Patient radiation doses in paediatric interventional cardiology procedures: a review

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Review

Patient radiation doses in paediatric interventional cardiology procedures: a review

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Abstract

A large number of investigations into the radiation doses from x-ray guided interventional cardiology procedures in children have been carried out in recent years. A review was conducted of these studies, gathering data on kerma area product ($P_{KA}$), fluoroscopic screening time (FT), air kerma, and estimates of effective dose and organ doses. The majority of studies focus on $P_{KA}$ and FT with no estimation of dose to the patient. A greater than ten-fold variation in average $P_{KA}$ was found between different studies, even where data were stratified by patient age or weight. Typical values of $P_{KA}$ were 0.6–10 Gy · cm² (<1 year/10 kg), 1.5–30 Gy · cm² (1–5 years), 2–40 Gy · cm² (5–10 years), 5–100 Gy · cm² (10–16 years) and 10–200 Gy · cm² (>16 years). $P_{KA}$ was lowest for heart biopsy (0.3–10 Gy · cm² for all ages combined) and atrial septostomy (0.4–4.0 Gy · cm²), and highest for pulmonary artery angioplasty (1.5–35 Gy · cm²) and right ventricular outflow tract dilatation (139 Gy · cm²). Most estimates of patient dose were in the form of effective dose (typically 3–15 mSv) which is of limited usefulness in individualised risk assessment. Few studies estimated organ doses. Despite advances in radiation protection, recent publications have reported surprisingly large doses, as represented by $P_{KA}$ and air kerma. There is little indication of a fall in these
dose indicators over the last 15 years. Nor is there much suggestion of a fall in doses associated with the use of flat panel detectors, as opposed to image intensifiers. An assessment of the impact of radiation dose in the context of overall patient outcome is required.

Keywords: cardiac catheterizations, interventional, radiation doses, cardiology

Online supplementary data available from stacks.iop.org/JRP/36/R131/mmedia

Context and objectives

Interventional cardiology procedures (ICP) are medical procedures in which the heart is catheterized under fluoroscopic x-ray guidance to obtain images of the heart chambers, valves and surrounding blood vessels. With improved technology, the role of ICP has changed, moving from diagnostic to therapeutic [1], including dilatation of narrowed vessels and valves and closure of anomalous ducts or septal defects. In recent years, an increasing number of ICP have been performed in children [2]. In various congenital heart diseases (CHD), ICP are a relatively non-invasive and complication-free alternative to surgery [3], usually performed in a dedicated cardiac x-ray laboratory with specially trained staff to ensure successful outcome and minimal patient risk. However, due to the complexity of these procedures, radiation doses can be high as a result of the extensive use of fluoroscopy and multiple digital, or ‘cine’ acquisitions. Furthermore, some complex CHD conditions require multiple catheterizations within the first few years of life [4]. Radiation exposure is associated with an increased lifetime risk of cancer development [5–8]. There is reasonable evidence that children are more sensitive to radiation induced cancer, although the relationship between risk and age-at-exposure varies between organs in a manner not fully determined [9].

Following concerns about the lack of information on typical dose levels in paediatric ICP [10] and the consequent difficulty in setting national reference levels, the last 15 years have seen a large number of studies published in this area [2, 11–48]. These have been conducted to evaluate quality assurance, optimisation techniques and equipment changes, establish local or national reference levels, or to estimate the risk of cancer and tissue reactions. A review of these studies was conducted with the objective of summarizing these data in a concise form and characterising and explaining patterns in dose variation.

