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Staff eye lens dose in interventional radiology and cardiology in Finland

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A B S T R A C T

Purpose: The aim of this study was to investigate the eye lens and whole-body radiation doses to interventional radiology and cardiology staff in two Finnish hospitals.
Methods: Simultaneous measurements of personal dose equivalent quantities $H_p(3)$ and $H_p(10)$ were conducted in clinical conditions during different radiological and cardiological interventional procedures. In order to study the feasibility to estimate eye lens dose with $H_p(10)$ measured over the protective apron or thyroid shield, the ratio between measured $H_p(3)$ and $H_p(10)$ was investigated.
Results and conclusions: Applying the obtained ratio on $H_p(10)$ records from national dose register showed that only a small number of interventional radiologists and cardiologists in Finland may exceed eye lens equivalent dose levels of 20 mSv per year or 100 mSv in five consecutive years, but likely do not exceed 50 mSv in a single year. For the most Finnish interventionalists, the eye lens dose is well below 10 mSv per year. Nurses and radiographers assisting in interventions are, on average, less exposed than interventionalists, and will not exceed 20 mSv per year. Based on our results, $H_p(10)$ measured over the protective apron or thyroid shield provides a conservative estimate of the eye lens dose for interventional radiologists and cardiologists, provided that appropriate protective glasses are used.

Introduction

Radiologists, cardiologists, radiographers, and nurses are exposed to ionizing radiation during x-ray guided procedures in interventional radiology (IR) and cardiology (IC). The International Commission on Radiological Protection (ICRP) provides recommendations and the International Atomic Energy Agency (IAEA) sets the international standards and guidelines for radiation protection and exposure monitoring of medical staff [1–3]. In the EU, basic safety standards (EU BSS) are set by the European Council Directive 2013/59/Euratom [4]. Dose limits for occupational exposure are defined in the EU BSS for effective dose, equivalent doses to skin and extremities and equivalent dose to the lens of the eye.

Numerous studies concerning medical staff have emphasized eye lens equivalent dose as the potentially limiting dose quantity for radiation protection, especially with respect to interventional radiologists and cardiologists who are among the most exposed workers [5–8]. Lens doses exceeding 20 mSv/year [7,9] and even 50 mSv/year [5,10] have been reported, raising concerns that the current ICRP nominal lifetime threshold dose of 0.5 Gy for cataract induction [11] might be exceeded. Considering the increasing evidence for cataract formation at even lower doses than 0.5 Gy [12,13], estimation of eye lens dose of the most exposed workers should be a priority.

Although $H_p(3)$ measurement by dedicated eye lens dosemeters is considered to be the most accurate method for eye lens equivalent dose estimation [14], estimating the eye lens dose by other means has also been proposed due to practical reasons [15–20]. According to ICRP Publication 139, a body dosemeter worn over the apron at collar level on the most exposed side of the interventionalist, provides a reasonable estimation of the equivalent dose to the lens of the eye [1]. Clear correlation between dose readings measured by body dosemeters ($H_p(10)$) at collar or chest height and eye dosemeter $H_p(3)$ readings have been reported [6,8], although large differences in the conversion factors between dose quantities were observed [6,15]. For many workers, eye lens dose estimation based on body dosemeter readings (measured over the protective apron) and application of a conversion factor might be adequate to ensure that the eye doses of these workers do not exceed the legal limits [15]. This approach has the advantage of exploiting only one personal dosemeter, which is more convenient and less expensive for the user. However, the approach induces increased uncertainty of eye lens dose estimates that must be accounted for in the interpretation of the results, especially while determining appropriate radiation protection measures and classification of workers into A and B categories according to the 15 mSv per year limit for category B workers [4].

Our aim was to explore the level of staff radiation exposure by measuring both $H_p(3)$ and $H_p(10)$ during clinical routine for

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interventional radiologists, cardiologists, radiographers, and nurses. A second aim was to determine whether eye lens dose estimation by conversion from body $H_p(10)$ readings is sufficiently accurate to ensure compliance with the eye dose limits for these workers. The ratio of the measured $H_p(3)$ and $H_p(10)$ combined with national dose registry data was used to estimate maximum eye lens doses among interventional radiologists and cardiologists in Finland during a five year period.

