Review Article

OCCUPATIONAL RADIATION DOSES TO OPERATORS PERFORMING CARDIAC CATHETERIZATION PROCEDURES

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Abstract—**Cardiac catheterization procedures using fluoroscopy reduce patient morbidity and mortality compared to operative procedures. These diagnostic and therapeutic procedures require radiation exposure to patients and physicians. The objectives of the present investigation were to provide a systematic comprehensive summary of the reported radiation doses received by operators due to diagnostic or interventional fluoroscopically-guided procedures, to identify the primary factors influencing operator radiation dose, and to evaluate whether there have been temporal changes in the radiation doses received by operators performing these procedures. Using PubMed, we identified all English-language journal articles and other published data reporting radiation exposures to operators from diagnostic or interventional fluoroscopically-guided cardiovascular procedures from the early 1970's through the present. We abstracted the reported radiation doses, dose measurement methods, fluoroscopy system used, operational features, radiation protection features, and other relevant data. We calculated effective doses to operators in each study to facilitate comparisons. The effective doses ranged from 0.02–38.0 μSv for DC (diagnostic catheterizations), 0.17–31.2 μSv for PCI (percutaneous coronary interventions), 0.24–9.6 μSv for ablations, and 0.29–17.4 μSv for pacemaker or intracardiac defibrillator implantations. The ratios of doses between various anatomic sites and the thyroid, measured over protective shields, were 0.9 ± 1.0 for the eye, 1.0 ± 1.5 for the trunk, and 1.3 ± 2.0 for the hand. Generally, radiation dose is higher on the left side of an operator's body, because the operator's left side is closer to the primary beam when standing at the patient's right side. Modest operator dose reductions over time were observed for DC and ablation, primarily due to reduction in patient doses due to decreased fluoroscopy/cineradiography time and dose rate by technology improvement. Doses were not reduced over time for PCI. The increased complexity of medical procedures appears to have offset dose reductions due to improvements in technology. The large variation in operator doses observed for the same type of procedure suggests that optimizing procedure protocols and implementing general use of the most effective types of protective devices and shields may reduce occupational radiation doses to operators. We had considerable difficulty in comparing reported dosimetry results because of significant differences in dosimetric methods used in each study and multiple factors influencing the actual doses received. Better standardization of dosimetric methods will facilitate future analyses aimed at determining how well medical radiation workers are being protected.**

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Key words: exposure, occupational; fluoroscopy; medical radiation; occupational safety

INTRODUCTION

CARDIAC CATHETERIZATION refers to a group of procedures in which the cardiac chambers or coronary vessels are accessed by inserting a catheter through blood vessels. The procedure can be diagnostic, therapeutic, or both. Diagnostic procedures are performed to identify or quantify structural or functional problems, which include congenital heart defects, vascular stenoses, and valvular or myocardial disorders.

Since the introduction of catheter-based procedures in 1930's, they have been demonstrated to have advantages over surgery including minimal invasiveness, reduced pain and risk, shorter hospital stays, and lower cost. As a result, they are performed frequently. An estimated 1,414,000 diagnostic cardiac catheterizations (DC) and 664,000 percutaneous coronary interventions (PCI) were performed in 2003 (Thom et al. 2006). Reported cardiac ablations increased from 450 in 1989 to about 15,000 in 1993 (Scheinman 1995). In 29 European countries, the number of coronary angiographies (CA) and PCIs increased 264% and 416%, respectively, between 1992 and 2001 (Togni et al. 2004). The number of operators has not increased in proportion to the number of procedures, resulting in increased workload per physician (Vano et al. 1998).

During cardiac catheterization procedures, catheters, guidewires and other devices are visualized and guided

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using real-time fluoroscopy. Supplemental cineradiography is used to obtain high-quality permanent images. Due to concerns about radiation exposure to the operator, various protective devices have been developed. Radiation protection relies mainly on personal protective devices, including leaded aprons, thyroid shields, leaded glasses and leaded gloves. The hands and eyes are generally less shielded because of relatively infrequent use of leaded gloves and leaded glasses (Marx et al. 1992). Movable shields have been installed on room or system structures and can provide additional protection. Leaded glass or plastic screens suspended from the ceiling, and located between the patient and the operator, are often used to protect the operator's upper body and eyes.

There have been a number of studies reporting operator doses. Earlier reports demonstrated large variations in dose assessment methods as well as wide variations in dose for most categories of procedures. Radiation doses to medical staff and dose rates at specific points in a laboratory have been measured either during clinical procedures or by simulating the procedures with human phantoms (Lindsay et al. 1992; Kuon et al. 2002). Direct measurements of radiation dose have been the most common method. Computer simulation with radiation transport software such as Monte Carlo N-Particle (MCNP) rather than direct measurement has also been used to assess radiation doses (Schultz et al. 2003).

Dosimeter locations for direct measurements have varied. In some cases, dosimeters are placed at the collar level, trunk level, or in both positions to estimate whole body exposure; at the eye, hand, or over gonads to estimate dose to those specific sites; or at multiple sites to assess the effects of inhomogeneous radiation fields. In addition, dosimeter locations can be over or under personal protective devices. Various types of dosimeters have been employed. Thermoluminescent dosimeters (TLDs) have been used most commonly because their small size allows them to be placed on various parts of the body.

Different investigators have observed substantial differences in doses received for the same type of procedure. These differences may be as large as an order of magnitude (Padovani and Rodella 2001; Tsapaki et al. 2004a; Trianni et al. 2005). Many factors influence occupational radiation exposures during fluoroscopy use (Balter 1999; ICRP 2000). No single standardized method has evolved to permit easy comparison of dosimetry results among studies. Padovani and Rodella (2001) reviewed published data on dose to medical staff in interventional cardiology and observed the difficulty in comparing these data. The objectives of the present investigation were to (1) provide a comprehensive and systematic summary of the reported radiation doses received by operators performing diagnostic or interventional cardiac catheterization procedures, (2) identify the primary factors influencing radiation dose, and (3) evaluate whether there have been significant temporal changes in the radiation exposures to operators performing these procedures.

MATERIALS AND METHODS

Data collection

This review focuses on doses to cardiologists and other physicians who are the primary operators during cardiac catheterization procedures. For this purpose, we carried out an extensive literature search using PubMed to identify articles in English on radiation dose to physicians associated with fluoroscopically-guided diagnostic and therapeutic cardiac catheterization procedures. A literature search was conducted using broad search terms such as "(dos* or exposure or radiation) and (occupational or personnel or staff or operator or physician or doctor) and (cardi* or electrophy* or hemodynamic* or cathet* or angiograph* or arteriograph* or angiopla* or intervention* or ablation or pacemaker or defibrillator)." In addition, references in each publication found to be useful were traced back to locate other relevant publications. From each paper, we abstracted the total number of examinations reported within each major procedure category, the reported dose to the operator by anatomic site, the dose measurement or estimation method used, the fluoroscopy system used, operational features including tube potential, tube current, beam filtration, frame rates, total fluoroscopy and cineradiography times, and dose area product (DAP), and radiation protection features used, including type and lead equivalent thicknesses of protective shields.