Methods

We reviewed the scientific literature on radiation dosimetry in ICP, published between 2000 and March 2016. This review focuses on doses to children and young adults. However, some studies included patients with CHD followed into adulthood, thus included some patients aged over 22 years. A literature search was conducted using PubMed with broad search terms such as (exposure or radiation) and (children or paediatric) and (dos’ or exposure or radiation) and (cardi” or hemodynamic* or cathet” or angiograph* or arteriograph* or angiopla” or intervention*). In addition, references in each publication were traced back to locate other relevant publications. From each paper, we extracted the number of examinations, the patient age/weight range considered, procedure type, the kerma area product ($P_{KA}$, also referred to as dose area product, DAP), fluoroscopy time (FT), and, where quoted, air kerma, effective
dose and organ doses. We converted all $P_{KA}$ figures to the units of Gy $\cdot$ cm$^2$, equal to 100 cGy $\cdot$ cm$^2$ or 100 $\mu$Gy $\cdot$ m$^2$. Smith et al [34] present their data in units of ‘mGy/cm$^2’’. The correct unit of $\mu$Gy $\cdot$ m$^2$ was obtained from medical physics staff at the hospital where data were acquired. In some studies, the $P_{KA}$ meter was only connected to a single output in biplane fluoroscopy systems. These studies were excluded from the analysis as the combined $P_{KA}$ from both planes was unknown. Air kerma, measured in milligray (mGy) is quoted for a point located on the source-detector central axis, 15 cm before the isocentre, i.e. the assumed position of the patient’s entrance surface, thus providing an approximation of skin dose [49]. These figures do not usually include corrections for backscatter and table attenuation [50]. Furthermore, where multiple beam angles are used, the irradiated area of skin may change, thus air kerma may over-estimate dose to a particular area of skin.

Where carefully analysed, $P_{KA}$ and air kerma can be useful dose indicators to evaluate optimization of radiological practice, compare performance of equipment and operator skill or to compare the practice among different centres. Effective dose ($E$) and mean absorbed dose ($H$) to an organ or tissue can be estimated from $P_{KA}$, using an $E/P_{KA}$ or $H/P_{KA}$ conversion factors derived from Monte Carlo simulations [45, 46] or physical measurements [47]. Fluoroscopic screening time is usually measured in minutes. In the absence of dose rate, FT is a non-dosimetric quantity, though it is widely reported since it is readily available.

In all of the published manuscripts that provided organ doses, the quantity of interest was the absorbed dose, averaged over the organ volume, in milligray (mGy), or equivalent dose, measured in millisieverts (mSv) which are numerically equal in the context of medical x-rays [6]. Effective dose, as reported in ICRP 103 [6], was originally introduced, as a risk-adjusted dosimetric quantity to primarily control occupational exposure. It is also expressed in mSv [6]. Cautious use of effective dose to compare doses from different examinations or procedures or different technologies in medicine should be limited to comparisons for an average population. It is inappropriate for the paediatric population, as substantial differences in cancer risk are observed for males and females, and at different ages. Effective dose should not be used to provide estimates of risk to individual patients [6, 51, 52].

Organ doses and effective doses are estimated in all publications using either physical measurements in anthropomorphic phantoms, or PCXMC, a Monte Carlo code dedicated to the estimation of patient doses in medical diagnostic x-ray settings [53]. With PCXMC, doses to 29 organs are estimated by Monte-Carlo simulations of the interactions between photons and matter, the body of the patient being simulated by mathematical hermaphrodite phantoms. These phantoms were based on the 6 models developed by Cristy [53, 54] and were adapted to enable calculation of the effective dose according to ICRP publication 103 weighting factors [6].

Results

Data were obtained from 36 studies published in the scientific literature between 2000 and March 2016 concerning paediatric doses during ICP. Details of studies included in the review are given in table 1. The complete table of gathered data is very large and is presented in the supplementary materials (stacks.iop.org/JRP/36/R131/mmedia). Values of median $P_{KA}$ presented by 5 large studies with adequate age/weight stratification, for the 4 most commonly reported procedure types is given in table 2. Details of the equipment used in each study, including quoted filtration, tube potential and frame rates, are also included with the supplementary materials.

The most frequently reported interventional procedures were PDA (patent ductus arteriosus) occlusion, ASD (atrial septal defect) and PFO (patent foramen ovale) occlusion, atrial
septostomy, aortic dilatation, aortic valvuloplasty, pulmonary valvuloplasty and pulmonary artery angioplasty. Most diagnostic procedures were grouped together into a single category, although some studies provided information separately for coronary angiography.

$P_{KA}$ was generally in the range 1–100 Gy·cm$^2$, varying considerably between studies. For example, there is a more than 50-fold variation in median $P_{KA}$ for interventional procedures in studies by Ait Ali et al [11] (though based on only 5 procedures) and Smith et al [34]. Where stratified by procedure type, $P_{KA}$ tended to be highest for right ventricular outflow
### Table 2. Median (interquartile range) of kerma area product (Gy · cm²) for four procedure types, presented in five studies.

