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EYE LENS RADIATION EXPOSURE TO INTERVENTIONAL CARDIOLOGISTS: A RETROSPECTIVE ASSESSMENT OF CUMULATIVE DOSES

Sophie Jacob[1,*], Laurent Donadille[2], Carlo Maccia[3], Olivier Bar[4], Serge Boveda[5], Dominique Laurier[1] and Marie-Odile Bernier[1]
[1]Institut de Radioprotection et de Sureté Nucléaire (IRSN), PRP-HOM, SRBE, LEPID, Laboratoire d'Epidémiologie, BP17, Fontenay-aux-Roses cedex 92262, France
[2]Institut de Radioprotection et de Sureté Nucléaire (IRSN), PRP-HOM, SDE, Laboratoire de dosimétrie des rayonnements ionisants, Fontenay-aux-Roses, France
[3]Centre d'Assurance de qualité des Applications Technologiques dans le domaine de la Santé (CAATS), Bourg-la-Reine, France
[4]Service de cardiologie interventionnelle, Clinique St Gatien, Tours, and Groupe Athérome Cardiologie Interventionnelle/Société Française de Cardiologie, Tours, France
[5]Département de Rythmologie, Clinique Pasteur, Toulouse, and Groupe Rythmologie Stimulation Cardiaque/Société Française de Cardiologie, Toulouse, France

*Corresponding author: sophie.jacob@irsn.fr

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Radiation dose to the eye lens is a crucial issue for interventional cardiologists (ICs) who are exposed during the procedures they perform. This paper presents a retrospective assessment of the cumulative eye lens doses of ICs enrolled in the O'CLOC study for Occupational Cataracts and Lens Opacities in interventional Cardiology. Information on the workload in the catheterisation laboratory, radiation protection equipment, eye lens dose per procedure and dose reduction factors associated with eye-protective equipment were considered. For the 129 ICs at an average age of 51 who had worked for an average period of 22 years, the estimated cumulative eye lens dose ranged from 25 mSv to more than 1600 mSv; the mean ± SD was 423 ± 359 mSv. After several years of practice, without eye protection, ICs may exceed the new ICRP lifetime eye dose threshold of 500 mSv and be at high risk of developing early radiation-induced cataracts. Radiation protection equipment can reduce these doses and should be used routinely.

INTRODUCTION

Cardiac catheterisation procedures require the radiation exposure of patients and also induce the exposure of physicians. Interventional cardiologists (ICs), who are the primary operators during cardiac catheterisation procedures, are among the medical professionals most highly exposed to X-rays, and there have been a number of studies reporting the operator doses per procedures, notably eye doses[1–3].

Lens opacities are a potential and serious consequence of eye exposure to ionising radiation[4–7]. In April 2011, the International Commission on Radiological Protection (ICRP) revised its lifetime eye dose threshold for cataract induction downwards from 2000 mSv to 500 mSv, and the occupational annual dose limit from 150 mSv to 20 mSv y^{-1}[6, 8]. Depending on their level of eye exposure, ICs are potentially at risk of developing radiation-induced cataracts[9]. With regard to the interventional cardiology procedures, there has been extensive concern on radiation protection during percutaneous coronary interventions (coronary angiography and angioplasty), mainly performed by coronary ICs (CICs). However, over the last decades, the number and complexity of invasive electrophysiological procedures for the treatment of cardiac arrhythmias [pacemaker implantation or radiofrequency catheter ablation (RFA)] performed by cardiac electrophysiologists have dramatically increased.

Excess risks of cataract among CICs were observed in some previous epidemiological studies[10–13]. The retrospective assessment of cumulative eye lens doses, considering the past and recent activity of ICs is an important step to establish a dose–response relationship. In contrast to the whole-body dose and chest dosemeter, routine follow-up of eye lens doses does not exist. The retrospective assessment needs to be based on the reconstruction of the laboratory workload (types and numbers of procedures) with questionnaires and the application of assumptions about past catheterisation laboratory activity (procedures performed, corresponding doses based on previous dosimetric studies and the use of radiation protection tools)[11, 12]. However, neither the description of the CICs' workload and use of radiation protection equipment nor a detailed description of retrospective evaluations have been presented in these previous publications.

In France, the O'CLOC (Occupational Cataracts and Lens Opacities in interventional Cardiology) epidemiological study aims to estimate the risk of lens opacities for French ICs[14]. Unlike earlier studies, it included both CICs and electrophysiologists. As part of the O'CLOC study, the issue of retrospective evaluation of cumulative eye lens exposure was raised again. Information on the catheterisation laboratory activity was first collected in a very detailed occupational questionnaire that inquired about procedures (those used by CICs and electrophysiologists) and the radiation protection tools used in the past and present.

This paper, which is based on the occupational data collected from the sample used here, has two principal aims. The first is to describe the interventional cardiology practices of the sample used here, including their use of radiation protection tools, the type and cumulative number of procedures performed and their trends over time. The second is to describe in detail both the methods used for retrospective assessment of eye exposure and the results, expressed as cumulative eye exposure and average annual doses for ICs.

