Radiation dose in paediatric cardiac catheterisation: a systematic literature review.

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Abstract

It is believed that children are more sensitive to ionising radiation than adults. This work reviewed the reported radiation dose estimates for paediatric cardiac catheterisation. A systematic literature review was performed by searching healthcare databases for studies reporting radiation dose using predetermined key words relating to children having cardiac catheterisation. The quality of publications was assessed using relevant Critical Appraisal Skills Programme questions and their reported radiation exposures were evaluated.

Introduction

Children undergoing paediatric cardiac catheterisation (PCC) receive essential diagnosis and treatment of congenital heart disease (CHD). The greatest radiation doses may occur during complex procedures, which are likely to involve longer fluoroscopy times (FT) and digital acquisitions. Radiation exposures in PCC are justified because the benefit outweighs the risk in accordance with national and European guidelines[1-2]. A number of factors affect radiation dose including the type and complexity of CHD, imaging protocols, X-ray equipment, and operator experience. Furthermore, there exists a large variation in patient size, as well as type of radiation dose units used for dosimetry, potentially causing confusion for clinicians. The development of new technology continues to potentially affect the radiation dose in PCC. During the last decade there have been major technological advances in surgical equipment used in PCC such as the amplatzer closure device for patent ductus arteriosus (PDA) interventions[3]. Likewise imaging equipment in developed countries has transitioned from the use of image intensifier (II) to flat panel detector (FPD) technology. A recent survey of clinical centres in the United Kingdom (UK) (n=13) and Ireland (n=1) demonstrated that more than half of surveyed centres were using FPDs during PCC[4]. A review of published radiation doses in PCC is necessary to provide clinicians and researchers with an accurate depiction of current clinical radiation exposures. The aim of our work was to perform a systematic literature review to determine the current radiation doses reported from PCC.

Methodology

The systematic literature search was performed using the following healthcare databases: Medline (1949 - present), Pubmed (1947 - present), Science Direct (1823 - present), Cumulative Index to Nursing and Allied Health (CINAHL) (1937 - present) and the Cochrane Library Database (1974 - present). The Transparent Reporting of Systematic Reviews and Meta-Analysis group flow chart demonstrates the search strategy used[5] (Figure 1). The "Medical Subject Heading" (MeSH) was used to help identify related keywords (Table 1). The reference list of each relevant article was searched for additional publications and a zetoc alert was set up to identify current and future publications (www.zetoc.mimas.ac.uk). Identified articles were included if they were in English, measured radiation dose in PCC and were fully peer reviewed. Articles were excluded if they were review articles or if they only observed dose in patients >18 years of age. Each study was assessed by one reviewer using a scoring scale based on selecting 7 relevant cohort study Critical Appraisal Skills Programme (CASP)[6] as follows: (i) Did the study address a clearly focused issue? (ii) Was the cohort recruited in an acceptable way? (iii) Was the radiation dose accurately measured to minimise bias? (iv) Have the authors identified and taken into account confounding factors? (v) Do you believe the results? (vi) Can the results be applied to the local population? (vii) Do the results of the study fit with other available evidence? Two additional reviewers assessed the resultant scores given by reviewer one.

Results

The literature review search results are summarised in Table 2. The additional reviewers had no disagreements with the scoring of article quality. Thirty-one

relevant articles were reviewed and included studies relating to radiation dose, dose optimisation, risk estimates, biological effects and image quality. Approximately 50% of studies were published from 2010 - 2015 yet accounted for 95% of the data observed in the literature. The smallest studies consisted of 18 children [7-8] whilst the largest studies were performed in the United States of America (USA) and UK and consisted of 8,267 and 7,726 children respectively[9-10]. The most commonly observed measurements were dose area product (DAP) (n=26) and fluoroscopy time (n=23). A larger number of studies provided data using an II (n=18) compared to a FPD (n=12). The majority of studies presenting data from FPD (n=12) were published in the last 5 years (n=9). The CASP quality scores were consistently high. All articles scored between 5 - 7 with a mean score of 6. Radiation dose estimates by Verghese et al[11] (n=3,365) and Harbron et al[10] (n=7,726) demonstrated a clear decline in radiation doses in PCC from 2004 - 2008. All but two small studies[12-13] stated that they had calibrated or performed quality assurance on their either their DAP meters or radiographic film.