<table>
<thead>
<tr>
<th>Study</th>
<th>Age/weight range</th>
<th>PDA occlusion</th>
<th>ASD/PFO occlusion</th>
<th>Pulmonary valvuloplasty</th>
<th>Aortic valvuloplasty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>Median P&lt;sub&gt;KA&lt;/sub&gt; (IQR)</td>
<td>n</td>
<td>Median P&lt;sub&gt;KA&lt;/sub&gt; (IQR)</td>
<td>n</td>
</tr>
<tr>
<td>Ghelani (2009–2013) [22]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;1 year</td>
<td>130</td>
<td>5 (75%; 8)</td>
<td>219</td>
<td>9 (75%; 17)</td>
<td>155</td>
</tr>
<tr>
<td>1–4 years</td>
<td>294</td>
<td>7 (75%; 12)</td>
<td>180</td>
<td>14 (75%; 25)</td>
<td>24</td>
</tr>
<tr>
<td>5–9 years</td>
<td>60</td>
<td>13 (75%; 22)</td>
<td>127</td>
<td>39 (75%; 67)</td>
<td>35</td>
</tr>
<tr>
<td>10–15 years</td>
<td>38</td>
<td>33 (75%; 85)</td>
<td>64</td>
<td>198 (75%; 448)</td>
<td>65</td>
</tr>
<tr>
<td>&gt;15 years</td>
<td>25</td>
<td>96 (75%; 151)</td>
<td>194</td>
<td>89 (75%; 204)</td>
<td>35</td>
</tr>
<tr>
<td>Barnaoui (2010–2011) [13]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;6.5 kg</td>
<td>23</td>
<td>2.1 (R: 1–7.1)</td>
<td>4</td>
<td>1.8 (R: 0.1–3)</td>
<td></td>
</tr>
<tr>
<td>6.5–14.5 kg</td>
<td>85</td>
<td>1.4 (R: 0.39–9.7)</td>
<td>4</td>
<td>2.91 (R: 0.38–18.93)</td>
<td></td>
</tr>
<tr>
<td>14.5–25.5 kg</td>
<td>29</td>
<td>2.8 (R: 0.3–7.5)</td>
<td>25</td>
<td>0.7 (R: 0.1–2.9)</td>
<td></td>
</tr>
<tr>
<td>25.4–43.5 kg</td>
<td>8</td>
<td>4.3 (R: 0.8–11.2)</td>
<td>13</td>
<td>1.1 (R: 0.4–6.8)</td>
<td></td>
</tr>
<tr>
<td>&gt;43.5 kg</td>
<td>6</td>
<td>10.8 (R: 0.6–20.1)</td>
<td>12</td>
<td>2.8 (R: 1–15)</td>
<td></td>
</tr>
<tr>
<td>All weights</td>
<td>98</td>
<td>1.8 (R: 0.3–20.1)</td>
<td>54</td>
<td>0.9 (0.1–15)</td>
<td></td>
</tr>
<tr>
<td>0–10 kg</td>
<td>87</td>
<td>1.37 (R: 0.38–18.93)</td>
<td>6</td>
<td>2.91 (R: 1.78–8.82)</td>
<td>216</td>
</tr>
<tr>
<td>10–20 kg</td>
<td>122</td>
<td>2.45 (0.48, 12.38)</td>
<td>141</td>
<td>2.83 (R: 0.34–42.68)</td>
<td>40</td>
</tr>
<tr>
<td>20–30 kg</td>
<td>34</td>
<td>4.11 (R: 0.91–19.48)</td>
<td>80</td>
<td>4.71 (R: 1.93–29.87)</td>
<td>9</td>
</tr>
<tr>
<td>&gt;30 kg</td>
<td>25</td>
<td>20.87 (R: 7.94–181.31)</td>
<td>118</td>
<td>12.70 (R: 1.93–244.56)</td>
<td>22</td>
</tr>
<tr>
<td>All weights</td>
<td>266</td>
<td>2.54 (R: 0.38–181.31)</td>
<td>345</td>
<td>5.04 (R: 0.34–244.56)</td>
<td>286</td>
</tr>
<tr>
<td>5–12.5 kg</td>
<td>2.63 (1.78, 3.53)</td>
<td>5.03 (2.97, 6.61)</td>
<td>5.78 (4.80, 9.32)</td>
<td>4.71 (3.13, 7.06)</td>
<td></td>
</tr>
<tr>
<td>12.5–25 kg</td>
<td>5.56 (3.52, 9.85)</td>
<td>16.21 (11.87, 24.33)</td>
<td>30.63 (14.33, 43.53)</td>
<td>58.93 (33.79, 107.01)</td>
<td></td>
</tr>
<tr>
<td>All weights</td>
<td>92</td>
<td>3.52 (2.29, 7.09)</td>
<td>10.38 (6.29, 28.78)</td>
<td>4.05 (2.33, 14.34)</td>
<td>26</td>
</tr>
<tr>
<td>Verghese (2005–2009) [40]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;1 year</td>
<td>8.00 (5.58, 14.30)</td>
<td>21.97 (16.14, 30.48)</td>
<td>28.16 (14.31, 39.78)</td>
<td>74.92 (44.19, 105.82)</td>
<td></td>
</tr>
<tr>
<td>1–4 years</td>
<td>61</td>
<td>110.18 (56.51, 271.45)</td>
<td>99</td>
<td>98.71 (60.97, 153.41)</td>
<td></td>
</tr>
<tr>
<td>5–9 years</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10–15 years</td>
<td>27</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;16 years</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: R = range, 75% = 75th percentile
tract (RVOT) dilatation and pulmonary artery angioplasty, and lowest for atrial septostomies and heart biopsies. A strong trend of increasing $P_{KA}$ with increasing patient weight/age is also apparent. This is unsurprising given the increased x-ray output required to maintain the same intensity at the detector as attenuator thickness increases, and also the increased beam area required to include the region of interest. Where patient ages from new-born to adults were studied, the ratio in $P_{KA}$ between these two patient size groups varied between studies, ranging from around 5 to over 50. Median fluoroscopy times (FT) were in the range 5–20 min, though with less variation between studies than that which was observed for $P_{KA}$. There is little suggestion of a trend in FT with patient size.