MATERIALS AND METHODS

The O'CLOC study included a group of volunteer French ICs aged at least 40 y and still working in a catheterisation laboratory at inclusion. They were asked about their lifetime occupational activity in such laboratories by trained interviewers using a specific questionnaire[14].

Occupational questionnaire

The questionnaire asked questions separately about the six most common procedures: (1) coronary angiography; (2) coronary angioplasty, also called percutaneous coronary intervention; (3) implantation of pacemakers or defibrillators; (4) resynchronisation with pacemakers or defibrillators, also known since the mid-1990s as cardiac resynchronisation therapy; it is similar to device implantation but more complex and thus longer; (5) RFA, which first appeared around 1990 and (6) RFA of atrial fibrillation (RFA-AF), the most complex and longest RFA, introduced around 2000. Standard CICs mainly perform the first two procedures, and electrophysiologists the other four. The questionnaire was intended to obtain a report as precisely as possible of the workload of ICs in every centre where they had worked or were working. For each type of procedure, they reported the mean number of procedures they had performed each year in each centre. All respondents also reported when they started using, and at what frequency (never, occasionally, regularly, always), the following radiation protection equipment: lead eyeglasses (goggles), lead face shields, ceiling-suspended shields and radiation protection cabins, all directly linked to eye protection. The radiation protection cabin is an individual protection apparel that surrounds the operator on two sides and from above which is composed of 2-mm lead equivalent transparent walls. The authors also asked about the use of lead aprons, thyroid shields and lead gloves; although they have no direct effect on eye exposure, their use by ICs might be considered as an indicator of their awareness of radiation protection.

Methodology for retrospective assessment of eye exposure

A bibliographic review of eye lens doses per procedure for the six procedures presented above examined all *in vivo* studies in the literature from the 1970s to 2011, i.e. those based on measurements from dosemeters worn by cardiologists and distinguishing between doses measured with or without a ceiling-suspended shield. The articles presented in the review by Kim *et al.*[1] for the period from the 1970s to 2006 and those found by applying the same criteria to a search from 2006 to 2011 was used[15–18]. Finally, we considered the results from the European ORAMED (Optimisation of RAdiation protection for MEDical staff) project[19, 20]. The ORAMED sought to develop methods to improve the assessment and reduction of exposures to medical personnel during procedures that can potentially cause large doses or complex radiation fields, such as those in interventional radiology and cardiology, and other fields of nuclear medicine. The project brought together a consortium of 12 partners from 9 European countries. One work package (WP1) was dedicated to dose measurements for extremities and eye lenses in interventional radiology and cardiology; it measured eye lens doses per procedure in around 650 procedures (coronary angiographies and angioplasties, pacemaker and defibrillator implantations and RFAs) performed in several hospitals by >150 ICs[21]. The measurements were performed such that the dosemeters were not shielded by individual radiation protection equipment. The dose reduction factors associated with lead eyeglasses, lead face shields and protective mobile screens were collected from the ORAMED project[22] and analysed by an expert group including dosimetrists, cardiologists and epidemiologists.

Based on this review and the available data, a 'procedure-exposure matrix' was developed and used for the retrospective assessment of each cardiologist's cumulative eye lens dose. For each of the six procedures, an average dose per procedure was selected, both with and without a ceiling-suspended shield (D_{ws} and D_{wos}, respectively). Influence on eye doses of the access route (axial or femoral) was not considered in the selection of the average dose per procedure.

In the last decade, the effects of individual protective equipment (lead eyeglasses, face shields and radiation protection cabins), in terms of dose reduction, have been taken into account. Theoretical dose reduction factors were calculated for 120 kV in the tube according to its lead equivalent (*XCOMP5* software), and practical dose reduction factors were separated according to the procedures: for face shields, the theoretical value was applied to all procedures, as this tool can always be used; for lead glasses, a mean value was extracted from ORAMED results[22] combining different types of glasses (large or small) and was applied to all procedures, because these too could always be used; for the radiation protection cabin, the theoretical value was weighted by possible partial use of the cabin during some procedures (~80 % of the time for CA and 50 % for PCI during cinegraphic frames; it cannot be used for implantation or resynchronisation; and can always be used throughout ablation procedures). Reduction factors for eyeglasses (RF_g), for face shields (RF_f) and for radiation protection cabins (RF_{ca}), which were applied in the retrospective assessment, were thus obtained. Lifelong occupational activity was divided in years from the starting date of the catheterisation laboratory activity to the interview date. For each year information on the reported annual mean number of each type of procedure, the corresponding eye lens doses and the reported frequency of use of radiation protection equipment ('never', corresponding to 0 % of the time; 'occasionally' to 33 %, 'regularly' to 66 % and 'always' to 100 % of the time) was combined. The cumulative eye lens dose for each cardiologist was calculated as the sum of all yearly eye doses according to the formulas presented below.