Dosimetry units and quantities: A unified approach for conversion to comparable measures

While organ-averaged absorbed dose is the preferred metric of individual exposure for studies of radiation health risks (Simon et al. 2006), it was generally not possible to quantify organ doses from the literature. To simplify our data analysis and to reduce the data to a single consistent metric of exposure, we transformed the different types of dosimetric units and quantities presented in literature to personal dose equivalent, $H_P(10)$ and $H_P(0.07)$, as defined by the International Commission on Radiation Units and Measurements (ICRU). Both are used as standard dosimetric quantities (ICRU 1993) in radiation protection. Radiation doses measured under a leaded apron were converted to personal dose equivalent, $H_P(10)$, and those over a leaded apron, thyroid shield,

leaded glasses, and leaded gloves were converted to personal dose equivalent, $H_P(0.07)$. The $H_P(0.07)$ is more appropriate for the skin and the eye than $H_P(10)$ because doses to the skin and the lens of the eye are defined at a depth of 0.07 mm and 3 mm in tissue, respectively.

Early studies used exposure (R) rather than absorbed dose. In this work, exposure was converted to $H_P(10)$ and $H_P(0.07)$ based on the method and calculations described by Simon et al. (2006), which used data from International Commission on Radiological Protection Publication 74 (ICRP 1996). The energy spectrum of x rays for fluoroscopy procedures in Simon et al. (2006) was assumed to be generated by 80 kV potential with 3 mm Al filter (IPEM 1997). For those exposure conditions, the calculated conversion factors were 0.0116 Gy R^{-1} for $H_P(10)$ and 0.0119 Gy R^{-1} for $H_P(0.07)$. The average values of peak potential and filtration abstracted from the studies reviewed here closely agreed with the values assumed by Simon et al. (2006).

The peak potential can vary depending on the operator but fluctuates during fluoroscopy by an automatic brightness control (ABC) system. Attenuation of x-ray beams in the human body varies with the beam energy, and thus organ dose and effective dose for the same badge dose reading will differ depending on x-ray energy. If fluoroscopy is operated at lower than 80 kV, effective dose would be overestimated. However, the overestimation would be not more than a factor of two for the diagnostic x-ray energy range (NCRP 1995; ICRP 1996). Although peak potential fluctuates during fluoroscopy depending on the thickness of the body at the examination site, it does not change dramatically during a cardiac procedure. Abstracted data in this study indicate that peak potential during cardiac procedures maximally deviates only by about 10–20% from average peak potential for most cases. Therefore, effective dose estimation using the average potential is reasonable for our purposes.

Although some recent studies have reported absorbed doses, other dosimetric quantities and terminologies have been used to express dose. These have included badge dose, deep dose, shallow dose, skin dose, entrance surface dose (ESD), and scattered entrance surface air kerma (S-ESAK). When dosimetric results were indicated as a badge measurement under or over a leaded apron, the reported values were assumed as an $H_P(10)$ or $H_P(0.07)$ estimate, respectively. When only $H_P(10)$ was used for all measurement sites, the given doses measured over personal protective shields were converted to $H_P(0.07)$ by adding 3% to the reported dose because there is about 3% difference between $H_P(10)$ and $H_P(0.07)$ for the assumed diagnostic energy spectrum. ESD and S-ESAK, which include backscatter (Kosunen et al. 2006), were converted to $H_P(10)$ and $H_P(0.07)$ by assuming a backscatter factor of 1.40 (Petoussi-Henss et al. 1998).

Estimation of effective dose

There have been many efforts to estimate effective dose or effective dose equivalent using personal monitors (NCRP 1995). Two simple algorithms have been commonly used to convert radiation dose measured by the personal dosimeters to an estimate of effective dose (Niklason et al. 1994; Rosenstein and Webster 1994). Padovani et al. found better agreement between the Niklason algorithm and experimental assessment (Padovani et al. 2001). Therefore, effective dose was estimated with the Niklason algorithm, which is based on two dosimeter readings (Niklason et al. 1994). One reading is the dose measurement value under the leaded apron and the other is the value over the leaded apron or thyroid shield. When the dosimeter reading under the apron was not available, a modified Niklason approach was employed that is derived from one dosimeter reading (Padovani and Rodella 2001). The conversion algorithms are given below:

$$E = 0.02(H_{os} - H_u) + H_u \quad (1)$$

or

$$E = 0.03\ H_{os} \text{ for person with thyroid shield,} \quad (2)$$

and

$$E = 0.06(H_{os} - H_u) + H_u \quad (3)$$

or

$$E = 0.07\ H_{os} \text{ for person without thyroid shield,} \quad (4)$$

where E is effective dose, H_{os} is $H_P(0.07)$ measured over shield on thyroid level, and H_u is $H_P(10)$ measured under apron. Estimation of effective dose is substantially modified by the use of a thyroid shield, because a thyroid shield protects much more than the thyroid gland per se, including protection of the underlying regions of the skin, esophagus, vertebrae, and bone marrow. Based on the Niklason algorithm, the effective dose is two-fold higher when a thyroid shield is not used. In this analysis, effective dose was calculated assuming use of a thyroid shield. While use of thyroid shields is clearly not universal, our assumption about usage was based on 30 of 62 publications reviewed that discussed thyroid shield usage. Of those 30 publications, 28 reported routine usage of a thyroid shield while only two publications report it was not used. If measurements over a thyroid shield were

not available, then eye dose, trunk dose, or hand dose measured over personal protective devices were substituted, in that sequence, because there were small differences in radiation doses at these various anatomic sites during the same procedure (see below).

Data tabulation and analysis

Cardiac catheterization procedures were categorized into four major types: DC, PCI, ablation, and implantable devices, which include pacemaker (PM) and intracardiac defibrillator (ICD) placement. Dosimetry results obtained from incompletely specified procedures (e.g., interventional cardiology procedures) or mixtures of different procedures (e.g., diagnostic and therapeutic procedures) were summarized separately. The most commonly reported anatomic sites where dosimeters were placed, based on our literature review, were operators' hands outside of gloves, eye level outside of protective glasses, thyroid level outside of a thyroid shield, and the trunk level either outside, inside, or on both sides of leaded aprons. The radiation dose data obtained from the literature were tabulated and organized by type of procedure, the anatomic site(s) where dosimeters were placed, and the year of publication. If available, DAP and fluoroscopy and cineradiography times were also tabulated, because occupational dose is strongly related to patient dose and fluoroscopy and cineradiography times.

Some dosimetry studies compared dose results under different conditions. For example, Watson et al. compared radiation doses to cardiology fellows with one and two years of experience (Watson et al. 1997). Lange and von Boetticher (2006) compared operator radiation exposures when using radial or femoral artery approaches. In these instances, the results under different conditions were tabulated separately and the differences were also provided. These data were one source of useful information to identify dose-influencing factors and to quantify their degree.

Radiation doses at different anatomic sites were compared because the large variations in radiation intensity around a patient table during a fluoroscopically-guided procedure may cause substantial variation in dose at different anatomic sites on the operator. Ratios of doses received by different pairs of anatomic sites were calculated using eqn (5):

$$DR_{A,B} = \frac{H_A}{H_B}, \quad (5)$$

where $DR_{A,B}$ is the dose ratio and H_A and H_B are doses measured at two different anatomic sites, A and B. Dose ratios were calculated using appropriate dose measurements or estimates from those studies which provided measurement data over personal protective shields at more than two different anatomic sites. All of the calculated ratios for specific sites obtained from different publications were averaged in the analysis presented here.