Articles presenting DAP as mean or median are demonstrated in Tables 3 - 4. The majority of studies (90%) observed greater DAP from interventional procedures compared to diagnostic. Mean diagnostic DAP ranged from 294 cGycm²[14] - 2,080 cGycm²[8]. Mean DAP for interventional procedures ranged from 312.9 cGycm²[14] - 10,900 cGycm²[8]. Median interventional DAP was as high as 30,067 cGycm². This occurred with patients >16 years undergoing proximal right or left angioplasty and/or stent insertions[11]. In one imaging centre median DAP of 71,240 cGycm² was observed for diagnostic procedures all children observed[10]. In the same imaging centre however, this figure was found to be 2,740 cGycm² by 2010. Interventional FT

was substantially greater compared to diagnostic FT in 15 of the 23 studies. The highest reported diagnostic and interventional FTs were 41 minutes[14] and 77 minutes[11,15] respectively. However a median FT of 90 minutes was also reported for a pulmonary vein dilation procedure[11]. Children undergoing PDA and ASD closures resulted in the lowest radiation doses [11-12,16-19] whilst angioplasty, in particular pulmonary and right ventricular outflow tract angioplasty, resulted in the greatest radiation doses[11-12,17].

Effective dose *(E)* estimates (Table 5) were greater for interventional procedures in studies that recorded data for both diagnostic and interventional procedures[20-22,17]. The largest *E* estimate was 77 mS however no information was given on the procedure type[23].

All but one study that recorded entrance surface dose (ESD) was published prior to 2010 and consisted of relatively small cohorts (n=18 - 137). The majority of studies observed greater ESD for interventional procedures compared to diagnostic. Few studies provided specific minimum or maximum range of ESD however the largest observed ESD was 1,674 mGy[7]. Only five studies recorded and published air kerma (AK). All of these articles were published since 2008. Several authors observed greater AK for interventional procedures[11,18,24]. Although a greater range of AK for diagnostic procedures was reported by Harbron et al[10], in many of their observed procedures, the AK was not recorded.

There was a paucity of peak skin dose (PSD) recordings with only four studies providing this data (Table 6). Radiographic film was placed on the patients skin for

three studies[19-20,23], whilst Martinez et al[25] used correction factors in combination with exposure parameters to determine PSD. The greatest PSD observations were made by Song et al[19] who published PSDs of up to 410 mGy for an ASD closure and 1,020 mGy for a radiofrequency ablation procedure.

Radiation dose observations were more commonly categorised according to age (n=8) compared to weight (n=4). It was observed throughout the studies that radiation dose increased with age and weight, and regardless of patient size, radiation dose was greater for interventional procedures. Observation of these studies found a better correlation between weight and radiation dose compared to age and radiation dose. Numerous authors observed no increase in radiation dose with increasing age[21,23,25-27], however these studies represented smaller cohorts of between 40 - 249 children.

Radiation dose was most commonly reported for the thyroid and gonads compared to the other internal organs (Table 7). The lowest thyroid dose was 0.5 mGy for a diagnostic procedure[15], whilst the highest dose was 73.1 mGy from an unspecified procedure[7]. Greater mean thyroid dose was observed for interventional procedures[13,15,28-29]. Gonadal dose was much lower compared to the thyroid and ranged from 0.1 - 2.1 mGy with the highest dose observed by Papadopoulou et al[15] for an ASD procedure (2.1 mGy). Only two studies performed radiation dose estimates to other internal organs, from which the heart, lungs, thymus and breast were estimated to receive the greatest radiation dose[16-17].