Material and methods

Data collection

Measurements at the clinics

$H_p(3)$ and $H_p(10)$ were measured in one IR and two IC departments in two different university hospitals during 2019 and early 2020. According to the hospitals, the COVID-19 pandemic did not have an effect on the workload or type of procedures at the participating clinics during the data collection period. Each measurement period lasted for approximately one month, and the exact number of working days during each measurement period was determined based on the procedure records kept by the participants. $H_p(10)$ was measured with electronic direct ion storage dosimeter DIS-1 (Mirion Technologies Inc., San Ramon, CA, USA), which were worn in addition to the standard thermoluminescent dosimeter (TLD) badges (Doseco, Jyväskylä, Finland) used for regulatory dosimetry. The DIS-1 dosemeters were used to ensure precise dose calculation by allowing subtraction of the parallelly measured background dose. In the case of regulatory TLDs, the dosimetry service provider accounts for the background dose. For the DIS-1 dosemeters, background was subtracted based on measurements with control dosemeters placed in the shielded control room. Care was taken to position the DIS-1 dosemeters and the routine TLD badges in such a way that the dosemeters would not interfere with each other. $H_p(3)$ was measured by EYE-D thermoluminescent dosemeters [21], (RadCard, Poland).

Personal $H_p(3)$ and $H_p(10)$ dosemeters were worn by five interventional radiologists and by five interventional cardiologists. Other staff members wearing personal dosimeters involved two radiographers and one nurse at the IC department. Additionally, two group dosemeters were shared by radiographers in one of the IC departments and at the IR department, radiographers and nurses used two group dosimeters in two intervention rooms. Individual data were coded, and the results were stored anonymously. $H_p(3)$ was measured at the eye level at the left side of the head, with the exception of one cardiologist, who wore the dosemeter at the right side of the head. This was due to that cardiologist performing mostly pacemaker implantations, where the right side of the head was facing the direction of the scattered radiation and thus being the most exposed side. All staff members attached the eye dosemeter to the protective glasses, outside the protective material. $H_p(10)$ was measured by DIS-1 dosemeters worn either above the protective apron on the most exposed side of the body at chest height or attached on the protective thyroid collar, above the protective material. A more detailed description of dosemeter positions for each staff member is provided in Table 1 in the results section.

All participants wore protective aprons, thyroid shields, and protective glasses. All the angiography rooms had protective shields mounted at the side of the patient table, and ceiling-mounted protective shields. These were used consistently, except for pacemaker implantations where the ceiling mounted shield was not used due to ergonomic difficulty it presents.

Displayed total kerma-area product (KAP) values were collected for each procedure, making it possible to calculate average $H_p(3)$ and $H_p(10)$ per KAP during the measurement periods. No energy response correction was applied to the KAP measurements. The accuracy of the KAP displays of the x-ray equipment are checked once a year by the equipment manufacturers and daily quality assurance checks are performed to monitor the constancy of radiation output and image quality of the systems.

Collection of data from the national dose register

$H_p(10)$ dose records for years 2016–2020 including data for all category A Finnish radiologists (N = 1474 annual $H_p(10)$ readings) and cardiologists (N = 1110 readings), grouped according to the profession, were formally requested from the national dose registry. With appropriate permission granted, the authors received the dose register data in completely anonymous format (i.e., no individuals or employers could be identified from the data).

Dosimetry

$H_p(3)$ and $H_p(10)$ measurements and uncertainty estimations

The EYE-D dosemeters for $H_p(3)$ measurements were read by a TOLEDO 654 TLD reader (Vinten Instruments Limited, UK). TLD reader background and sensitivity were checked every time prior to reading the actual eye dosemeters. The $H_p(3)$ values were calculated by multiplying the TLD reading (in reader units) with a sensitivity coefficient obtained from calibration measurements performed with RQR-7 radiation quality.

Calibration of the EYE-D -dosemeters as well as investigation of uncertainties were done in a national secondary standard dosimetry laboratory (SSDL). All the EYE-D laboratory irradiations were done using a 20 cm × 20 cm water-filled PMMA cylindrical phantom [22,23]. The uncertainty of the relative dose response in the range 20 μSv to 5000 μSv of the EYE-D dosemeters was investigated using the RQR-7 radiation quality. The uncertainty was estimated to be 5%, based on maximum deviation of the mean of each dose group from a linear response. Energy response was checked with ISON80-N250 x-ray qualities and Cs-137, and the corresponding uncertainty component was estimated to be ca. 2% and the TLD angular dependency 7% for angles between 0 and 60°. Combined uncertainties for dosemeter reading repeatability, batch homogeneity and background reduction were estimated together to be 3 %. The effect of fading was estimated to be ≤5% per year, given by the dosemeter manufacturer. Combining these uncertainties, the expanded uncertainty (k = 2) of $H_p(3)$ in laboratory conditions was 20%. It should be noted that the described uncertainty estimation for $H_p(3)$ measurements should be considered as indicative. It includes laboratory evaluation of the basic technical factors, such as angular response and energy response, with parameter ranges chosen to mimic those found in clinical conditions. However, in laboratory conditions, it is not possible to fully estimate the effect originating from factors such as head movement and the exact positioning of the dosemeter relative to the radiation source, although these have a significant contribution to the uncertainty of the eye lens equivalent dose estimation.