To evaluate temporal trends in radiation doses, effective doses were plotted by publication year. Because most studies did not provide the dates of data collection, publication year was used to approximate the year of the measurements. Moreover, we only used those publications in our analysis whose data were derived from direct measurement. Dosimetry methods and study size (i.e., number of procedures conducted during an occupational dosimetry study) varied. Most studies collected occupational radiation dose using direct measurements over a wide range, from a few examinations to thousands of examinations. Outliers were identified by Studentized residuals and excluded from the fit. We regressed log-transformed effective dose on time using weighted least-squares (Myers 1990). The number of procedures included in each study was used as a weight. The regression procedures used available statistic software (SAS Institute, Inc. 2004) The t tests were conducted to evaluate the significance of temporal trends using p-values of less than 0.05 to indicate significance.

Because physician dose is strongly correlated with patient DAP and fluoroscopy and cineradiography times (Williams 1997; Servomaa and Karppinen 2001), we also investigated temporal trends in fluoroscopy and cineradiography times. Radiation dose rate during fluoroscopy and cineradiography operations directly influences cumulative radiation dose to patients as well as operators. The possibility of a temporal trend of dose rate during procedures was investigated by analyzing the temporal trend of cineradiography frame rates. Frame rates given in each publication were plotted by publication year and were fit similarly to that described above except for the weighting procedure. Because the frame rate can vary depending on laboratory, x-ray system, or operator rather than patient, there was no basis for weighting each publication by number of procedures.

RESULTS

Although radiation exposures to physicians during cardiac catheterization were reported in the literature as early as 1950 (Hills and Stanford 1950), the data in that publication were excluded from this study because the techniques and fluoroscopy technology which were employed in those years differed greatly from more recent techniques. Additionally, two early studies on operator dose during DC reported very high radiation levels compared to all of the other DC studies (Malsky et al. 1971, 1972). Those data were also excluded from further

analysis based on extensive clinical experience by two of us (DLM, SB) and because we suspect that either measurement error or very unusual conditions make them unrepresentative.

Radiation dose by procedure type

Tables 1 to 5 present the operator effective doses organized by procedure type. Our estimates of operator effective dose per procedure was found to range from 0.02 to 38 μSv for DC, 0.17 to 31 μSv for PCI, 0.24 to 9.6 μSv for ablation, and 0.29 to about 17 μSv for PM/ICD implantation. Comparison of the mean values in Tables 1 to 5 gives results which are difficult to generalize because the exposure conditions are specific to each procedure type and study. Direct comparisons are most appropriate when comparing doses for the same procedure or under similar exposure conditions.

Reported mean fluoroscopy times were 2 to 30 min (weighted mean = 8) for DC, 10 to 35 min (weighted mean = 18) for PCI, 11 to 166 min (weighted mean = 47) for ablation, and 4 to 12 min (weighted mean = 6) for PM/ICD implantation. Reported mean patient DAP per procedure ranged from 13 to about 130 (weighted mean = 41) Gy cm^2 for DC, 46 to 180 (weighted mean = 85) Gy cm^2 for PCI, 11 to about 120 (weighted mean = 58) Gy cm^2 for ablation, and 5 to 15 (weighted mean = 12) Gy cm^2 for PM/ICD implantation. For the same patient DAP, operator doses vary substantially. Effective doses for operators, normalized to patient DAP, were 0.002 to 0.13 (weighted mean = 0.038) μSv Gy^{-1} cm^{-2} for DC, 0.002 to 0.17 (weighted mean = 0.046) μSv Gy^{-1} cm^{-2} for PCI, 0.011 to 0.022 (weighted mean = 0.018) μSv Gy^{-1} cm^{-2} for ablations, and 0.057 to 0.076 (weighted mean = 0.069) μSv Gy^{-1} cm^{-2} for PM and ICD insertions.

Radiation dose by anatomic site

Mean dose per procedure measured over personal protective devices at different anatomic sites ranged from 0.4 to about 1,100 μSv at eye level, 1.2 to 580 μSv at thyroid level, 3.5 to 750 μSv at trunk level, and 0.4 to about 790 μSv at hand level. Under-apron measurements at the trunk level yielded much lower doses, ranging from 0 to 16 μSv per procedure.

We estimated the ratio of $H_P(0.07)$ between various anatomic sites with these results: eye to thyroid was 0.9 ± 1.0 ($\pm 1\sigma$), trunk to thyroid was 1.0 ± 1.5 ($\pm 1\sigma$), and hand to thyroid was 1.3 ± 2.0 ($\pm 1\sigma$). In general, radiation doses were highest when measured over protective devices on the operator's hand, with progressively lower doses measured over the trunk, neck, and eye, in that order.

Temporal trends in dose

Fig. 1 shows our estimates of temporal trends in effective dose to operators from cardiac catheterization procedures. In general, effective doses determined from indirect measurements deviate more from the observed trend. A modest reduction in average dose was observed over time for DC ($p = 0.03$) and ablation ($p = 0.02$), although it is difficult to precisely quantify the degree of reduction with time because of the very wide variations in dose (for DC) and the small number of reported studies (for ablation). Our best estimate of the degree of change in dose is about four-fold reduction from 1971 to 2006 for DC. For PCI, an increasing pattern was observed over time; however, it is not statistically significant ($p = 0.18$).

We found modest but statistically significant reductions in average fluoroscopy durations for DC ($p << 0.01$), PCI ($p << 0.01$), and ablation ($p = 0.042$) procedures over calendar time (Fig. 2). Cineradiography times during DC have also decreased over time ($p << 0.01$). On the contrary, cineradiography time for PCI showed a statistically significant increase over time ($p = 0.008$). Reported cine frame rates varied by a factor of 6 depending on the study, ranging from 12.5 to 75 frames per second. We also observed a reduction of cine frame rate over time ($p = 0.002$) (Fig. 3).

DISCUSSION

Radiation doses to operators during cardiac catheterization procedures varied by 2 to 3 orders of magnitude and were related to the type of procedure. While the average operator dose was quantitatively related to the average patient dose, we observed much greater variation in operator doses than in patient doses. This could be due to several factors. Different operators use different personal and movable protective devices. The amount of scattered radiation varies greatly depending on the specifics of the fluoroscopy system, its operation, and the position of the cardiologist relative to the x-ray tube and to the patient. The degree of radiation protection provided by each protective device also varies depending on type, lead equivalent thickness, and (for movable shields) position. We found that for the same patient DAP, occupational doses vary widely. This implies that the radiation dose to the operator during cardiac procedures might be reduced by improving radiation protection practices.

Radiation exposure during cardiac catheterization procedures

DC and PCI. As a consequence of the large number of DC and PCI procedures performed, there have been

Table 1. Radiation exposure to operator during a diagnostic cardiac catheterization (DC).