Statistical analysis

To assess the average dose per procedure for each specific procedure, a weighted mean that considered the number of procedures reported in each article from the literature review and an arithmetical mean of doses from the ORAMED database was used. The cumulative eye lens dose was calculated according to the following formula:

$$\text{Cumulative dose} = \sum_{\text{each year}} \Bigg[\Bigg(\sum_{6\text{ procedures}} N_{\text{proc}} \times (D_{\text{ws}} \times F_{\text{s}} + D_{\text{wos}} \times (1 - F_{\text{s}})) \times (\text{RF}_{\text{ca}} \times F_{\text{ca}} + (1 - F_{\text{ca}}) \Bigg) \times ([\text{RF}_{\text{g}} \times F_{\text{g}} + (1 - F_{\text{g}})] \times [\text{RF}_{\text{f}} \times F_{\text{f}} + (1 - F_{\text{f}})]) \Bigg]$$

where N_{proc} corresponds to the reported mean annual number of procedures performed of a given type; F_s, F_{ca}, F_g and F_f the reported frequency of use of a ceiling-suspended shield, radiation protection cabin, eyeglasses and face shield, respectively; D_{ws} and D_{wos} the mean doses/procedure with and without the use of a suspended ceiling shield; RF_{ca}, RF_g and RF_f the dose reduction factors associated with the use of a radiation protection cabin, eyeglasses and face shield, respectively.

Continuous variables were expressed by their means (± standard deviation) or medians (min–max) and compared with Wilcoxon tests. Categorical variables were expressed as percentages and compared with chi-square tests.

RESULTS

Description of ICs' past and present workload

In total, 129 ICs were interviewed (73 % were CICs and 27 % electrophysiologists). Their mean age at the time of the interview was 50.7 y, with a mean duration of 21.8 y spent working in catheterisation laboratories (Table 1). This work spanned the period from 1970 to 2010, and 54 % had started working before 1990. Lead aprons were used systematically (100 %) for the entire period (Figure 1); the lead thyroid shield was common in 2010 (93 %), up gradually from around 20 % in the 1970s; and lead gloves were very rarely used (3 %). CICs and electrophysiologists did not differ significantly for these variables.

The use of equipment to protect the eyes varied. CICs reported that their use of ceiling-suspended shields increased from 10 % in the 1970s to 90 % after 2000, while electrophysiologists did not begin using them until the 1990s, and only 54 % were using them at the time of the interview. This difference (90 vs. 54 %) is significant ($P < 0.001$). The use of lead eyeglasses increased markedly over the past two decades, but has still reached only 56 % among CICs and 40 % among electrophysiologists. The ratio of years using lead glasses (weighted by the frequency of use) to the number of years of practice showed that 41 % of the years of practice were protected (1170/2852 y). Fewer than 10 % of the cardiologists used other types of eye protection (radiation protection cabins or lead face shields).

The distribution of procedures (Table 2) was mixed: all CICs performed coronary angiographies and angioplasties and one-third also performed electrophysiology (pacemaker and defibrillator implantation, mainly); 97 % of electrophysiologists implanted pacemakers and defibrillators and 77 % also performed RFA and 69 % resynchronisations; one-third also performed angiographies. Only RFA-AF was specific to electrophysiologists. Among

Table 1. Description of cardiologists and their work in interventional cardiology.

	All ICs (n=129)	CICs (n=94)	Electros (n=35)	P-value
Age at interview in years				
Mean ± SD (min–max)	50.7 ± 7.2 (40.0–69.7)	51.1 ± 7.2 (40.0–69.7)	49.8 ± 7.2 (40.7–66.6)	n.s.
Men, n (%)	120 (93 %)	87 (93 %)	33 (94 %)	n.s.
Starting period of IC practice, n (%)				
1970–1980	29 (22)	21 (22)	8 (23)	
1980–1990	41 (32)	33 (35)	8 (23)	n.s.
1990–2000	54 (42)	37 (39)	17 (49)	
≥2000	5 (4)	3 (3)	2 (6)	
Cumulative duration of IC activity in years				
Mean ± SD (min–max)	21.8 ± 8.2 (8.1–41.2)	22.1 ± 8.1 (8.1–41.2)	21.2 ± 8.5 (8.8 38.8)	n.s.
Use of radiation protection tools[a], n (%)				
Lead apron	129 (100)	94 (100)	35 (100)	n.s.
Lead thyroid shield	120 (93)	87 (93)	33 (94)	n.s.
Lead eyeglasses (goggles)	67 (52)	53 (56)	14 (40)	n.s.
Lead face shield	13 (10)	10 (11)	3 (9)	n.s.
Lead gloves	4 (3)	3 (3)	1 (3)	n.s.
Ceiling-suspended shield	105 (81)	86 (91)	19 (54)	<0.001
Radiation protection cabin	14 (11)	9 (10)	5 (14)	n.s.

n.s. non-significant (P > 0.05). ICs, interventional cardiologists; CICs, Coronary interventional cardiologists; Electros, Electrophysiologists; P-value corresponding to the difference between CICs and Electros.
[a]Regardless of the frequency of use.

CICs, the individual mean cumulative number of coronary angiographies and angioplasties was around 10 000 and 4000, respectively, while electrophysiologists performed on average 2500 implantations and 3000 ablations. The trends over time of these annual means show two patterns (Figure 2). For CICs, workload (angiographies and angioplasties) increased from the 1970s to the 1990s and remained stable or decreased slightly from the 1990s onwards. In contrast, electrophysiologists' workload (implantations, resynchronisations and RFA) has not stopped rising since the 1970s. Although the electrophysiologists' work was limited to implantations and occasionally CA procedures in the 1970s, new procedures appeared after 1990, increasing and varying their workloads. Moreover, the annual number of CIC procedures performed by electrophysiologists appeared to increase with time. Similar trends were observed among CICs performing electrophysiology procedures, except for RFA-AF. A mixed activity increased in both groups.