DIS-1 dosemeters and the reader were calibrated at the factory, and the calibration was checked at the SSDL prior to the actual measurements. The manufacturer reported expanded uncertainties (k = 2) of ±5% for calibration accuracy, ±30% for energy response (between 15 keV and 9 MeV) and ±20% for directional response (up to 60° at 65 keV). Combining these components resulted to an $H_p(10)$ uncertainty estimate of 37% (expanded uncertainty, k = 2).

Calculation of $H_p(3)/H_p(10)$ ratios, $H_p(3)$/KAP and estimation of annual $H_p(3)$ based on measurements and national dose register data

The $H_p(3)/H_p(10)$ ratios for each participant or group dosemeter pair were calculated simply by dividing measured $H_p(3)$ by $H_p(10)$. In addition to the individual ratios, a relation between $H_p(3)$ and $H_p(10)$ was calculated for interventional radiologists and cardiologists by using a simple linear regression model (Microsoft Excel, linear least squares fit), shown in Fig. 2. $H_p(3)$/KAP were calculated by dividing the measured $H_p(3)$ by KAP value displayed by the x-ray equipment. Based on conservative estimation from regulatory limit, the uncertainty of KAP measurement was assumed to be uniformly distributed between ± 25%, and a standard error of ca. 15% was thus obtained for the KAP display.

Estimates of total $H_p(3)$ per year for the participants (or worker group) were calculated by first calculating an average daily dose based on the measured cumulative values and the number of working days during the measurement period and then multiplying the results with an estimated number of 220 working days during a year. Maximum annual and five-year cumulative eye lens doses nationally were estimated by using $H_p(10)$ data from the national dose register and the $H_p(3)/H_p(10)$ regression model.

Results

$H_p(3)$ and $H_p(10)$ measurements at the clinics

An overview of cumulative $H_p(3)$ values measured during ca. one month's time for each worker (or worker group) is shown in Fig. 1, demonstrating large variation in the received dose.

A linear fit to indicate the relationship between measured cumulative $H_p(3)$ and $H_p(10)$ values for all interventional radiologists and cardiologists is displayed in Fig. 2., showing the regression equation of $H_p(3) = (0.53 \pm 0.45) \cdot H_p(10)$ and the coefficient of determination $R^2 = 0.96$. The intercept value is set to zero in the regression analysis. It is apparent that the data point with highest dose (participant R1/1) had a considerable weight on the regression results. Removing the highest dose point yielded an alternative regression equation of $H_p(3) = (0.69 \pm 0.60) \cdot H_p(10)$, $R^2 = 0.91$.

The measured $H_p(3)$ values per KAP, procedure and extrapolated $H_p(3)$ per year are given in Table 1. The maximum extrapolated annual $H_p(3)$ was ca. 7.5 mSv for the interventional radiologist R1/1, who also had the highest workload in terms of number of performed procedures.

Ratios of $H_p(3)$ and $H_p(10)$ values for interventional radiologists and cardiologists are shown in Fig. 3. The individual ratios ranged from 0.50 to 0.91 for interventional radiologists and from 0.23 to 1.21 for interventional cardiologists, respectively. Cardiologist C1/1 had dosemeter readings equivalent to background dose. The ratio is not reported for Cardiologist C5/2 due to a misunderstanding, which resulted to the participant wearing the EYE-D only during pacemaker implantations and DIS-1 during all procedures, also including a number of CA/PCI, yielding an unrealistic $H_p(3)/H_p(10)$ ratio. Estimating the total $H_p(3)$ for cardiologist C5/2 based on the regression model from Fig. 2 yields a calculated $H_p(3)$ of (310 ± 260) μSv. For radiographers and nurses, larger differences in the $H_p(3)$ / $H_p(10)$ ratios were observed, with the ranges of $H_p(3)$ / $H_p(10)$ being 1.0–3.6 and 0.8–4.1 in IR and IC, respectively.