Author (publication year)[a]	No of exams[b]	DAP (Gy cm^2)[c]	Fluoro/Cine time[c] (min s^{-1})	Mean dose per procedure (μSv)[c,d]						Note
						Trunk level[g]				
				Eye level[e]	Thyroid level[f]	Over apron	Under apron	Hand level[h]	Effective dose[i]	
Wold (1971)	9			309 (111–500)	333 (226–547)	286 (95–476)		381 (108–821)	10.0	
Ardran (1973)	18		18.6 (6–38.5)/35 (9–136)		42 (0–405)	52 (24–345)	17 (0–23)	55 (24–190)	17.5	
Gignac (1974)	6			76	199			84	6.0	
Kaude (1974)	10		19 (5–43)/(13–40)					110 (<20–410)	3.3	Adult patient
Kaude (1974)	29		16 (3–39)/(13–40)	<20				150 (<20–900)	4.5	Pediatric patient
Stacey (1974)	12			55 (±43)		753 (±818)		787 (±895)	22.6	Under couch x-ray tube
Stacey (1974)	10			1,117 (±109)		154 (±139)	16 (±24)	488 (±689)	38.0	Over couch x-ray tube
Wholey (1974)	rate			121				190	3.6	
Begg (1975)	47		8.4 (3–15.2)/54	11	14			33	0.4	Table side with 0.5 mm thickness of Pb
Begg (1975)	18			127	255	100		226	7.7	No table side
Properzio (1975)	13		14.7/39	83 (<12–178)	190 (48–452)	179 (<12–321)	23 (<12–35)	333 (48–1297)	26.3	Adult patient
Properzio (1975)	7		22/12	48 (<12–71)		202 (36–298)	12 (<12–35)	428 (<83–761)	12.7	Pediatric patient
Balter (1978)	300		12.1/104	71 (67–80)	99 (104–162)	69 (55–90)	5 (0–5)	77 (55–120)	6.9	No table side shield, Apron of 0.5 mm Pb
Balter (1978)	300		13.2/117	26 (14–42)	16 (8–30)	9 (4–20)	<1 (0–1)	39 (16–75)	0.5	Table side shield, Apron of 0.5 mm Pb
Balter (1978)	100		8.7/62	6 (6–6)	1.2 (0–1.2)	5 (5–6)	0	5 (5–5)	0.02	Table side shield, Apron of 0.75 mm Pb
Rueter (1978)	rate			370 (251–469)	328 (307–402)				9.8	Estimation from time lapse and dose rate
Rueter (1978)	10–12		29.9 (±13.7)/74 (±21)	237 (±186)	194 (±68)			151 (±133)	5.8	
Rueter (1979)	4			331	283			89	8.5	
Gustafsson (1981)	4		18 (13–23.5)/	210 (130–490)	240 (140–360)		<10	280 (70–830)	7.2	
Burgess (1984)	73		5.9/					390	11.7	
Dash (1984)	16		13.5 (±4.8)/48.7 (±8.6)	90					2.7	1st phase study for head exposure
Dash (1984)	34		9.6 (±6.1)/42.5 (±5.5)	41					1.2	2nd phase study for eye exposure
Jeans (1985)	rate			560				2,140	16.8	Cardiologist keeps position during cine
Jeans (1985)	rate			20				290	0.6	Cardiologist stands back during cine
Le Heron (1985)	41				20.5				0.6	Femoral approach
Le Heron (1985)	24				67				2.0	Radial approach
Finci (1987)	10		3.7 (±2.0)/49 (±9)	60	80			310	2.4	
Holmes (1990)	11,840		10.3/59		35.7				1.1	
Janssen (1992)	5			55 (±58)	135 (±124)		1.7 (±2.2)	248 (±249)	4.4	
Grant (1992)	53		3/	25					0.8	Hand contrast injection
Grant (1992)	50		3.3/	5					0.2	Mechanical contrast injection
Grant (1993)	140	40 (35.7–44.3)[ci]	8 (1.9–3.8)[ci]	11 (8.3–138)[ci]					0.3	Hand contrast injection
Grant (1993)	150	45.1 (41–49.2)[ci]	2.6 (1.7–3.5)[ci]	5.2 (2.6–7.8)[ci]					0.2	Mechanical contrast injection
Axelsson (1995)	phan			238			3.1	353	7.8	Simulation based on 10 patient examinations
Karppinen (1995)	phan		7 (±3.6)/60 (±30)	470 (±440)				1,100 (±800)	14.1	Simulation based on 14 lab exams

Table 1. Continued.

Author (publication year)[a]	No of exams[b]	DAP (Gy cm^2)[c]	Fluoro/Cine time[c] (min s^{-1})	Mean dose per procedure (μSv)[c,d]						
						Trunk level[g]				
				Eye level[e]	Thyroid level[f]	Over apron	Under apron	Hand level[h]	Effective dose[i]	Note
Steffenino (1996)	15		3.4 (±2)/42 (±11)	12.7	24.6	28.7	<3.5	36.5	0.7	Cine with 25 f s^{-1}
Steffenino (1996)	15		2.8 (±1)/51 (±13)	5	14.3	14	<3.5	20	0.4	Cine with 12.5 f s^{-1}, Extra 0.5 mm rubber shield
Watson (1997)	155		8.8 (±6.8)/63 (±17)		48.2 (±38.3)				1.4	1st year fellow physician
Watson (1997)	215		6.8 (±6.5)/59(±14)		29.4 (±27.8)				0.9	2nd year fellow physician
Padovani (1998)	13	39.3 (±18.0)	3.6 (±3.3)/42.5 (±5.5)		30 (±30)			50 (±70)	0.9	CA[j]
Padovani (1998)	76	55.9 (±30.2)	4.0 (±3.5)/43.5 (±15.4)		40 (±70)			80 (±80)	1.2	CA (LC + CA + LV + Other)[j]
Padovani (1998)	49	74.6 (±37.7)	9.0 (±5.7)/42.7 (±13.8)		50 (±50)			110 (±110)	1.5	CA (LC + CA + LV + RC + Other)[j]
Lima (2000)	6			236^{md} (117–505)				302^{md} (229–463)	7.1	
Padovani and Rodella (2001)	20[k]	100							2.2	Spain
Padovani and Rodella (2001)	20[k]	83							0.5	Italy
Padovani and Rodella (2001)	20[k]	125							1.0	Greece
Kuon (2002)	phan	6.2 (±3.4)	6.4/13.7	0.444			0.0079	0.379	0.02	Simulation based on 112 patient examinations
Delichas (2003)	27	84.9 (±32.9)			60.3 (±31.3)				1.8	Hospital A
Delichas (2003)	45	76.6 (±32.2)			97.1 (±64.7)				2.9	Hospital B
Efstathopoulos (2003)	20	29 (±9)	2.0 (±1.5)/36 (±6)	3.3		3.2	0	12.5	0.1	
Schultz (2003)	MC	4.45							0.1	Pediatric congenital heart defects
Tsapaki (2004b)	100	33.5			59 (±56)				1.8	
Tsapaki (2004a)	10	44.1 (±18.6)	5.8 (±6.2)/95 (±40)		6.0 (±2.6)				0.2	
Goni (2005)	21	45 (±14)			32 (±12)	35 (±17)		84 (±36)	1.0	
Trianni (2005)	40	39.8 (±19.1)	6.2 (±3.7)/		13.1 (±12.5)				0.4	
Lange (2006)	103	13.1 (±8.5)	1.7 (±1.4)			33 (±40)			1.0	Femoral approach
Lange (2006)	92	15.1 (±8.4)	2.8 (±2.1)/			66 (±57)			2.0	Radial approach

[a] References are arranged by publication year.
[b] Number of performed diagnostic or therapeutic procedures during a dosimetry study. Rate indicates that dose was estimated with dose rate measurement data and fluoroscopic time. Phan and MC indicate that dose was measured by phantom simulation or calculated by Monte Carlo computer program simulation.
[c] Numbers in parenthesis are standard deviation (±) or minimum–maximum (–). Superscripts of *md*, *ci* and *iq* indicate median value, 95% confidence interval, and inter-quartile.
[d] Exposure unit (R) in some studies was converted into $H_p(10)$ for trunk level dose under apron by 11.6 mSv R^{-1} and into $H_p(0.07)$ for doses outside shield by 11.9 mSv R^{-1}.
[e] Dose data measured on eye, forehead, glabella, maxilla, or temple outside shield.
[f] Dose data measured on neck, collar, clavicle, or shoulder outside shield.
[g] Dose data measured on chest, sternum, umbilicus, waist, or abdomen over or under apron.
[h] Dose data measured on wrist, hand, or finger outside shield.
[i] Effective doses were calculated using Niklason (2 dosimeters) and Padovani et al. (1 dosimeter) algorithms. If no thyroid level dose outside shield was given, eye dose, trunk dose, or hand dose substituted for it by the order.
[j] CA, LC, LV, RC, and others indicate coronary angiography, left catheterism, left ventriculography, right catheterism, and 1–2 other acquisitions, respectively.
[k] Data provided directly from Padovani.