The types of digital acquisition data published varied considerably making it difficult to compare. Mesbahi and Aslanabadi[30] recorded mean digital acquisition DAP (70

cGycm²) and AK (7.2 mGy) whilst Li et al[7] recorded the range of tube potentials (54 - 125 kVp), tube currents (28 - 1080 mA) and digital acquisition times (42 - 133 secs). Tsapaki et al [27] recorded greater median digital acquisition DAP for interventional procedures (1,000 cGycm²) compared to diagnostic (120 cGycm²). Meanwhile the mean number of digital acquisition acquisitions was greater for interventional procedures in three studies[20,24,31] reported a greater percentage of radiation dose from digital acquisitions compared to fluoroscopy during interventional procedures (77% versus 67%). Chida et al[31] found that mean digital acquisition acquisitions were greatest for balloon dilatations (n=16.3). Barnaoui et al [17] reported that the greatest mean number of digital frames occurred for "angioplasty" procedures (1,088).

Discussion

A broad systematic review identified 31 articles that made radiation dose estimates for PCC. These articles were individually assessed using a CASP scoring assessment. In order to interpret radiation dose estimates it is important to understand the numerous radiation dose measurements reported. AK is a measurement of the kinetic energy released in air and is measured in Gy[32]. In PCC, AK is measured at the interventional reference point, which approximates the location of the skin at 15 cm from the heart. DAP, also known as the kerma air product is a quantity of radiation that reflects not only the dose but also the area of tissue irradiated. The ESD is the skin dose at the point of intersection of the X-ray beam. Unlike AK, the ESD includes all scatter radiation, thought to contribute to approximately 27 - 45% of the skin dose[33]. The *E* is used to describe the detrimental effects of radiation exposure upon organs and is not a measurement of the amount of radiation but is an assessment of the link between the radiation dose received and the potential detrimental effect [34].

Finally, the PSD is the highest dose at any portion of a patients skin when several regions of the skin have been exposed to the X-ray beam[32].

Owing to the relative ease of obtaining DAP and FT from X-ray systems, these were the most widely published measurements. Whilst DAP is a crucial measurement of the radiation dose the FT is a poor indicator of radiation dose. Nonetheless FT continues to be recorded since times of >60 minutes are associated with an increased potential of deterministic skin injury[35]. In general, individual patients undergoing PCC have received significant ionising radiation doses, including DAPs greater than of 71,240 cGycm²[10], *E* up to 77.2 mSv[23], ESD up to 1674 mGy[7] and AK up to 4,842 mGy[11]. In comparison an *E* from a single chest radiograph is approximately 0.02 mSv[36]. The FT for patients undergoing PCC can be >90 mins[8]. In general, radiation dose varied considerably due to patient size and procedure type.

The decline in observed radiation dose estimates in PCC from 2004 – 2008 by Verghese et al[11] and Harbron et al[10] appear attributed to the installation of newer X-ray systems. This is namely the widespread introduction of caesium iodide FPDs in clinical practice, which convert X-ray photon energy into electrical signal more efficiently than older II technology[37]. Other contributing aspects may include increasing awareness by clinicians for radiation dose optimisation for children and an increase in operator skill and experience. The majority of studies demonstrated that radiation dose is generally greater for interventional procedures compared to diagnostic. This is likely because interventional procedures are often more complex. Despite these findings there were numerous reports of diagnostic procedures resulting in a similar or greater radiation dose than interventional procedures [10-11,23,26,38].

Patient weight was an important factor on influencing radiation dose recordings given that the X-ray beam transverses a thicker volume of tissue and because the FOV is also increased. The most recent publications made the important distinction between radiation dose and corresponding weight category[9-10,18,39]. These studies have provided benchmark data for future dosimetry in PCC according to patient weight. It should be noted that no study presented data on chest circumference, which could be explored for potential classification for radiation dose. This may provide a better correlation for radiation dose due to potential variation in patient shape. For example a tall and slender child may be the same weight as a shorter and wider child yet they are likely to have a difference in their chest size. Consequently the radiation beam would transverse a different volume of tissue and could therefore skew comparisons for radiation dose comparisons in weight groups.