Quoted air kerma tended to be the sum of both imaging planes, making analysis of the potential for deterministic skin injuries difficult. More usefully, Glatz et al [24] provide the percentage of examinations in which an air kerma of over 2 gray was exceeded in any single plane. This was 1.8% for all procedures combined, 4.3% for interventional and 0.9% for diagnostic procedures. These figures increased with increasing patient size, reaching 32.9% and 6% in the >65 kg group for interventional and diagnostic procedures respectively. These total air kerma figures were reasonably similar to those reported by Verghese et al [40] and Ghelani et al [22], though much higher than those reported by Ubeda et al [39], even accounting for the adjustment for table attenuation in the latter study.

Many papers estimated effective dose [2, 12, 13, 16, 20, 23, 24, 26, 32, 33, 35, 41–44] which was generally in the range 3–15 mSv. A summary of the $E/P_{KA}$ conversion factors used to calculate effective dose is given in table 3. Relatively few papers quoted estimated organ doses [13, 23, 24, 26, 32, 35, 41, 43, 44]. The organs receiving the highest doses were the lungs, heart, oesophagus and breasts. Organ doses were generally less than 20 mGy for procedures conducted using modern equipment, though occasionally reached 50 mGy or above. Doses to bone marrow were relatively low, being around 1–3 mGy for recent examinations. A summary of organ dose/$P_{KA}$ conversion factors derived from three studies is shown in table 4.

Discussion

While $P_{KA}$ is an easily acquired dose indicator well suited to fluoroscopy, it is important to note that the relationship between $P_{KA}$ and doses to the patient tissues and organs is not straightforward, depending strongly on beam angle, field size, beam quality and patient morphology. Consequently, comparison of $P_{KA}$ values acquired using different equipment and for different patient ages and procedure types is problematic. This is not always appreciated, and many published audits of $P_{KA}$ simply refer to the figure as ‘dose’, providing little information on equipment used and typical beam quality levels.

In order to compare results between studies and minimize the discrepancies of the results, we restricted this review to studies published from 2000 only. However, when reviewing the various studies on patient dosimetry in ICP, there appears to be great variability in radiation doses received by patients. There are a number of possible explanations.