Table 2. Radiation exposure to operator during a percutaneous coronary intervention (PCI).

Author (publication year)[a]	No of exams[b]	DAP (Gy cm^2)[c]	Fluoro/Cine time[c] (min s^{-1})	Mean dose per procedure (μSv)[c,d]						Note
				Eye level[e]	Thyroid level[f]	Trunk level[g]		Hand level[h]	Effective dose[i]	
						Over apron	Under apron			
Dash (1984)	8		34.5 (±17.7)/44.1 (±14.0)	170					5.1	
Jeans (1985)	rate			1040				4160	31.2	No stand back during cine
Jeans (1985)	rate			680				1870	20.4	Stand back during cine
Finci (1987)	10		17.1 (±15.9)/32 (±7)	40	100			300	3.0	1 vessel PCI
Finci (1987)	10		19.8 (±9.9)/49 (±13)	30	130			470	3.9	2 vessel PCI
Holmes (1990)	1532		22.3/41		45.4				1.4	
Axelsson (1995)	phan			156			6	192	9.0	
Mann (1996)	126		15.8 (±1.4)/	91 (±13)					2.7	Femoral approach
Mann (1996)	66		19.2 (±2.4)/	139 (±22)					4.2	Radial approach
Mann (1996)	72		19.2 (±2.1)/	34 (±24)					1.0	Radial approach, Extra floor shield
Padovani (1998)	54	101.9 (±84.9)	18.5 (±15.5)/57 (±30)		120 (±320)			140 (±220)	3.6	
Padovani and Rodella (2001)	20[j]	133							4.4	Spain
Padovani and Rodella (2001)	20[j]	167							1.0	Italy
Padovani and Rodella (2001)	20[j]	182							2.0	Greece
Delichas (2003)	33	125.5 (±90.6)			34.8 (±34.4)				1.0	Cine radiography with 25 f s^{-1}
Delichas (2003)	37	59.8 (±31.4)			35.3 (±30.7)				1.1	Cine radiography with 50 f s^{-1}
Efstathopoulos (2003)	20	75 (±30)	9.7 (±5.9)/60 (±18)	8.7		8.3	0	32.5	0.2	
Tsapaki (2004b)	100	88.4			98 (±102)				2.9	
Tsapaki (2004a)	18	53.6 (±22.1)	13.9 (±6.3)/102 (±50)		9.3 (±5.3)				0.3	
Goni (2005)	21	120 (±49)			54 (±24)	97 (±35)		161 (±62)	1.6	
Trianni (2005)	33	71.6 (±39.0)	13.4 (±9)/		20.1 (±25.9)				0.6	
Whitby (2005)	13	61.5	11.8/					60 (30–170)	1.8	Femoral approach
Whitby (2005)	13	61.5	11.8/					350 (160–760)	10.5	Radial approach
Lange (2006)	48	51.0 (±29.4)	10.4 (±6.8)/			113 (±118)			3.4	Femoral approach
Lange (2006)	54	46.3 (±28.7)	11.4 (±8.4)/			171 (±194)			5.1	Radial approach

[a–i] See footnotes in Table 1.
[j] Data provided directly from Padovani.

Table 3. Radiation exposure to operator during an ablation.

Author (publication year)[a]	No of exams[b]	DAP (Gy cm^2)[c]	Mean dose per procedure (μSv)[c,d]							
			Fluoro time[c] (min)	Eye level[e]	Thyroid level[f]	Trunk level[g]		Hand level[h]	Effective dose[i]	Note
						Over apron	Under apron			
Calkins (1991)	31		44 (±40)	281 (±183)	156 (±110)	532 (±443)	<20	993 (±509)	4.7	Accessory AV[j] connection
Lindsay (1992)	phan		55	320					9.6	Supraventricular tachycardia
Kovoor (1995)	10		46[md] (39–65)[iq]		60[md] (30–90)[iq]			40[md] (0–80)[iq]	1.8	AVJRT[k]
Kovoor (1995)	5		55[md] (52–60)[iq]		50[md] (40–100)[iq]			60[md] (10–70)[iq]	1.5	APT at LFW[l]
Kovoor (1995)	4		107[md] (89–140)[iq]		200[md] (90–480)[iq]			120[md] (80–330)[iq]	6.0	APT at septum[m]
Kovoor (1995)	3		166[md] (128–176)[iq]		110[md] (90–130)[iq]			160[md] (130–190)[iq]	3.3	APT at RFW[n]
McFadden (2002)	30	123 (21–430)	67 (15–164)	47				233	1.4	RF ablation
Macle (2003)	20		20 (±10)		28[md]	30[md]	1[md]		1.5	Common flutter
Macle (2003)	16		22 (±21)		33[md]	12[md]	<0.5[md]		1.0	Accessory pathway
Macle (2003)	43		57 (±30)		66[md]	27[md]	2[md]		3.3	Atrial fibrillation
Trianni (2005)	21	18.8 (±11.1)	13.3 (±5)		14 (±13)				0.4	AV[j] nodal tachycardia
Trianni (2005)	15	11.0 (±7.5)	11.8 (±3.3)		8.1 (±5.5)				0.2	WPW[o] syndrome
Trianni (2005)	10	11.8 (±10.8)	10.7 (±9.1)		8.6 (±10.3)				0.3	

[a–i] See footnotes in Table 1.
[j] Atrioventricular.
[k] Atrioventricular junctional re-entry tachycardia.
[l] Accessory pathway tachycardia at left free wall.
[m] Accessory pathway tachycardia at septum.
[n] Accessory pathway tachycardia at right free wall.
[o] Wolff-Parkinson-White syndrome.

many reported doses received by operators from those procedures. Our analysis indicates that higher patient as well as operator doses during PCI are primarily due to long fluoroscopy times rather than longer cineradiography times (see Fig. 2) (Johnson et al. 1992; Delichas et al. 2003; Efstathopoulos et al. 2003). The fluoroscopy contribution to total dose is about 30% for DC and 60% for PCI (Efstathopoulos et al. 2003).

Ablation. There have been a relatively small number of occupational dosimetry studies of cardiologists who perform ablation. Much of the radiation dose from this procedure is due to the use of fluoroscopy. In general, fluoroscopy times during ablation are much longer than during other procedures.

Implantation procedures. Two characteristics of PM and ICD implantation may result in a greatly different radiation dose to the operator compared to the other procedures we reviewed. In these two procedure types, fluoroscopy times tend to be short and there is no need for cineradiography. Both factors would be expected to reduce patient and operator dose (Jeans et al. 1985; Perna et al. 2000). Mean fluoroscopy times during implantation procedures range from about 4 to 12 min (Antkowiak 1980; Jeans et al. 1985; Perna et al. 2000; Trianni et al. 2005; Tsalafoutas et al. 2005). Conversely, operator positions and insertion sites near the edge of the x-ray beam can result in a higher operator dose. During PM or ICD implantation, the operator generally uses a subclavian approach, as opposed to the femoral or radial/brachial approach used for other procedures (Kawashima et al. 2004). The subclavian approach requires the operator to stand close to the patient's shoulder and adjacent to the x-ray tube, where exposure rates are considerably higher than for the radial/brachial approach (Lindsay et al. 1992; Limacher et al. 1998). In addition, protective devices such as screens or table-side shields may not be usable when the subclavian approach is employed (Trianni et al. 2005). Trianni et al. reported that, for the same total patient dose, the operator received a higher radiation dose during PM or ICD insertion compared to other procedures (Trianni et al. 2005). We found similar relationships in our analysis of the literature.