Dose register $H_p(10)$ and estimation of lens dose

The measured ratios of $H_p(3)/H_p(10)$ in combination with $H_p(10)$ data from national dose register were used to provide an order-of-magnitude estimation of the maximum $H_p(3)$ for interventional radiologists and cardiologists. The maximum annual $H_p(10)$ for an individual interventional radiologist or cardiologist and the corresponding $H_p(3)$ calculated from the $H_p(3)/H_p(10)$ ratio from 2016 to 2020 are shown in Fig. 4.

The $H_p(3)$ estimates in Fig. 4 show that during the last five years, the maximum $H_p(3)$ may have exceeded the five-year average of 20 mSv/year, but not 50 mSv/year, which is the national legal single year limit for eye lens equivalent dose. A more conservative estimate may be calculated by applying the maximum measured $H_p(3)/H_p(10)$ ratios (0.91 for interventional radiologists, 1.21 for interventional cardiologists) to the dose register data. This would result to an individual maximum $H_p(3)$ estimate of (37 ± 21) mSv per year among interventional radiologists and (22 ± 12) mSv per year among interventional cardiologists during 2016–2020. These estimates do not account for the dose reduction effect of protective glasses. The uncertainties are expressed as expanded uncertainty with a coverage factor k = 2. The maximum five-year cumulative $H_p(10)$ in the dose register was 159 mSv, recorded for an interventional radiologist. This was also the only instance of a worker exceeding five-year cumulative $H_p(10)$ of 100 mSv in medical X-ray guided interventions during 2016–2020. The next highest cumulative $H_p(10)$ were 91, 69, 67, and 63 mSv (three interventional radiologists and one interventional cardiologist). Applying the regression formula $H_p(3) = (0.53 \pm 0.45) \cdot H_p(10)$ to the highest cumulative doses would yield five-year cumulative $H_p(3)$ estimates of (85 ± 78 mSv, (49 ± 45) mSv, (37 ± 34) mSv, (36 ± 33) mSv and (33 ± 31) mSv. Thus, it appears that only one interventionalist would have possibly exceeded the five-year cumulative eye lens dose limit of 100 mSv defined in national legislation. A more conservative estimate may again be calculated by applying the maximum measured $H_p(3)/H_p(10)$ ratios (0.91 for interventional radiologists and 1.21 for interventional cardiologists) to the dose register data. This approach gives five-year

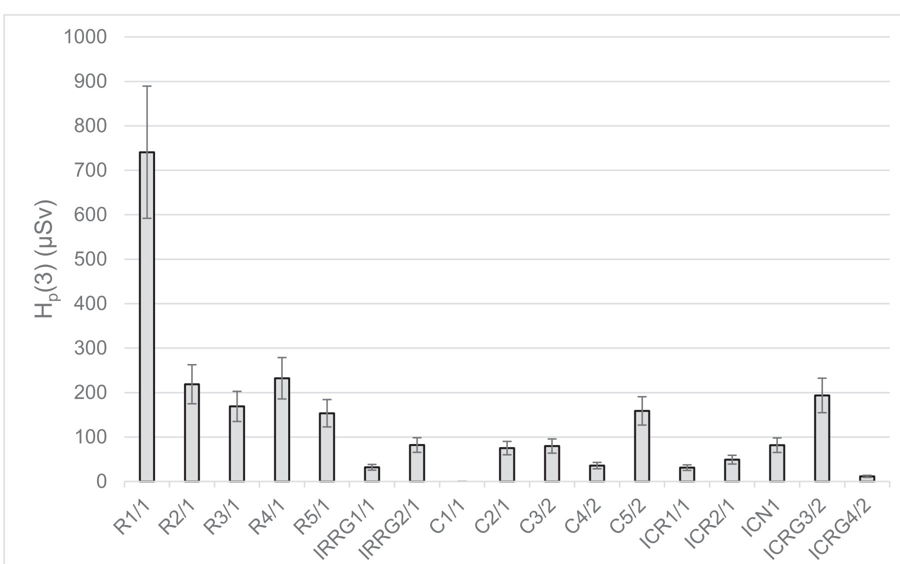

Fig. 1. Measured cumulative $H_p(3)$ values for all participants and group dosemeters from a period of approximately one month of work. Error bars correspond to an expanded uncertainty (coverage factor k = 2) of 20%. The workers R1/1-R5/1 are interventional radiologists, C1/1-C5/2 are interventional cardiologists and the remaining are individual or group dosemeters for IR/IC radiographers or nurses. For a more detailed description of the worker codes, see Table 1.