Firstly, the ages of patients may vary between studies. Given the up-to-fiftyfold increase in examination $P_{KA}$ between smallest and largest patient size groups, a small difference in the average age of study subjects could explain a sizeable difference in average $P_{KA}$. Yet large variations are seen even where data are stratified by patient age or weight. Interestingly, there is a tendency for $P_{KA}$ to explode upwards to very high values (over 100 Gy · cm$^2$) for larger patient sizes in some studies (e.g. Verghese [40], Glatz [24], Ghelani [22]), but not in others (e.g. Barnaoui [13], McFadden [30], Martinez [29]), where the increases in $P_{KA}$ with patient size are relatively restrained.
Table 3. Various quoted effective dose per unit $P_{K_A}$ conversion factors (in units of mSv (Gy · cm$^2$)$^{-1}$ for cardiac catheterizations.

<table>
<thead>
<tr>
<th>Methodology</th>
<th>Derived from Schmidt [45]</th>
<th>PCXMC v2.0</th>
<th>Modified from Schmidt [45]</th>
<th>PCXMC v1.3</th>
<th>ATOM phantoms/TLDs</th>
<th>PCXMC</th>
<th>ATOM phantoms/ RPLGDs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>65 kV, 3.0 mm Al</td>
<td>70 kV, 3.0 mm Al</td>
<td>60–85 kV, 6 mm Al, 0.3 mm Cu</td>
<td>65 kV, 3.0 mm Al$^b$</td>
<td>58–70 kV, 3.0 mm Al</td>
<td>HVL = 6.0 mm Al (PA)/5.57 (LAT)</td>
<td>HVL = 7.6/6.4/6.6 mm Al (0 year) and 7.7/6/6.6 mm Al (1 year)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Patient age (years)</th>
<th>0</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.72 (3.4 kg)</td>
<td>1.01 (9.2 kg)</td>
<td>0.49 (19.0 kg)</td>
<td>0.29 (32.4 kg)</td>
<td>0.16 (56.3 kg)</td>
<td>0.13 (73.2 kg)</td>
</tr>
<tr>
<td></td>
<td>3.5/3.5</td>
<td>1.6/2.6</td>
<td>0.8/1.3</td>
<td>0.5/0.8</td>
<td>0.3/0.4</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>3.7/3.7</td>
<td>1.9/1.9</td>
<td>1.0/1.0</td>
<td>0.6/0.7</td>
<td>0.4/0.4</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>2.05/2.34</td>
<td>0.82/1.16</td>
<td>0.42/0.64</td>
<td>0.24/0.38</td>
<td>0.13/0.22</td>
<td>0.10/0.16</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>1.8/1.4</td>
<td>0.9/0.07</td>
<td>0.71/0.65</td>
<td>0.41/0.39</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>2.19/2.17</td>
<td>0.91/0.87</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>3.61/3.31</td>
<td>1.27/1.4</td>
<td>2.34/2.4/0</td>
<td>1.27/1.4/2.7</td>
<td>1.27/1.4/2.7</td>
<td>—</td>
</tr>
</tbody>
</table>

$^a$ Note: Figures quoted by Onnasch based on 9.26 mSv per Gy · cm$^2$ kg$^{-1}$.

$^b$ Authors also quote adjustments for other energy levels, albeit a limited range. For 3.5 mm Al and 0.1 mm Cu, this adjustment ranges from 1.2 to 1.4 depending on phantom size or projection angle.

$^c$ Conversion factors quoted by Kawasaki are for fluoroscopy (f) and cine acquisitions (a). PA = posteroanterior, Lat = lateral, HVL = half value layer, RPLGD = radiophotoluminescent dosemeter.
A second reason for variation in $P_{KA}$ is that studies may include a different mix of procedure types, each with a characteristic degree of complexity and thus likely fluoroscopy time and number of acquisitions. If a particular hospital specialises in complex procedures such as valve replacements, this could result in an unusually high average $P_{KA}$ where data for all procedure types are presented together. However, large discrepancies remain, even where studies are stratified by procedure type. For example, a 10–60 fold variation in median $P_{KA}$ for ASD occlusions was seen between studies by Barnaoui et al [13], and Verghese et al [40], depending on age group. The fluoroscopy times of the latter study are longer, but to a much smaller extent than the increase in $P_{KA}$. There is little reason to suspect the complexity of a given procedure type varies between centres. Although specialist children’s hospitals may be expected to treat more complex conditions, there was little suggestion that they delivered higher doses, accordingly. A related issue is that of cardiologist experience and training in radiation protection [55, 56]. Even short training courses can result in significantly decreased

![Table 4](image-url)
There is, however, no suggestion that training explains the overall variation in doses between studies.