Assessment of cumulative eye lens doses

The literature review found few available data for any of these types of procedures (Table 3), particularly electrophysiology procedures. The mean doses do not appear to have changed notably for any of these procedures from the 1970s to the 2000s, and the values reported are concordant with those from the ORAMED database. The ORAMED eye lens doses were thus chosen to build the 'procedure-exposure matrix' (Table 4). Neither ceiling-suspended shields nor protection cabins were considered for pacemaker or defibrillator implantation and resynchronisation, because the cardiologist's position during these procedures (with the X-ray tube just beside the operation zone) makes their use impossible; the doses observed in ORAMED for these implantations, with or without ceiling-suspended shields were thus pooled and averaged together. Doses for resynchronisation and RFA-AF were not available in the ORAMED database. It was thus considered that the resynchronisation dose[23] was about four times the implantation dose, based on ref. (24) which reported a resynchronisation fluoroscopy time, dose–area product and patient effective dose all four times higher than for less complex implantations. In a similar approach, the dose for RFA-AF was considered to be about twice that of a standard RFA[25]. Without any radiation protection equipment, eye lens doses per procedure ranged from 0.046 mSv for coronary angiography to 0.236 mSv for cardiac resynchronisation. On average, the use of suspended ceiling shields resulted in halving the dose. Theoretical dose reduction factors associated with individual protective equipment according to the lead equivalent showed that radiation protection cabins were the most effective protection. In practice, however, they were effective only for ablations, and eyeglasses appeared to be the most effective tool usable for any procedure (Table 4). Table 5 summarises the cumulative eye lens dose of the ICs participating in the O'CLOC study. CICs

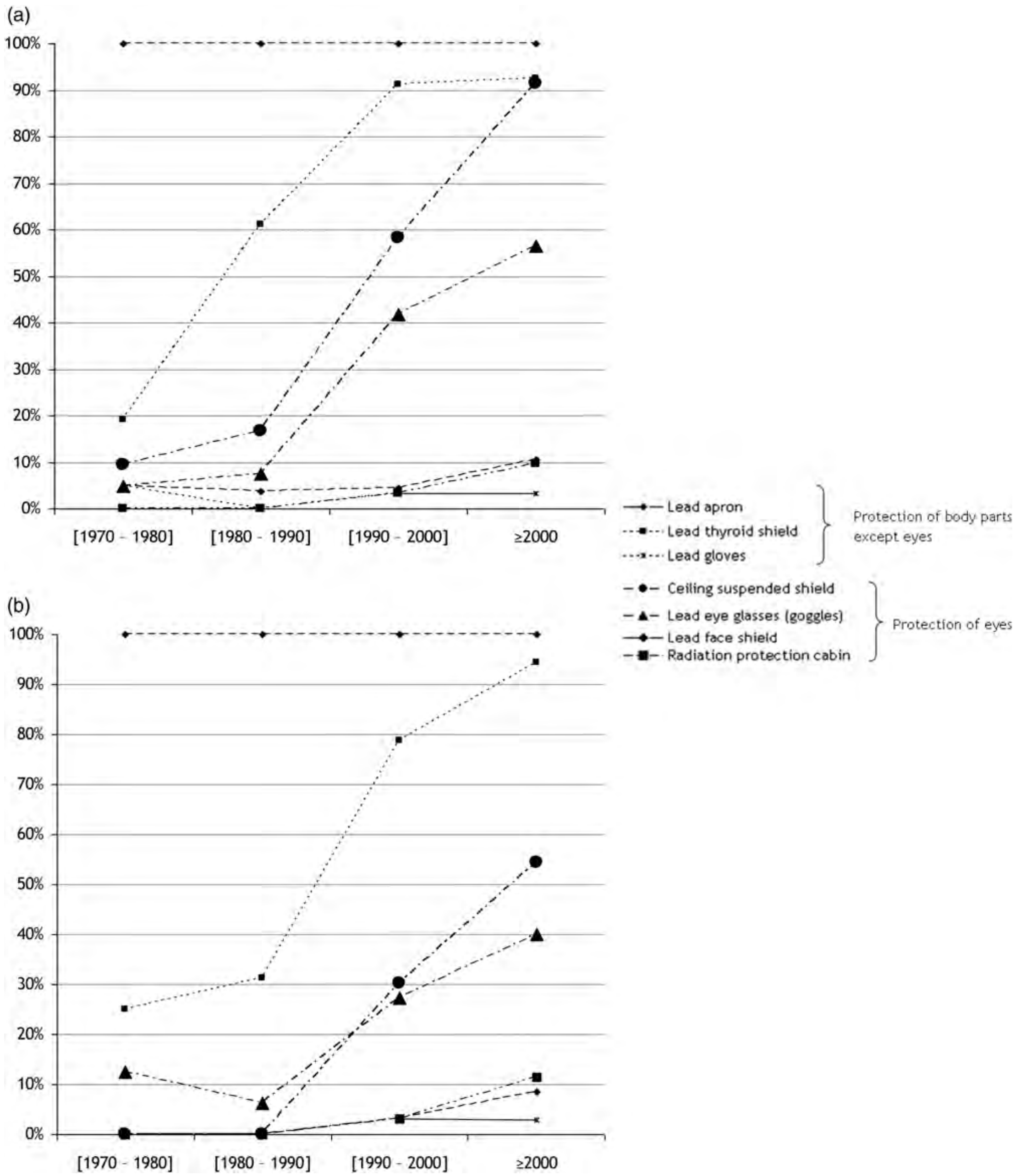

Figure 1. Trends over time in the use of radiation protection tools (in % of the population) for (**a**) coronary ICs and (**b**) electrophysiologists.