Radiation dose by anatomic site

Radiation dose to operators varies at different points on their bodies because of non-uniformly scattered radiation and individual differences in the use of personal protective shields. For that reason, multiple site measurements are necessary to accurately assess occupational dose when radiation fields are inhomogeneous (Balter et

Table 4. Radiation exposure to operator during a PM/ICD implantation.

				Mean dose per procedure (μSv)[c,d]						
						Trunk level[g]				
Author (publication year)[a]	No of exams[b]	DAP (Gy cm^2)[c]	Fluoro time[c] (min)	Eye level[e]	Thyroid level[f]	Over apron	Under apron	Hand level[h]	Effective dose[i]	Note
Antkowiak (1980)	10		12 (±11)					255 (±257)	7.7	Pacemaker
Jeans (1985)	rate		6.7	50				150	1.5	Pacemaker
Perna (2000)	5				580 (±664)			1,046 (±965)	17.4	Pacemaker
Trianni (2005)	36	4.5 (±3.1)	3.8 (±3.3)		9.6 (±11.1)				0.3	Pacemaker
Trianni (2005)	18	15.3 (±17.0)	7.3 (±7.1)		29.0 (±31.7)				0.9	Defibrillator
Tsalafoutas (2005)	55	15.4 (±7.3)	7.0 (±2.3)	39 (±31)		87 (±71)		295 (±240)	1.2	Pacemaker

[a–i] See footnotes in Table 1.

al. 1978; Wu et al. 1991; Vano et al. 1998). Because measurements at multiple sites are expensive and inconvenient (Vano et al. 1998), most dosimetry studies have been conducted using only 1 or 2 dosimeters. Generally, the operator's hands are located closest to the patient, with the trunk, neck, and eyes progressively further away. Hence, it can be deduced that radiation doses to those anatomic sites will be ranked in the same order.

Because differences in average occupational doses to different anatomic sites have not been well quantified, a summary of the observed ratios of doses between sites may be useful to estimate dose to certain anatomic sites when no measurement data are available. For these purposes, it is necessary to estimate hand and eye doses, as well as effective dose, because many recommendations and regulations limit the dose to the skin and the lens of the eye as well as to the whole body (ICRP 1991; NCRP 1993; CEU 1996). We observed that the dose ratios between the eye and thyroid, the trunk and thyroid, and the hand and thyroid were all close to unity. Hence, if radiation dose to the thyroid is not available, in theory it can be approximated from measurements of the radiation dose to the eye, trunk, or hand.

Radiation dose also varies depending on whether it is measured at the left or the right side of the operator's body. Generally, the operator receives a higher dose on the left side of the body because the left side of the operator is closer to the source of scattered radiation (the patient) when standing at the patient's right side near the patient's groin, the most common position for DC, PCI, and ablation procedures (Kaude and Svahn 1974; Balter et al. 1978; Rueter 1978; Gustafsson and Lunderquist 1981; Vano et al. 1998; Chong et al. 2000; Lima et al. 2000; Goni et al. 2005). This position is standard because it is the easiest working position for a right-handed operator using a femoral approach. Kicken et al. reported a 1.5 to 2.5 times greater entrance dose on the operator's left side compared to the operator's front (Kicken et al. 1999). Chong et al. reported a six-fold higher exposure to the lens of the left eye than the to the lens of the right eye (Chong et al. 2000). Eye dose was also closely related to the location of the fluoroscopic monitor (Balter et al. 1978; Chong et al. 2000; Kuon et al. 2003).

Temporal pattern of radiation doses

Changes over time in the radiation doses to patients and physicians can be attributed to changes in procedure protocols and technology. Improvements in procedure protocols and the technology of x-ray equipment, catheters, and other devices generally decrease procedure time, fluoroscopy/cineradiography times, and the related radiation dose, at least, for procedures with similar degree of difficulty and complexity. In addition, improvement of technology has reduced dose rates from x-ray equipment. Newer systems have employed more sensitive radiation detectors, more filtration (e.g., copper filter rather than aluminum filter), pulsed fluoroscopy mode, and low dose mode (Mahesh 2001; Hirshfeld et al. 2005; Chida et al. 2007). These various features decrease the radiation output (after the filter) for equal exposure times. An opposing factor, however, is that improved protocols and technologies can make more complex procedures possible which can negate improvements that could otherwise reduce operator dose. In such cases, radiation doses may not decrease because more complex procedures demand longer fluoroscopy time, cineradiography time, or both.

Our analysis indicated a modest reduction in average operator dose over time for DC and ablation. In the same years, we observed a reduction of fluoroscopy time (for DC and ablation), cineradiograpy time (for DC), and cineradiography frame rate. Procedure protocols for DC are relatively standardized and have not changed substantially for many years. Hence, reductions in fluoroscopy time, cineradiography time, and dose rate by new technologies have resulted, to some degree, in concomitant reductions in operator dose for DC.

For PCI, operator doses have not been reduced over time. Cineradiography times per PCI procedure have increased over time (Fig. 2). Decreases in dose due to

Table 5. Radiation exposure to operator during mixture of different cardiac catheterization procedures.

Author (publication year)[a]	Procedure[j]	No of exams[b]	DAP (Gy cm^2)[c]	Fluoro/Cine time[c] (min s^{-1})	Mean dose per procedure (μSv)[c,d]						Note
							Trunk level[g]				
					Eye level[e]	Thyroid level[f]	Over apron	Under apron	Hand level[h]	Effective dose[i]	
McParland (1990)	Cardiac cath. lab	43			167	145	384	54	470	59.5	
Wu (1991)	Pediatric	61		6 (±5)/11 (±5)	2 (±3)	6 (±3)	7 (±3)	2 (±2)	8 (±4)	2.1	
Renaud (1992)	CA/PCI	15,359				40				1.2	
Pratt (1993)	Cath/PCI/EP/PM	900			53.3 (±29.8)					1.6	Femoral approach, Cine with 50 f s^{-1}
Pratt (1993)	Cath/PCI/EP/PM	900	44 (±2.2)		14.7 (±7.2)					0.4	Radial approach, Cine with 30–50 f s^{-1}
Pratt (1993)	Cath/PCI/EP/PM	800			45.6 (±29.6)					1.4	Mixed femoral and radial approaches
den Boer (1994)	Int. cardiology	phan		13.8/	160	180	250			5.4	Continuous x-ray mode
den Boer (1994)	Int. cardiology	phan		13.8/	60	80	110			2.4	Pulsed x-ray mode
den Boer (1994)	Int. cardiology	phan		13.8/	30	60	70			1.8	High-output pulsed x-ray mode
Li (1995)	Pediatric	18		18.2 (6.7–40.9)/67 (42–133)	88 (±78)	182 (±138)		5 (±4)		8.5	
McKetty (1996)	CA/PCI/EP/PM	448		17 (±6.9)/		153 (±83)		24.5 (±16.3)		27.1	
Zorzetto (1997)	CA/PCI	58	66 (43–79)[iq]	7.0 (6.1–9.14)/57 (42–66)[iq]		53 (23–49)[iq]		2.9		3.9	
Vano (1998)	CA/PCI	29			170 (53–460)	163 (43–398)			235 (60–740)	4.9	With lead screen
Vano (1998)	CA/PCI	25			439 (158–1005)	392 (60–816)			514 (65–1500)	11.8	Without lead screen
Chong (2000)	CA/PCI/EP/PM	49				149 (±139)	238 (±204)	3 (±2)	338 (±200)	5.9	
Perna (2000)	CA/PCI/ MV	82				90 (10–500)			(40–1300)	2.7	
Wittkampf (2000)	EPS/ RF	375				366				11.0	Baseline (A)
Wittkampf (2000)	EPS/ RF	302				42				1.3	Extra filter & LocaLisa system (B)
Wittkampf (2000)	EPS/ RF	597				11.1				0.3	(B)+pulse rate (25 → 12.5 Hz) + Pb screen
McCormick (2002)	Cardiac cath. lab	24,480				32.3		6.5		7.0	
Efstathopoulos (2006)	EPS/RF	43	32.7	16.2/	7.1	3.82	13.68	0.79	17.76	0.9	
Theocharopoulos (2006)	RF/BP	phan	43	40/	107/5.3					3.2	Femoral approach
Theocharopoulos (2006)	RF/BP	phan	43	40/	194/9.7					0.9	At 1 m from table
Theocharopoulos (2006)	RF/BP	phan	43	40/	31.2/1.6					0.9	At 1 m from table