A third explanation for \( P_{KA} \) variation relates to equipment differences. This includes not only the model of fluoroscopic equipment used, (e.g. Siemens Axiom Artis, Philips Integris etc.), but also includes the way the machine is set up, including frame rates, dose rate, use of additional filtration and antiscatter grid usage [58]. Here, the desire to reduce radiation doses conflicts with the desire to obtain satisfactory image quality [59]. Dose reduction techniques should be applied to keep the dose as low as reasonably achievable (ALARA) and to reduce the radiation risks. The goal of the ALARA concept as it applies to ICP is to provide maximal diagnostic and therapeutic benefit while requiring the lowest possible radiation dose [4]. This is even more challenging in paediatric ICP because of the higher heart rate in children, smaller cardiovascular structures, smaller body size and wider variety of unusual anatomic variants [4]. Today, several techniques that do not deteriorate image quality are available to decrease radiation exposure [4, 25], including use of copper filtration, close collimation, improved digital image processing techniques such as recursive filtering [60] and reduced frame rates.

A fourth potential explanation for variation in \( P_{KA} \) is measurement uncertainty and incorrect recording or reporting of dose indicators. Around half of reviewed publications did not mention calibration of dose measuring equipment or quality assurance measures. Recorded \( P_{KA} \) figures are subject to an uncertainty of around \( \pm 15\% \), even with regular calibration to national standards. Failure to ensure calibration of \( P_{KA} \) meters, while increasing this uncertainty, is unlikely to explain the observed magnitude of variation in \( P_{KA} \) between studies. Mixing up units, for example \( \mu \text{Gy} \cdot \text{m}^2 \) and \( \text{mGy} \cdot \text{cm}^2 \), could explain a ten- or even hundred-fold variation in \( P_{KA} \), however this again is an unlikely source of the variation.

There is no clear trend in \( P_{KA} \) or FT with study date. If anything, reported \( P_{KA} \) figures are higher in more recently published data, although this observation involves comparison between studies rather than comparison of different eras at the same centre. Recent years have also seen an increase in more complex procedures being carried out, such as trans-catheter pulmonary valve replacements [61]. Onnasch and colleagues [32] found a decrease in \( P_{KA} \) per patient mass with the replacement of a Siemens Bicor/Digitron with a Philips Integris 5000BH system (0.618 versus 0.278 \( \text{Gy} \cdot \text{cm}^2 \cdot \text{kg}^{-1} \)). This change involved a reduction in frame rate from 50 s\(^{-1}\) to 12.5–25 s\(^{-1}\) and the use of additional copper filtration. A greater than fourfold reduction in \( P_{KA} \) was reported by Smith et al [34] following the installation of new equipment. Again, the newer machine was able to use a lower frame rate (typically 7.5–15 s\(^{-1}\)). Other studies led by Verghese [40] and Borik [15] report reductions in \( P_{KA} \) following implementation of a range of exposure reduction techniques including reduced frame rates or patient size specific program settings. There was little indication of a reduction in \( P_{KA} \) or patient dose associated with the use of flat panel detectors, instead of image intensifiers. In fact the lowest \( P_{KA} \) figures, reported by Ubeda et al [39], involved the latter detector type. It is acknowledged, however, that flat panel detectors, along with more advanced signal processing, offer improved image quality per unit dose [62].

Quoted effective doses for coronary angiography of 2–12 mSv were reasonably similar than those reported for cardiac CT scans, which are generally 1–6 mSv [23, 41, 63]. Where both modalities were compared in the same study however, the effective dose for the latter was lower [23, 41]. Such comparisons are somewhat limited, however, as CT is restricted to diagnostic imaging, while catheterizations are often combined with biopsies and allow interventions such as stent insertion.