appeared to be slightly more exposed than electrophysiologists but not significantly so (455 vs. 343 mSv, $P = 0.09$). Overall, 29 % (27/94) of the CICs and 20 % (7/35) of the electrophysiologists had a cumulative dose exceeding 500 mSv. Of these 34 ICs, 13 had started work in the 1970s, 14 began in the 1980s, 6 in the 1990s and 1 in 2000. Mean annual individual eye lens doses were estimated per decade (Figure 3). The mean annual dose for CICs has tended to decrease since the 1990s (from 30 to 19

Table 2. Description of the cumulative number of procedures performed by cardiologists.

	All ICs ($n = 129$)	CICs ($n = 94$)	Electrophysiologists ($n = 35$)
All procedures			
Number of cardiologists	129 (100 %)	94 (100 %)	35 (100 %)
Total procedures per individual[a]	11 713, 10 550 (1250–33 566)	13 938, 12 252 (2841–33 566)	5737, 4240 (1250–19149)
Coronary angiography			
Number of cardiologists	106 (82 %)	94 (100 %)	12 (34 %)
Total procedures per individual	8921, 8064 (44–28 191)	9794, 8747 (2474–28 191)	2078, 848 (44–10 840)
Coronary angioplasty			
Number of cardiologists	97 (75 %)	93 (99 %)	4 (11 %)
Total procedures per individual	4201, 3423 (110–18 900)	4312, 3600 (110–18 900)	1608, 485 (360–3250)
PM or defibrillator: implantation			
Number of cardiologists	62 (48 %)	28 (30 %)	34 (97 %)
Total procedures per individual	1780, 1344 (7–6644)	930, 699 (7–3412)	2480, 1935 (79–6644)
PM or defibrillator: resynchronisation			
Number of cardiologists	29 (22 %)	5 (5 %)	24 (69 %)
Total procedures per individual	440, 352 (6–1316)	202, 150 (6–500)	490, 382 (52–1316)
RFA except AF			
Number of cardiologists	32 (25 %)	5 (5 %)	27 (77 %)
Total procedures per individual	2208, 1450 (80–8550)	666, 760 (80–1351)	2493, 1744 (200––8550)
RFA of AF			
Number of cardiologists	21 (16 %)	0	21 (60 %)
Total procedures per individual	577, 405 (10–2160)	—	577, 405 (10–2160)

[a]Mean, median (min–max); CICs, coronary interventional cardiologists; AF, atrial fibrillation; PM, pacemaker.

mSv y^{-1}, $P = 0.0006$), whereas the exposure for electrophysiologists seems to have increased over the past decade, from 6 to 25 mSv y^{-1} ($P < 0.0001$). Over the last decade, 40 % of the CICs and 50 % of the electrophysiologists exceeded the new annual ICRP limit of 20 mSv y^{-1}.

DISCUSSION

This study provides a detailed overview of catheterisation laboratory workload and lifetime occupational eye lens exposure in a sample of experienced French ICs still working at their enrollment in the O'CLOC study. A retrospective assessment of cumulative eye lens exposure showed potentially high doses among ICs, ranging from 25 to >1600 mSv for both coronary ICs (mean $\pm$ SD=455 $\pm$ 373 mSv) and cardiac electrophysiologists (mean $\pm$ SD=343 $\pm$ 308 mSv). These findings indicate that according to the revised ICRP lifetime eye dose threshold of 500 mSv, ~25 % of these cardiologists may already be at risk of developing early radiation-induced cataracts. Moreover, electrophysiologists may have had higher annual doses of eye exposure than CICs in recent years because they use eye protection equipment less.

Because eye exposure has not been systematically monitored, a survey combining the lifetime workload (number and type of procedures performed by cardiologists), radiation protection conditions and dose information is the only way to quantify eye doses for ICs in a retrospective assessment. These assessments were based on ICs' responses to a questionnaire. They were asked about the procedures they performed most frequently, including electrophysiology procedures, throughout their professional career. Previous epidemiological studies have considered only CICs and focused only on angiographies and angioplasties[11, 12]. The methods used here made it possible to observe that some CICs also performed electrophysiology procedures, which other studies failed to observe. Moreover, electrophysiologists had not been studied before, although their workload has been increasing markedly since the 1990s.