[a–i] See footnotes in Table 1.

[j] Pediatric (pediatric cardiac catheterization), CA (coronary angiography), PCI (percutaneous coronary intervention), Cath (cardiac catheterization), EP (electrophysiology), PM (pacemaker implantation), MV (mitral valvuloplasty), EPS (electrophysiology study), RF (radiofrequency ablation), and BP (biventricular pacing).

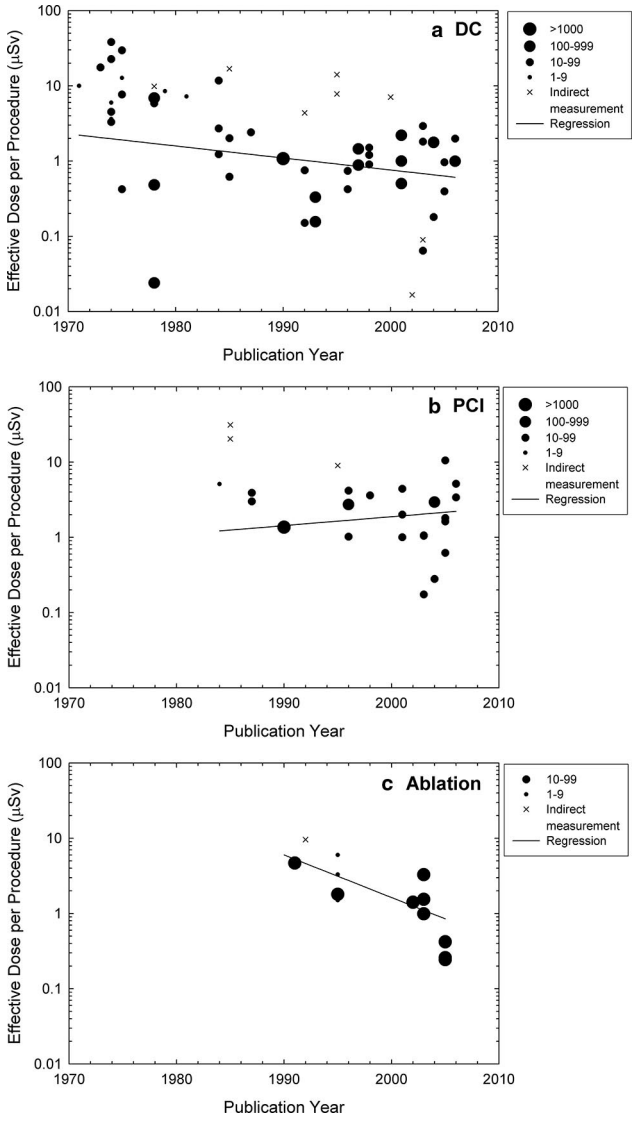

Fig. 1. Changes in average occupational effective radiation dose to operators over time for three types of interventional procedures: (a) DC, (b) PCI, and (c) ablation. Each data point represents the mean value from one published study under similar exposure conditions where the year of publication is used as a surrogate for the year when the procedures were conducted. Estimated average effective doses are shown either as filled circles (derived from personnel monitoring results) or crosses (representing indirect measurements, e.g., dose rate measurements, phantom and computer simulations). Size of filled circles represents the number of procedures reported.

reductions in fluoroscopy time over the past few decades have been offset by increases in dose due to increases in cineradiography time in the given data. Radiation exposure during PCI is strongly correlated with procedure complexity. The increasing complexity of PCI procedures over time appears to have offset dose reductions due to technology. As the outcomes of PCI have improved and catheter, guidewire, balloon, and stent technologies have evolved, PCI procedures have become more complex (Huckman and Pisano 2005; Tsapaki et al. 2006). Procedures are now being performed in vessels and lesions that are more challenging and technically difficult, and that could not have been performed a decade ago. Stents have been increasingly used since the mid-1990s, with a 147% increase in the rate of coronary stent insertion between 1996 and 2000 (Rosamond et al. 2007). In 2003, approximately 84% of hospitalized patients with PCI were reported to receive a stent (CDC 2005). Several studies have been conducted to assess quantitatively the complexity of PCI and to correlate radiation dose with degree of complexity (Bernardi et al. 2000; Padovani et al. 2001; Balter et al. 2006; Peterzol et al. 2006; Tsapaki et al. 2006; Nikolsky et al. 2007). Some of these studies divided PCI procedures into three groups: simple, medium, and complex (Bernardi et al. 2000; Padovani et al. 2001; Balter et al. 2006; Peterzol et al. 2006). Fluoroscopy time, number of cine frames, and DAP were consistently higher for the complex group. Mean DAP measurements in the complex group were about two-fold higher than for the simple group.

In an attempt to delineate other reasons for decreases in operator doses, doses collected in our analysis were normalized to DAP (see Fig. 4). The normalized values would be expected to decrease over time if there were any significant factors other than patient dose reduction. However, no decreasing temporal trend was observed. We conclude that reductions in occupational doses over time for DC and ablation can primarily, though not exclusively, be attributed to reductions in patient doses due to decreases in fluoroscopy/cineradiography times and dose rate of x-ray equipment.

Future studies

In this review, we had considerable difficulty in comparing dosimetry results from different studies because of significant differences in the dosimetry methods employed, the use of various dose metrics, as well as a general absence of information about factors influencing the dose in each study. Future studies on occupational exposures of radiologists and interventional physicians could benefit from standardization of dosimetry estimation methods and use of one consistent set of units.