Effective dose and organ dose estimates include all the uncertainties and variations associated with \( P_{KA} \), in addition to the variability of \( E/P_{KA} \) and \( H/P_{KA} \) conversion factors. These uncertainties include variation in beam angles and x-ray energy levels from expected values.
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(potentially a 2–3 fold variation in $H/IP_{KA}$), anatomical differences between patients and the crude phantoms used in dose estimations [26, 27] and accuracy of the Monte Carlo code itself [27]. The conversion factors calculated by Barnaoui et al [13] and Karambatsakidou et al [21] are more appropriate for examinations carried out using modern equipment utilising copper filtration, which while decreasing dose overall, increases patient dose per unit $P_{KA}$. The conversion factors of Schmidt et al [45], subsequently adapted by Onnasch et al [32], assume fairly low beam quality and are more suitable for examinations conducted on older equipment. Conversion factors depend on the ICRP weighting factors used. The weighting factor for the breasts increased from 0.05 to 0.12 between ICRP 60 [64] and ICRP 103 [6], while those for the liver, thyroid and oesophagus were reduced from 0.05 to 0.04. In addition, the heart was included in the ‘remainder’ category for ICRP 103. Overall these changes have resulted in an increase in effective dose per unit $P_{KA}$ for ICP [21].

Effective dose is age and sex averaged, and, although it can be used to enable comparison of relative detriment between procedures, it should kept in mind that the application of the underlying risk coefficients (averaged over several populations, both genders and all ages) to calculate this quantity is inappropriate in paediatric population. Rather risk is best evaluated from estimated equivalent doses to individual organs combined with age-, sex-, and organ-specific risk coefficients. Unfortunately, few estimates of organ doses from ICP have been published so far [13, 26, 42]. Those that have suggest relatively low doses to bone marrow and the thyroid, tissues known to be especially sensitive to radiation induced malignancies following childhood exposures [9].

Conclusion

In this review, we had considerable difficulty in comparing results from different studies because of significant differences in the dosimetry methods employed, the use of various dose metrics, and a general absence of information about factors influencing the dose in each study. Future studies on exposures of patients during ICP could benefit from standardization of dose estimation methods and use of consistent units (Gy · cm$^2$, rather than cGy · cm$^2$ or µGy · m$^2$ as recommended by the International Commission on Radiological Units, ICRU [65]). Classification of ICP is also challenging as some authors reported results for specific ICP whereas other authors reported results for broad categories only (diagnosis versus therapeutic). We acknowledge that stratification by procedure type is difficult where sample sizes are small, however. A consensus is needed on ICP nomenclature or grouping in order to allow a common assessment and comparison of doses. This is especially important in the setting of reference dose levels, as the mean doses vary significantly from one procedure type to the next. In clinical use, however, a single examination may involve different interventions or diagnostic tests (e.g. coronary angiography and heart biopsy done together) and at present there are no national guidelines or standardised clinical protocols for these procedures.

The potential benefits of higher doses in terms of improved image quality are acknowledged. However there is currently limited evidence to determine the relationship between radiation dose, image quality, cancer risks and overall patient outcome [59]. For patients with CHD, tracking of dose indicators should be done and made part of the patient’s record so that careful considerations of further exposure can be properly documented during the course of treatment, and alternative strategies to reduce patient-specific radiation burden can be developed and implemented [24]. Other imaging modalities such as echocardiography and magnetic resonance imaging (MRI) which do not require ionizing radiation should always be preferred for the pre-and post-surgical evaluation of the congenital heart disease (CHD).

Lastly, children exposed to radiation so early in life should be monitored to look for an increased risk of radiation induced diseases, mostly cancer. Because of the rather small number of patients treated in each centre, international pooling of cohorts from several countries is necessary to achieve sufficient statistical power to detect the small risk that could be associated with such exposures [66]. In France the epidemiological study ‘Coccinelle’ (acronym based on the French for ‘Ladybird’) is currently being carried out and is specifically designed to provide further knowledge on the potential cancer risks associated with paediatric ICP [67]. Up to now, around 5000 children have been included in the cohort but recruitment is still on going at a national level [68]. A similar study is currently being conducted in the UK by Dr M Pearce, University of Newcastle [26], and the feasibility of a pooled analysis to increase the statistical power of these individual studies is under discussion. Further pooling with other international studies is highly desirable.

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**Conflicts of interest**

None declared.

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