The number of studies that estimated *E* was relatively low compared to DAP recordings. This is likely due to the complexity involved in estimating *E* whilst in comparison the DAP is readily available from X-ray systems. The range of mean *E* observed in this review (3.42 - 26 mSv) was comparative to those observed in adults undergoing interventional cardiology procedures (7 - 17 mSv)[40-41].

The PSD, a more relevant measure for the risk of skin injury[35] was not commonly report in the reviewed articles. A concern regarding skin dose is the potential to exceed the deterministic threshold of a 2,000 mGy to the skin. Skin injuries are thought to be under-reported in clinical practice because the injury can be unrecognised or misdiagnosed because injury may manifest for several weeks or

years[41]. Older children appear to be more at risk because they receive greater amounts of radiation due to their greater size and there were some instances of potential for skin injury presented in the literature. Recent work by Jones et al [42-43] to validate PSD estimation could help predict and treat patients who have received high doses of radiation during PCC. Although the threshold PSD of 2,000 mGy was not exceeded in the observed studies, they consisted of low patient numbers ranging from 60 - 249[19-20,23,25]. Measurements of PSD therefore remain scarce. Although no study in this review reported a skin injury, 15 radiation skin injuries from 1,311 young adults undergoing cardiac catheterisation have been reported in the literature, with 3 of these patients >18 years of age[44]. The potential for skin injury should therefore be monitored.

The radiosensitive thyroid and gonads were the two most commonly assessed internal organs. The thyroid received greater radiation dose than the gonads because it is in closer proximity to the primary X-ray beam and consequent scatter radiation. Li et al[7] was the only study to measure radiation dose for both the right and left side of the thyroid. They observed a greater mean dose for the right side (13.6 mGy) compared to the left (8.3 mGy) because the lateral X-ray beam emerges from the patients right side. It is therefore more pertinent to assess radiation dose to the right side of the thyroid since this area receives the greatest dose. It has only been in the last 2 years that data has been published regarding other internal organs such as the heart and lungs[10,16-17]. These studies have demonstrated that the lungs, breast, heart and thymus receive substantial amounts of radiation. It may therefore be pertinent for future studies to further assess radiation exposure to these organs using film dosimetry on the anterior and posterior aspect of the chest. This is particularly

relevant due to the revised recommendations by the International Commission on Radiological Protection (ICRP) 2007[45], whereby breast tissue was determined to be at a substantially increased risk of radiation induced cancer risk than previously thought. When compared with organ dose observations in chest CT[46] the thyroid dose in PCC is similar whilst breast dose was reported to be 1.5 times greater by Barnaoui et al[17] and 9 times greater by Yakoumakis et al[16].

In the period 2010 - 2015 the number of PCC dosimetry studies performed has doubled and the number of patients observed since 2010 now account for 95% of all observations published. Large studies conducted in the USA[9,11,12,18] reported generally greater radiation exposure than the similar size study conducted by Harbron et al[10] in the UK. Similarly lower doses were also observed in smaller studies conducted in the UK and Europe by Martinez et al[25], Dragusin et al[47] and McFadden et al[14]. These differences may be due to operator practice indicated by generally longer FT in the USA population. Dose optimisation measures may also be better implemented in the UK and Europe such as collimation of the X-ray beam, length of digital acquisition, use of fluoroscopy instead of digital when possible, removal of the AS grid and the use of ultrasound guidance as an alternative to fluoroscopy.

This review has demonstrated the transition from II technology used in older publications, to the use of FPDs in recent studies. FPDs have been considered to offer greater patient dose saving[48]. Harbron et al[10] was the only author to observe radiation dose in a large number of patients undergoing PCC with both II and FPDs finding an obvious decrease in radiation dose using a FPD. The introduction of noise

reduction algorithms using newer FPD compared to older FPD however resulted in a 56% dose reduction in patients observed by Haas et al[39].