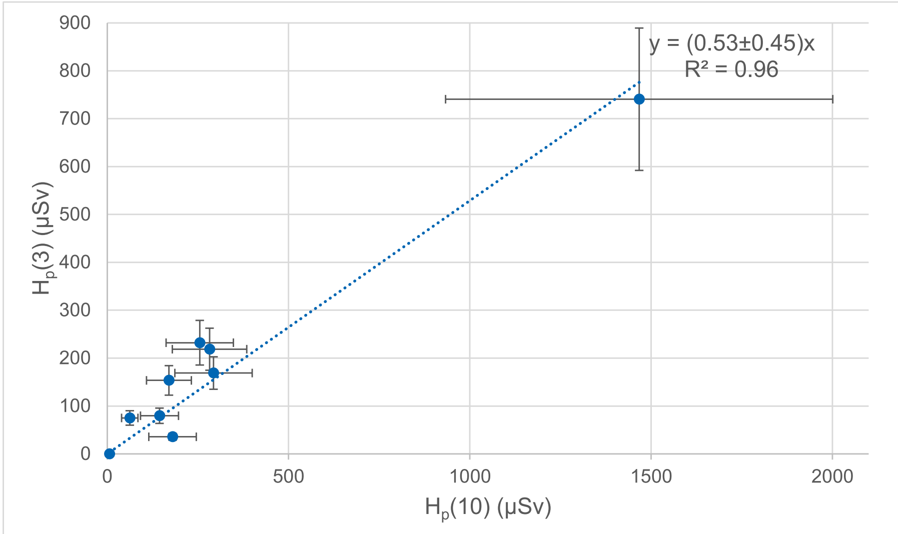

Fig. 2. A linear fit to measured cumulative $H_p(3)$ and $H_p(10)$ values for interventional radiologists and cardiologists. The x- and y error bars correspond to expanded uncertainties (coverage factor k = 2) of 37% and 20%. The intercept of the fit is set to zero. The error of the slope is defined as expanded uncertainty with a coverage factor of 2, corresponding to approx. 95% confidence interval.

Table 1
Description of the study cohort consisting of medical professionals from interventional radiology and cardiology units as well as their measured $H_p(3)$ values per KAP and procedure and estimated $H_p(3)$ per year. Dosemeters were worn on the left side, unless mentioned otherwise. DIS-1 was worn at chest height, unless stated otherwise. N = number of procedures during the measurement period. The uncertainties are reported as expanded uncertainties, k = 2.

Person/group	Code/clinic	Workload	N	Hp(3)/KAP (µSv/Gy·cm2)	Hp(3)/procedure (µSv)	Hp(3)/year (µSv)
Radiologist 1	R1/1	Mixed IR	48	0.44 ± 0.16	16 ± 3	7500 ± 1500
Radiologist 2	R2/1	Mixed IR	30	0.23 ± 0.08	7.3 ± 1.5	2200 ± 500
Radiologist 3	R3/1	Mixed IR	20	0.38 ± 0.14	9 ± 2	1700 ± 400
Radiologist 4	R4/1	Mixed IR	27	0.90 ± 0.33	9 ± 2	2400 ± 500
Radiologist 5	R5/1	Mixed IR	15	0.20 ± 0.09	11 ± 2	1600 ± 400
Cardiologist 1	C1/1	Electrophysiology	16	0	0	0
Cardiologist 2[a)]	C2/1	CA/PCI [c)]	15	0.30 ± 0.13	5.0 ± 1.0	550 ± 110
Cardiologist 3	C3/2	CA/PCI	26	0.20 ± 0.06	3.1 ± 0.7	610 ± 130
Cardiologist 4	C4/2	CA/PCI	11	0.20 ± 0.06	3.2 ± 0.7	280 ± 60
Cardiologist 5[b)]	C5/2	PM [d)]	7	9.0 ± 3.1	23 ± 5	1300 ± 250
IC radiographer 1 [a)]	ICR1/1	CA/PCI	27	0.04 ± 0.02	1.2 ± 0.3	290 ± 60
IC radiographer 2 [a)]	ICR2/1	CA/PCI, PM	16	0.08 ± 0.03	3.1 ± 0.7	520 ± 110
IC nurse 1 [a)]	ICN1/1	CA/PCI, PM	38	0.15 ± 0.06	2.1 ± 0.5	900 ± 200
IC radiographers group	ICRG3/2	CA/PCI	82	0.11 ± 0.04	2.4 ± 0.5	1800 ± 400
IC radiographers group	ICRG4/2	PM	14	0.26 ± 0.10	0.8 ± 0.2	110 ± 30
IR radiographers group, room 1	IRRG1/1	Mixed IR	10	0.10 ± 0.05	3.2 ± 0.7	320 ± 70
IR radiographers group, room 2	IRRG2/1	Mixed IR	17	0.10 ± 0.03	4.8 ± 1.0	900 ± 200

a) DIS-1 at collar height, b) Both dosemeters on the right side,
c) CA/PCI = Coronary angiography/percutaneous coronary intervention, d) PM = pacemaker implantation.