One area in need of standardization is how personal dosimeters are used. Personal dosimeter readings are typically used to estimate equivalent radiation dose to a specific site such as eye or hand. Therefore, a consistent strategy for their use would greatly benefit dose and risk estimations because data would be comparable. NCRP Report 122 (1995) contains recommendations for wearing a personal dosimeter when a protective apron is worn during diagnostic and interventional medical procedures

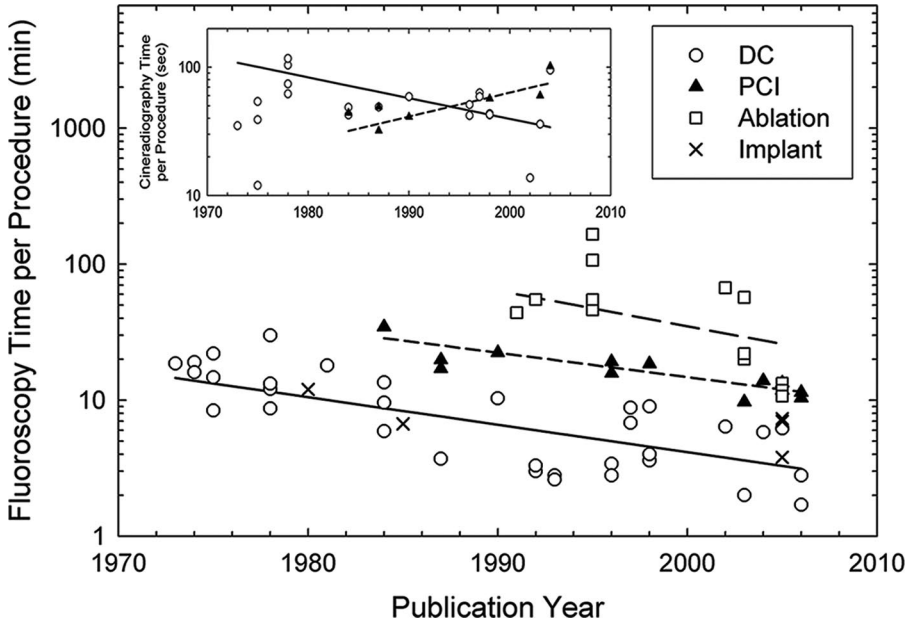

Fig. 2. Fluoroscopy and cineradiography times, categorized by procedure. The year of publication for each study is used as a surrogate for the year when the procedures were conducted. Each point represents the mean value from one published study under similar exposure conditions. Trend lines for mean fluoroscopy and cineradiography times are shown.

using fluoroscopy. When only a single dosimeter is used, placement on the neck outside and above the apron is recommended. When two dosimeters are used, placement of one on the neck outside and above the apron and the other on waist or chest under the apron are recommended. As mentioned earlier, radiation dose at the left and right sides of the operator's body can be different during fluoroscopically-guided procedures. Therefore, use of a personal dosimeter placed at the neck, chest, or waist level should also be considered. In addition to the correct use of personal dosimeters, consistency of use of personal dosimeters is another key issue for the protection of medical radiation workers. One study reported that almost half of the interventional radiologists rarely or never wore their dosimeters (Niklason et al. 1993). Possible reasons for noncompliance include lack of radiation protection training and to avoid problems related to exceeding dose limits (Niklason et al. 1993; Vano 2003). Both correct and consistent uses of personal dosimeters are clearly important to protecting medical radiation workers.

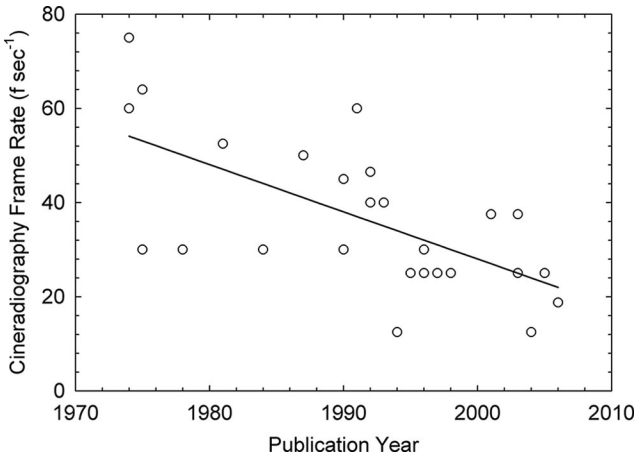

Fig. 3. Cine frame rates. The year of publication for each study is used a surrogate for the year when the procedures were conducted. Each point represents cine frame rate given in each published study. If more than two cine frame rates are given in a study, the average value is plotted. A trend line is shown.

While it is clear that operator dose depends on numerous factors, the degree that the dose depends on each factor has, for the most part, not been well quantified. Better understanding the relationship between all factors and the occupational dose would provide valuable information to optimize radiation protection in medical settings.

In addition, most previous studies have been conducted with a small number of operators and hospitals. Hence, these results are of limited value for characterizing operator dose on a national or international basis. Larger surveys would increase the likelihood of obtaining sufficient information to understand the exposure conditions under different working conditions and to develop strategies for further minimizing occupational dose.

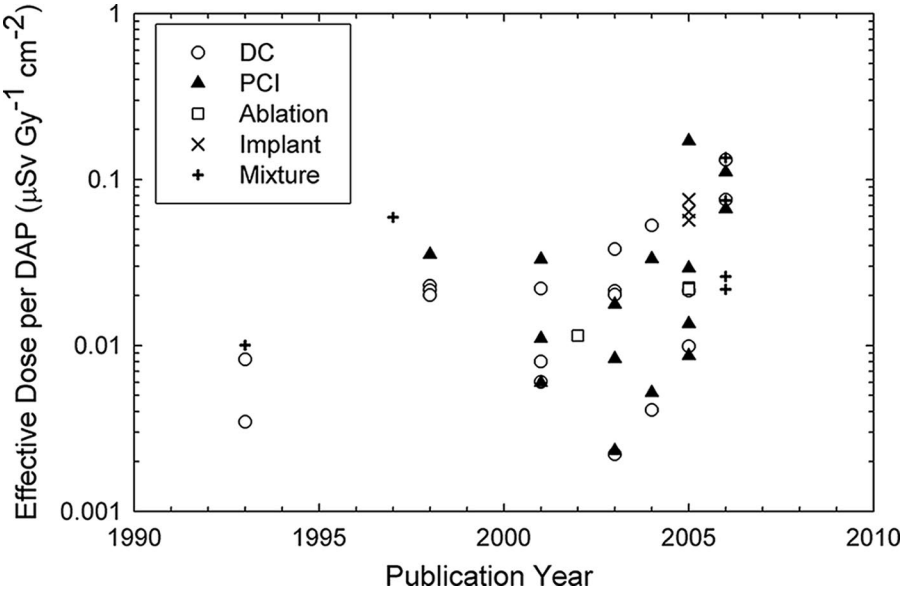

Fig. 4. Effective radiation doses to operators normalized by patient radiation dose (as dose area product). The year of publication for each study is used a surrogate for the year when the procedures were conducted.

CONCLUSION

Radiation doses to operators performing cardiology procedures vary over a range of two to three orders of magnitude, depending on the procedure type. Large variations in operator doses for the same type of procedure suggest that optimizing procedure protocols and using the most effective types of protective devices and shields may substantially reduce occupational radiation doses to these individuals. In general, higher doses were measured at the operator's hand, trunk, neck, and eye levels, in that order, though the absolute differences in radiation levels at these various anatomic sites were small. Modest operator dose reductions over time were observed for DC and ablation. This appears to be due to patient dose reduction as a result of decreased beam-on time and dose rate by improvement of technology rather than increased radiation protection for operators or improved protective practices by operators. Operator doses have not been reduced for PCI. Increased procedure complexity appears to have offset improvements in technology.

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