The detailed questionnaire used here also allowed one to examine the individual use of radiation protection equipment and to observe that its use depended on the awareness of radiation protection rules for cardiologists but also on the type of procedure performed. For CA, PCI and RFA, the suspended ceiling shield is the first bulwark for eye protection. In this study a significant difference in the use of suspended shields between CICs and electrophysiologists (91 vs. 54 %) was observed. This difference might be partly explained by the pacemaker and defibrillator implantations and resynchronisation procedures that require electrophysiologists to work very close to the patient's chest. Access to radiation protection devices is thus difficult, especially in the view of the tools already suspended from surgical

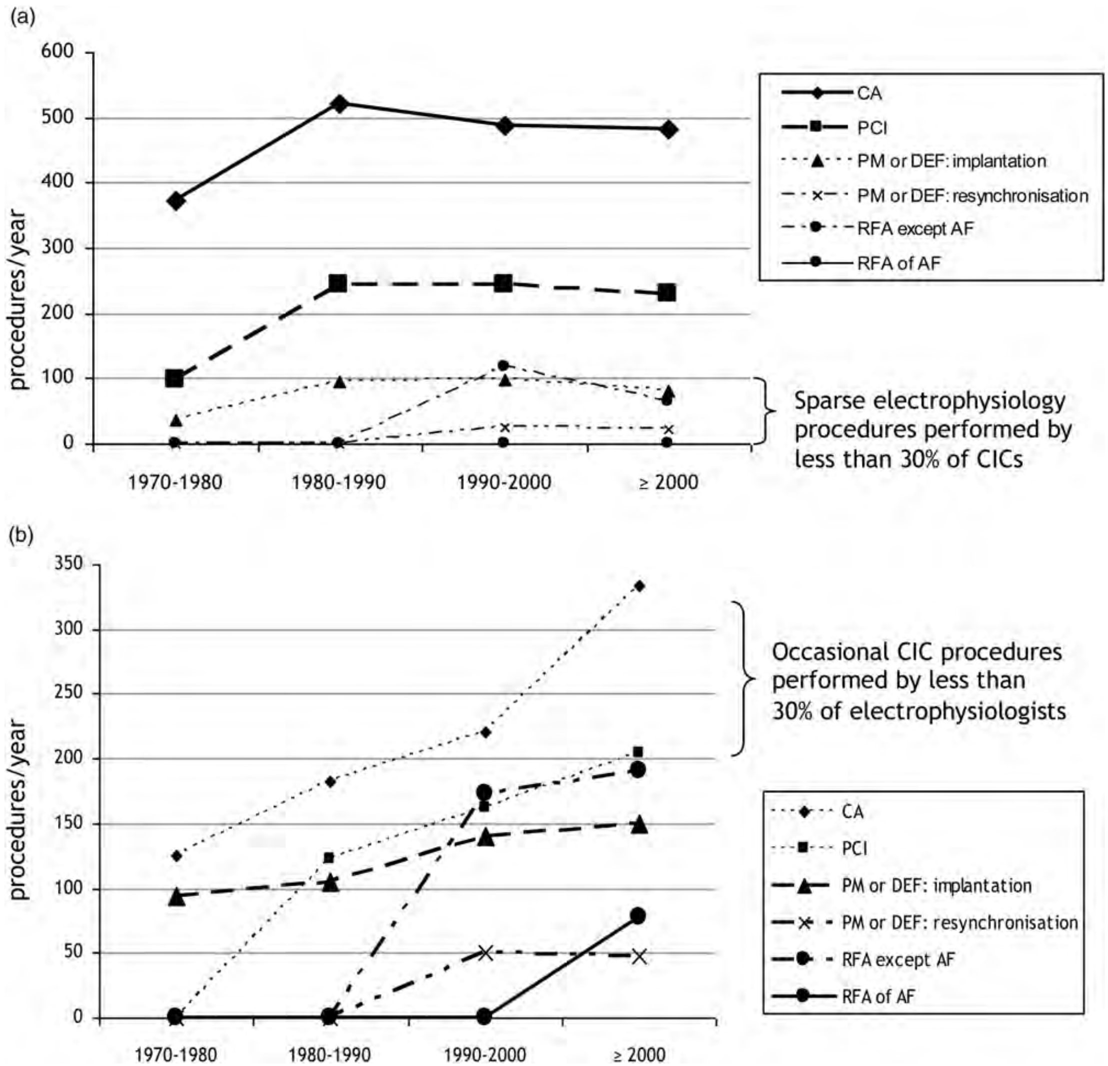

Figure 2. Trends in the mean annual number of procedures per year for (**a**) CICs and (**b**) electrophysiologists.

theatre ceilings. Lead eyeglasses may be a second bulwark, and applicable to all procedures, but only 40 % of the electrophysiologists questioned reported using them, compared with 56 % of CICs. Radiation protection cabins with a 2-mm lead equivalent are theoretically the best way to protect the body, in particular the eyes, but while they are feasible for radiofrequency ablations, their use may be impossible for others procedures, such as implantations, or only partially possible for CA and PCI. It was observed that <10 % of the sample reported using them. The information collected about procedures and radiation protection equipment came from the ICs' answers, and one cannot rule out the possibility that some information may not be completely accurate, for reasons that could range from a social desirability bias to memory bias.