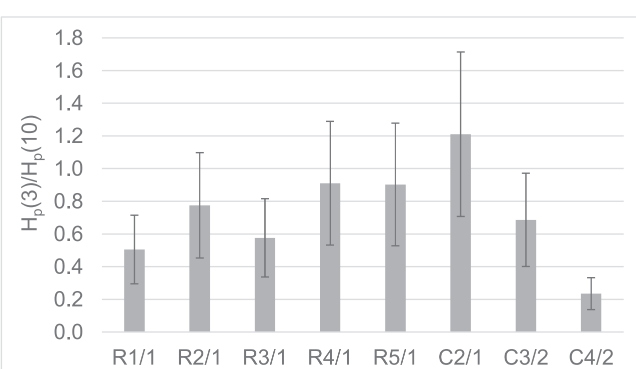

Fig. 3. Ratios of measured $H_p(3)$ and $H_p(10)$ values for interventional radiologists and cardiologists. Error bars correspond to an expanded uncertainty with coverage factor k = 2.

cumulative $H_p(3)$ estimates of (145 ± 81) mSv, (83 ± 47) mSv, (81 ± 45) mSv, (63 ± 35) mSv and (57 ± 32) mSv for the five most exposed workers nationally. Average five-year cumulative $H_p(10)$ calculated from the dose registry data was 23 mSv for interventional radiologists and 5 mSv for interventional cardiologists. The corresponding estimated average $H_p(3)$ were (12 ± 12) mSv and (2.6 ± 2.4) mSv. Median values of cumulative $H_p(10)$ were 11 mSv (IR) and 1.3 mSv (IC) and median estimated $H_p(3)$ were (6 ± 6) mSv and (0.7 ± 0.6) mSv for IR and IC, respectively. These average and median values were calculated using a $H_p(3)/H_p(10)$ ratio of 0.53 from Fig. 2.

Discussion

The extrapolated annual $H_p(3)$ data indicate that none of the participating workers have received eye lens equivalent doses even close to the limits of 50 mSv for a single year or 100 mSv for five consecutive years (allowing, on average, 20 mSv/year) defined in Finnish legislation. The maximum $H_p(3)$ extrapolated for a single year was 7.5 mSv, for

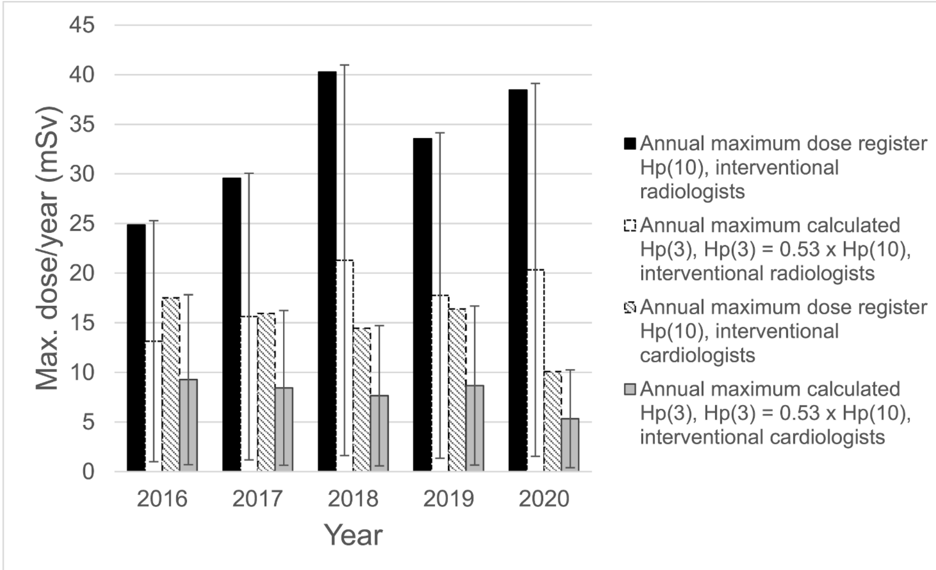

Fig. 4. The maximum individual $H_p(10)$ per year for interventional radiologists (black) and cardiologists (hatched), based on records from national dose register, and the respective individual maximum $H_p(3)$ values (white and grey) estimated using the $H_p(3)/H_p(10)$ ratio of 0.53 obtained from the linear fit in Fig. 2. Error bars correspond to the combined uncertainty estimate of dose register $H_p(10)$ and the slope ($k = 0.53 \pm 0.45$) from Fig. 2.