Limitations and recommendations

Despite a consensus by two additional reviewers who assessed the scoring performed for article quality, this review may have benefitted from these reviewers scoring the articles independently and then comparing quality scores. This may have avoided potential bias and helped to identify any areas of debate. Although DAP readings were subject to quality assurance, published *E* estimates used either monte carlo software or conversion factors to provide *E* however both of these methods provide on crude estimates due to their inaccuracies of up to 40%[23,32].

The conversion of AK from cGy to mGy and DAP from μGycm² to cGycm² for comparing the data between studies was trivial however heterogeneous data meant that only a summary of the qualitative data has been discussed and therefore limited conclusions that can be taken. Comparing larger cohort studies also remains informal due to the considerable variation in practice between imaging centres. Variations in clinical practice were insufficiently documented and include fluoroscopy pulse rate, number of CINE acquisitions, use of the anti-scatter grid, use of additional X-ray filtration and use of magnification. It is known that these factors vary in current UK practice that they have a substantial effect upon radiation dose[4]. Although two studies found that average CINE acquisitions were greater for balloon dilatation studies, there was paucity of this data found. Overall the types of CINE data published such as CINE DAP or CINE times varied considerably and were scarce.

Numerous studies presented mean DAP only, rather than median [8,14,16,19-21,23-27,29,31,38,49]. Contrary to this, data presented from the interquartile range such as the median and in particular the 75th percentile is instead recommended by recent European diagnostic reference levels for paediatric imaging (PiDRL) guidelines[50]. In harmony with this, larger and more recent studies in the review (n=>1000)[9-12,18] have published their radiation doses as median values. This method should be used for future dosimetry in PCC. There was a wide variation in radiation dose units published and as well categorisations of patient size and procedural type. This meant that there were inconsistent weight categorisation and procedure types for comparison. As well as recommending DAP as the basic quantification of radiation dose followed by AK and fluoroscopy time, the recent European PiDRL guidelines[50] have also identified the following appropriate weight categories for paediatric fluoroscopy: (1) < 5 kgs, (2) 5 – < 15 kg, (3) 15 - < 30 kg, (4) 30 - < 50 kg and (5) < 80 kg. In addition to these recommendations future attention should be given to developing methods of improving the ease of reporting radiation doses from PCC by making the best use of electronic information systems. At present the UK National Patient Dose Database collates information from typical radiation doses to patients however radiation dose from PCC has yet to be collated and published[51].

Conclusion

Larger studies in this review suggest that radiation dose in PCC has been lowered in recent years but it remains varied and substantial. Caution should be given to categorising anticipated radiation dose according to “diagnostic” and “interventional” procedures because diagnostic radiation doses can be greater on occasions. Emphasis should be placed on the purpose of the procedure and weight. Median DAP followed

by AK and FT is recommended as the most basic radiation dose estimates for these groups. The number of CINE acquisitions may be useful for comparing data. The large variation in radiation dose suggests that further attention should be given to optimising the radiation dose and standardisation of practice between imaging centres.

