image detector is a square FPD with a format of 20 × 20 cm (25 cm diagonal), with possibility of two magnified views (diagonal of 20 and 16 cm). The material used for the flat detector is α-Si with a CsI scintillator. Additional Cu filters with thickness from 0.1 to 0.9 mm are automatically inserted in the X-ray beam as a function of the patient absorption. Each tube has a DAP meter integrated into the collimator housing to measure the radiation dose.

During the commissioning of the X-ray system, basic information about the modes of operation had been obtained. For both operation modes (fluoroscopy and cineangiography), dosimetric and image quality evaluations were performed in concordance with the existing protocols. The half-value layer measured at 80 kVp is 6 mm Al for frontal X-ray tube (tube A) and 5.57 mm Al for the lateral tube (tube B). DAP meters were calibrated using a Magna 1cc ionisation chamber (RTI, Sweden) and Kodak X-Omat V films (Eastman Kodak). The mean values of the DAP calibration factors are 0.84 for the tube A and 0.78 for the tube B. The standard protocol for paediatric procedures employs the use of pulsed fluoroscopy for the tube B. The standard protocol for paediatric procedures employs the use of pulsed fluoroscopy at 15 pulses s⁻¹ and cineangiography at 30 frames s⁻¹. Almost all procedures are done in perpendicularly geometry. At the end of each procedure, a study dose report summarises detailed dosimetric information about exposure parameters for each cineangiographic series. On the basis of these information, we were able to estimate the E for each individual patient.

E takes into account the non-uniform irradiation of the organs and tissues of the body and yields a single computed value. The information needed for the calculation of the E are the radiation field size at the patient’s skin, the projection angle tube voltage, added filtration, patient weight and height, the distance from the focal spot to the skin and the DAP. The PCXMC software calculates organ doses and the E for specific patient models. The PCXMC uses five default paediatric patient sizes: neonate, 1, 5, 10 and 15 y. For all calculations, the arms were removed from the body phantom to simulate the normal clinical practice. As the calculation of E is complex and time consuming, a common practice is to use dose conversion factors (DCF) that relates DAP to E for each age group. The DCF is calculated as follows:

\[
\text{DCF} = \frac{E (\text{mSv})}{\text{DAP (Gy} \cdot \text{cm})^2}
\]

The DCF is calculated for each patient and for two projection angles: posteroanterior view (PA) and lateral view (LAT). Statistical calculations were performed with the SPSS v.9.0 software (SPSS Inc, Chicago, US). The two-tailed Mann–Whitney test is used to express differences between two independent skewed distributed populations. A significance level of 5% (P < 0.05) is considered.

RESULTS

This study contains dosimetric information of 273 patients from which 126 were diagnostic cases. The therapeutic interventions include 37 balloon dilatations of pulmonary valve, 24 balloon dilatations of peripheral pulmonary stenosis, 5 balloon dilatations for coarctation of the aorta, 32 stent implantations, 15 occlusions of patent ductus arteriosus, 16 closures of atrial septal defects and 6 closures of ventricular septal defects. Other 12 patients underwent complex therapeutic interventions involving at least two procedures described above. Table 1 presents the demographic patient data and the number of procedures corresponding to each age group.

The X-ray tube parameters that influence DAP measurements are peak tube voltage, tube current, pulse width and additional Copper filters. Median values for the frontal tube are 64 kVp, 289 mA, 7 ms and 0.3 mm Cu. For the lateral tube, median values are 66 kVp, 299 mA, 7 ms and 0.2 mm Cu.

<table>
<thead>
<tr>
<th>Group</th>
<th>A</th>
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<th>C</th>
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<th>E</th>
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<tr>
<td>Age</td>
<td>1–30 d</td>
<td>&gt;1–12 y</td>
<td>&gt;1–3 y</td>
<td>&gt;3–5 y</td>
<td>&gt;5–10 y</td>
<td>&gt;10–15 y</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>48.7 ± 2.2</td>
<td>59.5 ± 6.5</td>
<td>84.6 ± 7.4</td>
<td>102 ± 6.3</td>
<td>121.1 ± 10.2</td>
<td>151.5 ± 13.2</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>3.1 ± 0.6</td>
<td>5.7 ± 1.5</td>
<td>11.2 ± 2</td>
<td>15.9 ± 2.1</td>
<td>22 ± 6</td>
<td>40.7 ± 12.2</td>
</tr>
<tr>
<td>No. diagnostic procedures</td>
<td>9</td>
<td>27</td>
<td>19</td>
<td>24</td>
<td>34</td>
<td>13</td>
</tr>
<tr>
<td>No. therapeutic procedures</td>
<td>12</td>
<td>49</td>
<td>29</td>
<td>14</td>
<td>31</td>
<td>12</td>
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Mean ± SD of the height and weight of the patient, and the number of diagnostic and therapeutic procedures.
Descriptive statistics (75th, 50th and 25th percentile) of DAP and FT, and the median number of cineangiographies for diagnostic procedures are summarised in Table 2. For therapeutic procedures, the statistical parameters are summarised in Table 3.