a highly experienced interventional radiologist performing large quantities of complex and demanding procedures targeting a variety of different anatomical areas and treatment indications. Among interventional cardiologists, the maximum annual estimated $H_p(3)$ was 1.3 mSv for a cardiologist performing pacemaker implantations. For practical reasons, the ceiling-mounted shield is generally not used during pacemaker implantations, which increases the radiation exposure to the eyes compared to other IC procedures.

Eye lens dose measurements have been reported in several previous publications. A comparison of our results to some of the literature is provided in Table 2.

Previous studies have concluded that many staff members in IR and IC may exceed the eye lens dose level of 20 mSv per year [5]. However, none of the interventionalists participating in our study would seem to accumulate even 10 mSv of $H_p(3)$ per year, even though the cohort includes interventionalists with a high workload of complex procedures. The departments participating in our study use modern angiography equipment designed specifically for interventional radiology or cardiology. Radiation shields fixed to the patient table and mounted to the ceiling are used routinely, together with movable shields and personal protective equipment. In the participating IR department, the staff leave the interventional room during image series acquisition whenever possible. These observations combined with the low level of measured doses per procedure indicate that the effect of working culture related to well-implemented radiological protection and the availability of modern imaging equipment play an essential role in radioprotection of the eye lens in interventional radiology and cardiology. Based on the $H_p(10)$ data from the national dose register it is apparent that, in general, working practices vary to a large extent between departments and individual workers. In addition, it should be noted that our study cohort did not include the most exposed interventionalists on a national scale. Nevertheless, using the $H_p(3)/H_p(10)$ ratios defined in this study to approximate $H_p(3)$ using $H_p(10)$ records from national dose register, only a few interventionalists with the highest exposures are in risk of exceeding the legislative dose limits for eye lens equivalent dose and are in need of more rigorous monitoring.

It should be noted that the $H_p(3)$ values reported in this study do not account for the protective effect of the lead glasses, even though all study participants wore them regularly during the measurement period. All $H_p(3)$ doses were measured outside the glasses, with the dosemeter

Table 2
Comparison between some previously published data of eye lens dose per procedure and our results.

Publication	Procedure type	Mean eye lens dose per procedure (μSv)
Efstathopoulos et al. 2011 [24]	Mixed IR	47 (mean), 0–557 (range)
Efstathopoulos et al. 2011 [18]	Mixed IC	13 (mean), 0–61 (range)
Vanhavere et al. 2011 (ORAMED) [5]	Carotid & brain angiography/angioplasty	ca. 50 (mean)
Vanhavere et al. 2011 (ORAMED) [5]	Embolisations	ca. 200 (mean)
Vanhavere et al. 2011 (ORAMED) [5]	Lower limb angiography/ angioplasty	ca. 50 (mean)
Vanhavere et al. 2011 (ORAMED) [5]	Renal angiography/ angioplasty	ca. 50 (mean)
Vanhavere et al. 2011 (ORAMED) [5]	CA/PTCA	ca. 50 (mean)
Vanhavere et al. 2011 (ORAMED) [5]	RF ablation	ca. 40 (mean)
Vanhavere et al. 2011 (ORAMED) [5]	PM/ICD implantation	ca. 50–60 (mean)
Jacob et al. 2013 [9]	Cerebral angiography	25 (mean)
O'Connor et al. 2015 [7]	Mixed IR	55 (mean), 16.5–143.2 (range)
Principi et al. 2015 [25]	Mixed IC, physicians	42–251 (range)
Principi et al. 2015 [19]	Mixed IC, nurses	11–24 (range)
Aarsnes et al. 2018 [26]	TAVI	50–60 (median)
Morcillo et al. 2021 [6]	Mixed pediatric and adult IR	70–180 (range)
Our results, interventional radiologists	**Mixed IR**	**10 (mean), 7.3–16 (range)**
Our results, interventional cardiologists	**Mixed IC**	**6.8 (mean), 0.0–23 (range)**
Our results, IR radiographers	**Mixed IR**	**4.2 (mean), 3.2–4.8 (range)**
Our results, IC radiographers and nurses	**Mixed IC**	**1.9 (mean), 0.82–3.07 (range)**