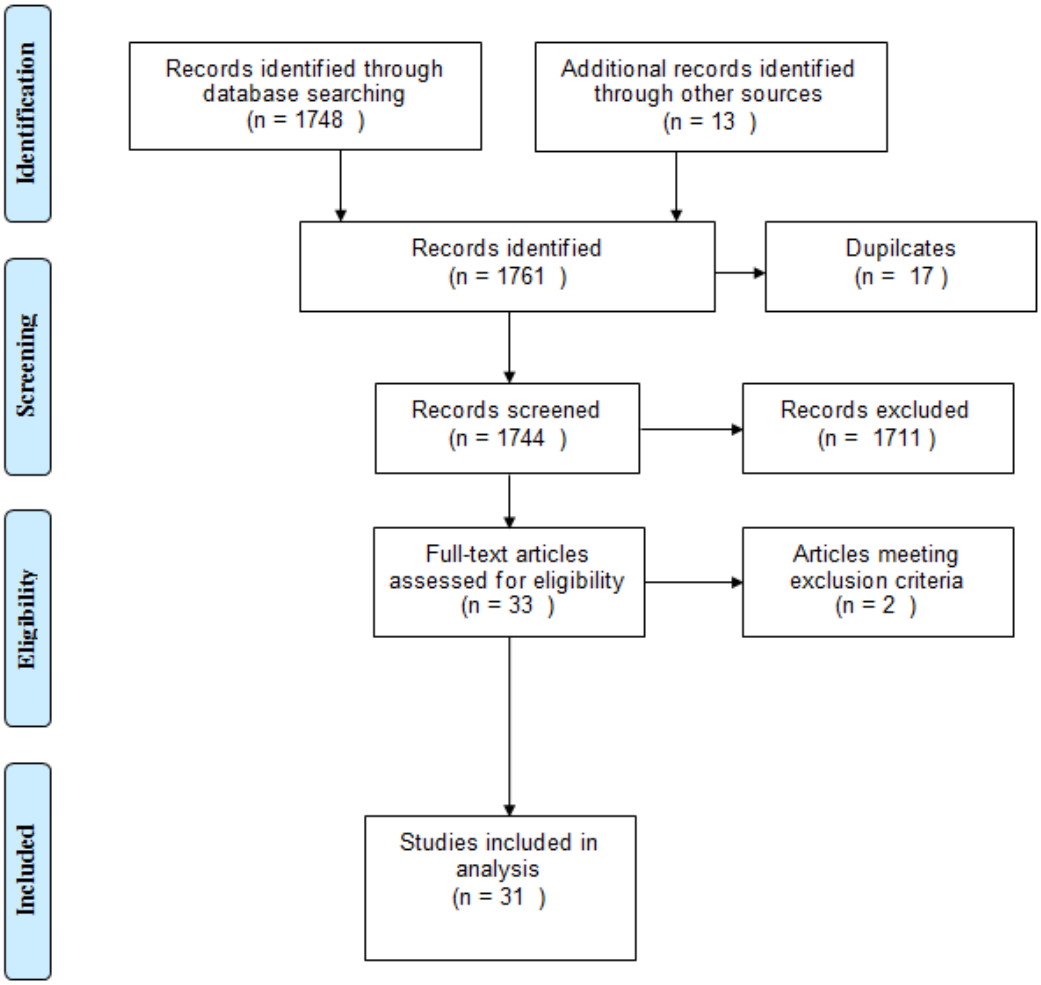

Figure 1 Summary of literature review search using the Transparent Reporting of Systematic Reviews and Meta-Analysis group flow chart (2009).

Table 1 Summary of keywords searched in the systematic literature review.

1st term	2nd term	3rd term
Pediatric OR Paediatric OR Newborns OR Adolescents OR Infants OR Children OR Congenital heart disease OR	Cardiac OR Catheterization OR Catheterisation OR Cardiology OR Interventional cardiology	Radiation dose OR Radiation exposure OR Radiation protection OR Radiation injuries OR Reference levels OR Dose reduction OR Dose optimization OR Dose optimisation OR Ionising radiation OR Ionizing radiation OR

Table 2 Characteristics of the 31 articles in the systematic literature review.