The quality of the eye lens dosimetric information per procedure must also be considered in evaluating any retrospective assessment. The doses used here were based on the most up-to-date database of *in vivo* measurements in catheterisation laboratories[21] and an analysis by a group of experts in dosimetry, cardiology and epidemiology. To optimise the consistency with real situations, dosimetric studies that measured doses by phantom simulation or computer program simulation were not considered here.

In contrast to similar previous studies on radiation-induced cataract risk among ICs where a single value of 0.5 mSv per procedure was used[11, 12], an

Table 3. Mean eye lens doses—H_p (0.07) per procedure (in mSv) based on the literature review of interventional cardiology and electrophysiology procedures.

	1970–1980		1980–1990		1990–2000		≥2000			
	Without ceiling shield	With ceiling shield	Without ceiling shield	With ceiling shield	Without ceiling shield	With ceiling shield	Without ceiling shield	With ceiling shield	Without ceiling shield (ORAMED)	With ceiling shield (ORAMED)
CA										
(References)	L1	—	L2	—	(27)	L3	(16)	(15)	(21)	(21)
Number of procedures[a]	n=634		n=56		n=5	n=223	n=6	n=20	n=14	n=66
Average dose per procedure (mSv)	0.060		0.063		0.055	0.014	0.236	0.0033	0.046	0.025
PCI										
(References)	—	L4	—	L5	(28)	—	—	(15)	(21)	(21)
Number of procedures		n=28		n=151	n=66			n=20	n=64	n=117
Average dose per procedure (mSv)		0.074		0.142	0.439			0.0087	0.102	0.040
PM or DEF: implantation										
(References)	—	—	—	—	—	—	(18)	—	(21)	(21)
Number of procedures							n=55		n=172	n=22
Average dose per procedure (mSv)							0.039		0.057	0.078
PM or DEF: resynchronisation										
(References)	0	0	—	—	—	—	—	—	—	—
Number of procedures										
Average dose per procedure (mSv)										
RF ablation except AF										
(References)	0	0	0	0	—	(29)	(17)	—	(21)	(21)
Number of procedures						n=31	n=16		n=61	n=110
Average dose per procedure (mSv)						0.281	0.049		0.065	0.031
RF ablation of AF										
(References)	0	0	0	0	0	0	—	—	—	—
Number of procedures										
Average dose per procedure (mSv)										

CA, coronary angiography; PCI, percutaneous coronary intervention (equivalent to coronary angioplasty); PM, pacemaker; DEF, defibrillator; RF, radiofrequency; AF, atrial fibrillation; –, no data available; 0, procedure not yet in use.

[a]Total number of procedures available in references – used to calculate the weighted mean doses: L1[30–37]; L2[38–40]; L3[41–43]; L4[38, 39]; L5[28, 44].

Table 4. 'Procedure-exposure matrix': average eye doses and reduction factors considered for interventional cardiology/electrophysiology procedures.

Procedures	Doses (mSv per procedure)		Dose reduction factors for individual protective equipment		
	Without ceiling shield (D_{wos})	With ceiling shield (D_{ws})	Lead face shields (0.1-mm Pb)	Lead eyeglasses (0.5-mm Pb)	Radiation protection cabins (2-mm Pb)
			Theoretical values[a]		
			≤0.5	≤0.1	≤0.001
			Values considered for a retrospective assessment according to the procedure		
			RF_f^b	RF_g^c	RF_{ca}^d
CA	0.046	0.025	0.5	0.2	0.2
PCI	0.102	0.040	0.5	0.2	0.5
PM or DEF: implantation	0.059[e]	0.5	0.2	n.a.	
PM or DEF: resynchronisation	0.236[f]	0.5	0.2	n.a.	
RF ablation except AF	0.065	0.031	0.5	0.2	0.001
RF ablation of AF	0.130[g]	0.062[g]	0.5	0.2	0.001

CA, coronary angiography; PCI, percutaneous coronary intervention (equivalent to coronary angioplasty); PM, pacemaker, DEF, defibrillator; RF, radiofrequency; AF, atrial fibrillation.
[a]Calculated for a maximum of 120 kV in the tube.
[b]Areduction factor for a lead face shield based on the theoretical value and applicable to all procedures.
[c]Areduction factor for an average type of lead glasses extracted from ORAMED results(22) and applicable to all procedures.
[d]Areduction factor for a cabin based on the theoretical value of 0.001 weighted by the partial use of the cabin during the procedures (~80 % of the time for CA; ~50 % during PCI; not used for implantation and resynchronisation; used throughout ablation procedures).
[e]Theuse of ceiling suspended shields for this procedure is impractical.
[f]= dose for implantation × 4 (22) and use of ceiling-suspended shields for this procedure impractical.
[g]= dose for RFA except AF × 2 (23).

Table 5. Cumulative eye lens doses (mSv).