In this study, the 75th percentile of the FT for diagnostic procedures is 18 min for neonates, 11 min for Group B, 14 min for C and D, 10.5 min for E and 16.5 min for F. Therapeutic procedures are performed with significantly longer FTs ($P = 0.014, 0.01, 0.03, 0.013, 0.015$ and $0.012$) and the 75th percentile values being $24.3, 25, 24.5, 33.5, 26$ and $39.75$ min, respectively. During fluoroscopy, the frontal tube had $\approx 80\%$ of total FT, whereas the use of frontal and lateral tubes was well balanced for cineangiography. The FT was not statistically different between age groups ($P = 0.086–0.93$), but the DAP values were increasing with the age group. This is expected because of the growing body height and weight with patient age and the corresponding increase of the attenuation of X-rays. In comparison with diagnostic, therapeutic procedures have higher DAP values (because of longer FT and more cineangiographic images). For therapeutic interventions, the 75th percentile of DAP values were $6.5, 9.2, 12.5, 22.2, 27$ and $74.4$ Gy cm$^2$ (Group A to E). The patient-specific dosimetric information was used for the calculation of E. Percentile values (25th, 50th and 75th) of E are plotted separately in Figure 1 for diagnostic procedures and in Figure 2 for therapeutic procedures.
DICUSION

Facts like the higher radiosensitivity of children when compared with adults, the possibility of repetition of therapeutic procedures in a short time, the significant fraction of the body irradiated by the radiation beam combined with the use of newer X-ray systems, are a major motivation to set-up a dose investigation of the paediatric patients in our Cath Labs.

In this study, we have proven the relevance of the grouping into age classes if the dosimetric parameters have to be analysed. The few studies on the radiation exposure of children during cardiac catheterisation refer to similar age groups: Rassow et al.\(^5\) use eight age groups from newborns to 21-y old and Hart et al.\(^6\) and Schmidt et al.\(^7\) report conversion factors for E/DAP for five age groups, neonates, 1, 5, 10 and 15 y. Other authors reported the doses as a function of the type of cardiac intervention (diagnostic and/or therapeutic)\(^8\)\(^{11}\). Separation of the data population function of the weight of the patient could further increase the accuracy of the conversion coefficients but it is more difficult to collect dose data as a function of weight in the clinical practice and during auditing periods.

Our reported DAP values were compared with the available published information. Rassow et al.\(^5\) reported DAP 75th percentile of 6.2, 6.1, 9, 10, 15, 20, 27 and 36 Gy cm\(^2\) for 2114 patients divided in eight age groups from newborns to 21 y. This study included diagnostic, therapeutic and myocardial biopsy procedures. Bacher et al.\(^10\) studied 60 patients of which 28 underwent diagnostic imaging. His patients ranged from new born to 10 y. The DAP range for diagnostic and therapeutic was 0.96–14.6 Gy cm\(^2\) and 0.4–20.4 Gy cm\(^2\), respectively. Schultz et al.\(^8\) reported some DAP values like 4.45 Gy cm\(^2\) for a newborn undergoing diagnostic procedure, 18.8 Gy cm\(^2\) for a 6 y child undergoing atrial septal defect closure and 110.4 Gy cm\(^2\) for a 14-y-old patients undergoing radiofrequency ablation. Boothroyd et al.\(^12\) studied 50 patients (30 diagnostic, 20 therapeutic, age interval 2 d–18 y). For diagnostic and therapeutic procedures, the reported DAP values were in the interval 5.6–43 Gy cm\(^2\) and 1.3–202.4 Gy cm\(^2\), respectively. Onnasch et al.\(^11\) expressed the results of dose data of a large population as DAP/body weight (Gy cm\(^2\) kg\(^{-1}\)) rather than DAPs for age groups. Using the 90th percentiles, he suggested as diagnostic reference level values of 0.81 Gy cm\(^2\) kg\(^{-1}\) for diagnostic procedures and 1.16 Gy cm\(^2\) kg\(^{-1}\) for therapeutic interventions. Comparative studies in terms of DAP would be easier if the way of reporting was standardised. For the same reason, it is difficult to propose diagnostic reference levels on the basis of literature data. This overview shows that our local data are probably typical values that may be representative for other departments too. E is an important quantity that is related to radiation risk. Some previous scientific papers estimated typical effective doses per paediatric cardiac procedure. Bacher et al.\(^10\) estimated values from 0.6 to 23.2 mSv for diagnostic procedures and from 1 to 37 mSv for therapeutic procedures. Effective doses calculated by Rassow et al.\(^5\) are increasing with decreasing age of the patients by a factor of \(~2\) and up to a factor of 4.5. Ninety percent of the values were below 18 mSv for newborns, 10.5 mSv for age band 5–10 y and 9.8 mSv for \(>10–15\) y. Schultz et al.\(^8\) calculated with PCXMC 7.4 mSv for a diagnostic

Table 4. Mean and standard deviation of the DCF (Dose conversion factors—mSv per Gy cm\(^2\)) from tube A, tube B and both tubes.