Lead author	Year	Patients (*n*)	Country	X-ray detector	Quantities	Quality score
Al-Haj [21]	2008	190	Saudi Arabia	II	DAP, FT, DA, E,	5
Ait-Ali [8]	2010	18	Italy	unknown	DAP, FT, E	6
Bacher [20]	2005	60	Belgium	II	DAP, FT, DA, E, PSD	7
Barnaoui [17]	2014	801	France	FPD	DAP, FT, E, O, DA	6
Beels [38]	2009	49	Belgium	II	DAP, FT, DA, E	6
Boothroyd [26]	1997	50	UK	II	DAP, ESD	6
Chida [31]	2010	239	Japan	II	DAP, FT, DA	7
Dragusin [50]	2008	273	Belgium	FPD	DAP, FT, DA	6
El Sayed [24]	2012	107	Egypt	II	DAP, FT, DA, E, AK	6
Ghelani [12]	2014	2,713	USA	unknown	DAP, FT	6
Gherardi [56]	2011	200	UK	FPD	DAP, E,	7
Glatz [18]	2014	2,265	USA	FPD	DAP, FT, E AK,	7
Haas [39]	2015	667	Germany	FPD	DAP, FT	7
Harbron [10]	2015	7,726	UK	FPD/II	DAP, FT, E, AK, O	6
Karambatsakidou [23]	2009	249	Germany	II	DAP, E, PSD	5
Kobayashi [9]	2014	8,267	USA	FPD/ II	DAP, FT	7
Li [7]	2001	18	Japan	II	ESD, FT, DA, O	5
Martinez [25]	2007	137	Spain	FPD	DAP, ESD, PSD	5
McFadden [14]	2013a	354	UK	II	DAP, FT	7
Mesbahi [30]	2008	32	Iran	FPD	DAP, FT, DA, AK,	5
Moore [13]	1999	25	USA	II	FT, DA, ESD, O	5
Papadopoulou [15]	2005a	46	Greece	II	FT, DA, ESD, O	6
Papadopoulou [29]	2005b	45	Greece	II	ESD, O	6
Schueler [55]	1994	175	USA	II	DAP, FT, DA	5
Shim [28]	2000	24	USA	II	ESD, DA, FT, O	5
Song [19]	2015	90	China	FPD	DAP, FT, E PSD	7
Tsapaki [27]	2008	40	Greece	II	DAP, FT	6
Verghese [11]	2012	3,365	USA	FPD	DAP, FT, AK	7
Walsh [52]	2015	99	Canada	FPD	DAP, FT, DA	6
Yakoumakis [22]	2009	98	Greece	II	ESD, E	5
Yakoumakis [16]	2013	53	Greece	II	DAP, ESD, O	6

DAP - Dose area product, PSD - Peak Skin dose, E - Effective dose, DA – Digital acquisition data, FT- Fluoroscopy time, O - Organ dose, AK – air kerma, ESD – Entrance surface dose

Table 3 Mean dose area product observations.

Lead author	Year	Mean Diagnostic DAP (cGycm²) (min-max)	Mean Interventional DAP (cGycm²) (min-max)	All procedures DAP (cGycm²)
Al-Haj	2008	777	1,085	
Ait-Ali	2010	2,080 (100 - 6500)	10,900 (1,200 - 27,700)	
Bacher	2005	442.5 (96 - 1461)	1,085	
Barnaoui	2014	490	536	
Beels	2009	555	270	
Boothroyd	1997	1,332.5 (558 - 15,860)	3,402.1 (126 - 20,239)	
Chida	2010	1,702	2,242	
El Sayed	2012	377.5	1,323.9	
Haas	2015			2343
Karambatsakidou	2009	2,088	1,156	
Martinez	2007	470 (190 - 860)	830 (240 - 1,780)	
Mesbahi	2008			200
McFadden	2013a	294 (10 - 5,648)	312.9 (13 - 7,961)	
Papadopoulou	2005a	411 (46 - 1,360)	873 (218 - 3,266)	
Papadopoulou	2005b	355 (36 - 1,360) (Posterior detector only)	572 (63 - 3,320) (posterior detector only)	
Tsapaki	2008	(10 - 3,670)	(150 - 19,480)	
Song	2015	-	1,339	
Yakoumakis	2013		2,230	
Walsh	2015	-	243	

Table 4 Median dose area product observations.