	Mean ± SD	Min	Q1	Median	Q3	Max	*P*-value
All ICs ($n = 129$)	423 ± 359	25	171	309	509	1658	
Coronary ICs ($n = 94$)	455 ± 373	29	184	370	634	1658	$P = 0.09$
Electrophysiologists ($n = 35$)	343 ± 308	25	148	235	440	1475	

ICs, interventional cardiologists; SD, standard deviation; Q1, 25th percentile; Q3, 75th percentile.

important strengths of this study were the detailed procedures and analysis of not only coronary angiographies and angioplasties but also electrophysiology procedures, in particular, the recent cardiac resynchronisation therapy and RFAs. The eye lens doses associated with these long and complex procedures have not yet been adequately studied. They are clearly reported here as a dose scale to allow future comparisons: without any radiation protection, cardiac resynchronisation appeared to cause the most eye irradiation (0.236 mSv per procedure), followed by RFA-AF (0.130 mSv per procedure), coronary angioplasties (0.102 mSv per, procedure) and finally coronarographies (0.046 mSv per procedure). Compared with the doses estimated in one previous study of coronary angioplasties(2), the doses considered here may seem very low (0.102 mSv per procedure against 0.439 mSv), but they do appear more consistent with other published studies, seen in Table 3. It was also important to take into account

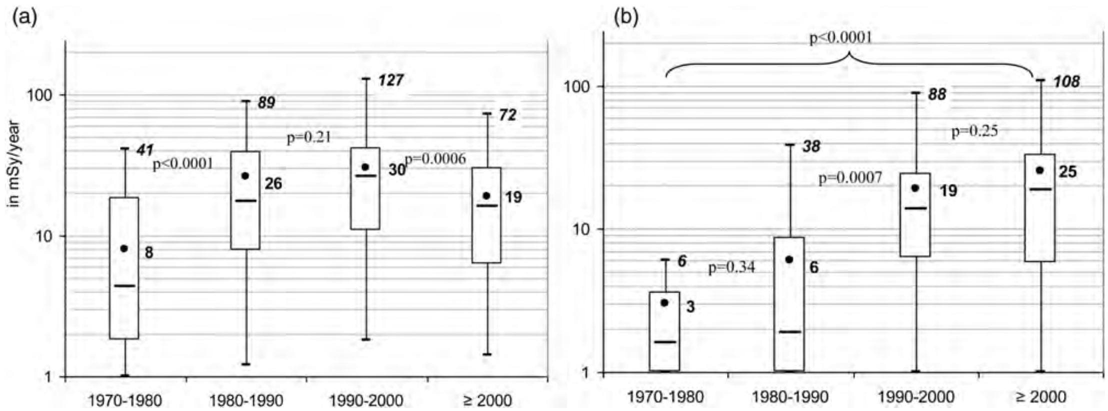

Figure 3. Trends in the mean annual eye dose according to decade [boxplots with a log scale presenting the min, Q1, median (horizontal line), Q3, max; numbers indicate the mean (dot) and *maximum*; *P*-value corresponding to increase or decrease] for (**a**) CICs and (**b**) electrophysiologists.

the impact of radiation protection equipment, quantified here by dose reduction factors, for the retrospective assessment of cumulative doses. Those proposed here were based on the ORAMED project and are reported here as means that are consistent with other studies and that can be used in large population studies[26].

Baseline doses per procedure play a major role in the range of occupational lifetime doses to the eyes. Ciraj-Bjelac *et al.*'s study[11], which was based on an earlier dosimetric study[2], attributed a mean working time of 9 y to CICs, and estimated their cumulative eye lens doses between 20 and 4300 mSv (median value = 1100 mSv); the corresponding figures in Vano's study[12] were 14 y and 100 to 2700 Sv (median value = 6000 mSv). Given that the threshold for the risk of lens opacities is now estimated at 500 mSv[6], the median dose of 6000 mSv in Vano's study suggests that more than half of the population would have exceeded the 500 mSv threshold and thus more than half the group would be at a very high risk of developing lens opacities. The actual percentage of opacities was 38 %, and an overestimation of eye lens doses might explain this discrepancy. The O'CLOC study applied lower doses to CICs, with a median cumulative dose of 400 mSv for a mean working time of 20 y, but the doses remain in the range of doses carrying a risk of radiation-induced lens opacities. At the time of their interviews, >28 % of the CICs and 19 % of the electrophysiologists had already exceeded the new ICRP lifetime threshold of 500 mSv[6]. The new annual dose limit of 20 mSv y^{-1} was exceeded at least once since 2000 by 60 % of the cardiologists studied, whereas only one cardiologist exceeded the old limit of 150 mSv y^{-1} during this time period. This result, although limited by its reliance on retrospective assessment and hypotheses about workloads and doses, is nonetheless a matter of serious concern. Only monitoring of the eyes with specific dosemeters for yearly follow-up can provide the exact annual doses, but such monitoring remains very rare. The ORAMED project did develop some tools for such monitoring[19]. Radiation protection equipment, in particular the routine use of eyeglasses, is highly recommended for medical staff to limit their risk of radiation-induced lens opacities and cataracts.

CONCLUSION

The application of the O'CLOC methodology for the retrospective assessment further delineated ICs' occupational exposure to radiation and classified these exposures according to workload and the use of protective equipment. The impact of uncertainties around these estimates of cumulative eye doses may be considered in future developments. The analysis of the O'CLOC data will shed light on the risk of cataract formation in this population, and information on radiation protection equipment may help determine and optimise risk reduction for cataracts. In the meantime, awareness of the need to optimise procedures and for radiation protection must continue to be reinforced among medical staff.

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