being fixed on the arm of the glasses, on the (presumably) most exposed side of the head. The dose reduction of lead glasses has been examined in, for instance, the ORAMED project (reported dose reduction of 70–87% [27]) and more recently by Moriarty et al. [28], who reported an average dose reduction of 79% for lead glasses in interventional radiology. A smaller dose reduction was reported by Magee et al. [29], who suggested that applying a dose reduction factor (DRF) of 2 for the lead glasses would yield a conservative estimate of the eye lens dose, given that the glasses provide some shielding on the side of the eyes (i.e., are of a wraparound design or have side shields). Furthermore, Magee et al. also concluded that the exact DRF of the glasses is dependent on factors such as direction of incident radiation (i.e., head angulation of the interventionalist) and the design and fit of the glasses. Some types of glasses even had DRFs of below two at head angulation of 60°. The variability of the dose reduction factors regarding protective glasses and the lacking knowledge of consistency in their use makes reliable implementation of both accurate and general dose reduction factor challenging. Therefore, our study reports only the measured $H_p(3)$ values as conservative estimates of the true eye lens equivalent doses and no correction for the dose reduction of the glasses is applied, even though all glasses provide at least some degree of additional protection. A dose reduction factor of two suggested by, for example, Magee et al. [23] could be considered as a conservative estimate for consistent use of appropriately designed glasses.

Indirect eye lens dosimetry practices based on estimation from body dosemeter measurements have been proposed in ICRP report 139 and implemented in practice, for instance, in Switzerland [15]. Such estimation has several sources of uncertainty. In addition to the uncertainty of $H_p(10)$ measurements themselves, there are other factors affecting the conversion to eye lens dose such as the effect of operator height [30], dosemeter positioning [31] and the previously discussed variability in dose reduction of lead glasses, which contribute to the total uncertainty. The $H_p(3)/H_p(10)$ ratios may vary between workplaces and individuals, due to differences in e.g., availability and consistency of use of ceiling-mounted lead shields and other protective equipment, or differences in C-arm angulations or tube/detector placement. These factors introduce extra uncertainty in indirect eye lens dose estimates, and also affect our analysis of eye lens dose based on national dose register $H_p(10)$. Additionally, personal dosemeters may sometimes not be worn during work. This introduces a possibility of underestimation of doses in the dose register records. Due to the generally good compliance to wearing the routine personal dosemeters among Finnish radiological and cardiological workers, this effect is unlikely to change the conclusions of this study. However, uncertainty of the indirect estimation of eye lens dose warrants caution regarding protective practices. It must be stressed that the conclusion of this study does not diminish the responsibility of operators to conduct eye lens dose measurements for highly exposed workers who may be at risk of exceeding the legal dose limits.

Study limitations

The limitations associated with this study include a small number of participants, and that all participants originated from the same university hospital district. Thus, the measured $H_p(3)$ results presented in this study do not give an overall picture about the eye lens doses or the $H_p(3)/H_p(10)$ ratio on a national scale. However, the participating departments rank highly in both the number of performed procedures and the procedure complexity and thus the study participants represented a group with potentially high doses within the departments. The dose register data analysis presented in this study covered all the interventional radiologists and cardiologists nationally, including the most exposed workers and is thus helpful in providing a more complete picture on the eye lens doses nationally.

Conclusions

The highest average $H_p(3)$ per procedure as well as the highest cumulative dose were measured for interventional radiologists, although one cardiologist was also significantly exposed and had the highest dose per procedure in the cohort. Radiographers and nurses were, on average, less exposed than interventional physicians. None of the workers who participated in our measurements is likely to reach the 20 mSv eye lens equivalent dose level annually, most likely not even 10 mSv/year, considering the routine use of protective glasses among the participants. However, based on the data from the national dose register, a small number of the most exposed interventional radiologists and cardiologists may potentially exceed the cumulative eye lens dose limit of 100 mSv for five consecutive years. In the case of interventional radiologists, even the limit of 50 mSv for a single year may possibly, although unlikely, be exceeded. $H_p(10)$ measured over the protective apron or thyroid shield provides a conservative estimate of the eye lens equivalent dose for interventional radiologists and cardiologists, provided that appropriate protective glasses are used.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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