Lead author	Year	Diagnostic Median DAP (cGycm²) (range)	Interventional Median DAP (cGycm²) (range)	All procedures Median DAP (cGycm²) (range)
Dragusin	2008	(250 - 990)	(480 - 4,680)	
Glatz	2014	(612 - 8,959)	(258 - 15,841)	
Ghelani	2014		(70 - 2,300)	
Gherardi	2011			200
Harbron	2015	(186 - 71,240)	(225 - 26,930)	
Haas	2015			396.3
Kobayashi	2014	(288 - 10,347)	(279 - 11,600)	
Schueler	1994			2,112* (376 - 12,467)
Papadopoulou	2005a	360	873 - ASD 2,223 - VSD	
Verghese	2012	215 - 1,247	797 - 30,067	

**Radiation dose measured as R-CM²*

Table 5 Summary of effective dose observations.

Lead author	Year	Mean effective dose (mSv) (min-max)	Median effective dose (mSv) (min-max)
Al-Haj	2008	D 8.7 I 13.5 (4 - 19.9)	
Bacher	2005	D (0.6 - 23.2) I (1 - 37)	
Barnaoui	2014	D 5.3 (0.3 - 23) I 5.68 (0.3 - 48.4)	
Beels	2009		6.4
Dragusin	2008		I 8.05
El-Sayed	2012	D 3.42 I 5.97	
Glatz	2014		D 4.8 -15.2 I 5.5 - 25.7
Gherardi	2011		D 5 (0.2 - 27.8)
Harbron	2015		6.7
Karambatsakidou	2009	(0.2 - 77.2)	
Song	2015	I 7.72	
Yakoumakis	2009	D 3.71 (0.16 - 16.44) I 5 (0.38 - 25.01)	D 2.9 (0.16 - 16.44) I 3.48 (0.38 - 25.01)
Yakoumakis	2013	I 26 (17 - 40)	

D – Diagnostic
I – Interventional

Table 6 Summary of peak skin dose observations.

Study	Year	Mean (mGy)	Median (range) mGy)
Bacher	2005		34.2 (12.1 - 144) Posterior 23.9 (1.49 - 297) Lateral
Karambatsakidou	2009	16 (0 - 60) Posterior	
Martinez	2007	D 51.75 I 98	
Song	2015	79 PDA 140 VSD 91 ASD 190 RFA 83 PV	42 (2 - 250) 120 (4 - 320) 49 (3 - 410) 140 (4 – 1,020) 74 (4 - 160)

D - Diagnostic
I - Interventional
PV - Pulmonary valvuloplasty
RFA - Radiofrequency ablation

Table 7 Summary of organ radiation dose observations.

Lead author	Year	Mean absorbed dose (mGy)	Median equivalent dose range (mSv)	Mean equivalent dose (mSv)
Barnaoui	2014	Thyroid 8.4 Breasts 15.75 Lungs 33.45 Oesophagus 26		
Harbron	2015		Thyroid 0.4 - 2.9 Breasts 5.7 - 69.2 Heart 9.5 - 72.4 Lungs 9.4 - 93.7 Lymph nodes 2 - 16.2 Oesophagus 7 - 54.4 Liver 2.3 Stomach 18.5	
Li	2001	Thyroid right side 13.6 Thyroid left side 8.3		
Moore	1999	D thyroid 5 I Thyroid 9.5 D gonads 0.6 PDA gonads 2 PV gonads 1		
Papadopoulou	2005a	D thyroid 2 (0.5 - 4) I thyroid 3.45 (0.4 - 8.3) D gonads 0.2 (0.1 - 0.3) I gonads 0.4 (0.1 - 2.1)		
Papadopoulou	2005b	D thyroid 6.9 I thyroid 9.2 D gonads 0.2 I gonads 0.2		
Shim	2000	D thyroid 6.9 ASD thyroid 9.2 D gonads 2 ASD gonads2.2		
Yakoumakis	2013			Thyroid 3.4 Breasts 87.8 Heart 90.4 Lungs 42 Liver 28 Stomach 34.7 Thymus 122.5 Pancreas 25.7 Skin 6.8 Spleen 16.9

D – Diagnostic, I – Interventional, ASD – Atrial septal defect

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