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<tr>
<td>PA view (tube A)</td>
<td>3.61 ± 0.79</td>
<td>2.19 ± 0.58</td>
<td>1.21 ± 0.26</td>
<td>0.91 ± 0.19</td>
<td>0.71 ± 0.16</td>
<td>0.41 ± 0.16</td>
</tr>
<tr>
<td>LAT view (tube B)</td>
<td>3.31 ± 0.81</td>
<td>2.17 ± 0.62</td>
<td>1.11 ± 0.25</td>
<td>0.87 ± 0.17</td>
<td>0.65 ± 0.16</td>
<td>0.39 ± 0.13</td>
</tr>
<tr>
<td>Both tubes</td>
<td>3.47 ± 0.61</td>
<td>2.18 ± 0.61</td>
<td>1.16 ± 0.25</td>
<td>0.91 ± 0.17</td>
<td>0.70 ± 0.16</td>
<td>0.39 ± 0.14</td>
</tr>
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</table>
procedure of a neonate and 6.6 mSv for 6-y-old child with atrial septal defect closure. Onnasch et al.\textsuperscript{[13]} reports the mean values of 3.9 mSv for atrial septal defect procedure, 3.2 mSv for patent ductus arteriosus and 12.1 mSv for ventricular septal defect. Nickoloff et al.\textsuperscript{[13]} estimated E in the range 7–75 mSv for diagnostic and 17–170 mSv for therapeutic procedures. The estimated values correspond to different selectable variables of the machine and are based on the conversion of entrance rate doses.

Conversion factors from DAP to E have been published for cardiology. For adults, DCFs range from 0.18 to 0.27 mSv per Gy cm\textsuperscript{2}\textsuperscript{(14)} for infants DCF varies significantly with the age. Rassow et al.\textsuperscript{[5]} calculated a DCF of 2.47 (LAT view) and 1.18 mSv per Gy cm\textsuperscript{2} (PA view) for babies less than 5 weeks and 0.32 (LAT) and 0.16 mSv per Gy cm\textsuperscript{2} (PA) for children from 10 to 15-y old. The DCFs calculated by Schmidt et al.\textsuperscript{[7]} and based on mathematical phantoms of the patients are 2.1 (PA view) and 2.3 mSv per Gy cm\textsuperscript{2} (LAT view) for neonates, 0.8 and 1.6 mSv per Gy cm\textsuperscript{2} for 1-y old, 0.4 and 0.6 mSv per Gy cm\textsuperscript{2} for 5-y old, 0.2 and 0.4 mSv per Gy cm\textsuperscript{2} for 10-y old, respectively 0.13 and 0.22 mSv per Gy cm\textsuperscript{2} for 15-y old. Our DCFs are higher than the values mentioned before and a strict comparison with other papers is difficult. The reason is the differences in tube voltage and Al filtration used in the calculation of DCFs. Schmidt's dose conversion factors are calculated at 65 kV\textsubscript{P} and 3 mm Al for all six age groups. He provides correction factors so that the DCF can be adjusted for different tube potentials and filtrations. But these correction factors are limited to 80 kV\textsubscript{P} and 3.5 mm Al for all six age groups. The mean value of DCF is 3.47 mSv per Gy cm\textsuperscript{2} for Group A, 2.18 for Group B, 1.16 for Group C, 0.19 for Group D, 0.7 for Group E and 0.39 for Group F.

CONCLUSIONS

The preliminary findings show that the calculation of E is influenced by the type of cardiac intervention and the patient's age (size). The use of smaller age groups could possibly further reduce the uncertainty on the calculation of the effective doses. Complementary information of tube angulations, detector magnification mode, tube voltage and added filtration is compulsory for exact calculations.

This study reports dosimetric data of paediatric patients undergoing cardiac catheterisations in a laboratory equipped with FPD. The 75th, 50th and 25th percentiles of DAP and FT values are presented for six age groups \(0–30\) d, \(1–12\) m, \(1–3\), \(3–5\), \(5–10\) and \(10–15\) y. We have used patient-specific data to calculate effective doses and to derive specific dose conversion factors for this system. The corresponding DCF shows highest values for neonates compared with the other age groups.

REFERENCES