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MEASUREMENTS OF EYE LENS DOSES IN INTERVENTIONAL CARDIOLOGY USING OSL AND ELECTRONIC DOSEMETERS†

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The purpose of this paper is to test the appropriateness of OSL and electronic dosemeters to estimate eye lens doses at interventional cardiology environment. Using TLD as reference detectors, personal dose equivalent was measured in phantoms and during clinical procedures. For phantom measurements, OSL dose values resulted in an average difference of −15 % vs. TLD. Tests carried out with other electronic dosemeters revealed differences up to ±20 % versus TLD. With dosemeters positioned outside the goggles and when TLD doses were >20 μSv, the average difference OSL vs. TLD was −9 %. Eye lens doses of almost 700 μSv per procedure were measured in two cases out of a sample of 33 measurements in individual clinical procedures, thus showing the risk of high exposure to the lenses of the eye when protection rules are not followed. The differences found between OSL and TLD are acceptable for the purpose and range of doses measured in the survey.

INTRODUCTION

Interventional cardiology (IC) is one of the medical specialties with major exposure to ionising radiation for patients and staff. Minimally invasive procedures offer advantages versus surgery in certain pathologies and the emergence of new practices has caused an increasing number and complexity of procedures in the last years. Professionals involved in these procedures have shown a greater interest in occupational doses since the International Commission on Radiological Protection (ICRP) recommended a reduction of the occupational dose limit to the lens of the eyes from 150 to 20 mSv·y^{-1}(1). Recent studies have also reported a statistically significant radiation-associated increase in lens injuries (posterior subcapsular opacities) in some non-optimised interventional cardiology laboratories(2–4). Measuring eye lens doses is bound to become a necessity as occupational eye lens doses can be close or greater than the new dose limit(5) depending on the workload and on the level of protection used. Some authors(6, 7) reported average lens doses per IC procedure of 140–170 μSv. But doses can be reduced substantially depending on the efficiency of the ceiling suspended protective screen. Other papers(8–10) mentioned 50 μSv per procedure as an average eye lens dose for IC procedures, which may be indicative of a diligent use of protective screen. But even with such reduced dose values, the eye lens doses received can still be ≥20 mSv·y^{-1} if goggles are not used and if the workload is >400 procedures per year. There is an agreement that eye lens doses should be monitored with typical workloads in the range of 400–900(8, 9) procedures per year. Different options are available to estimate eye lens doses in personal dosimetry, from personal dosemeters to be used over the protective apron(11) to specific $H_p(3)$ dosemeters to be carried at an eye level(12).

In this work, authors have tested two kinds of dosemeters: one based on optically stimulated luminescence dosimetry (OSLD) and another one based on active solid-state electronic dosimetry, both to be used to monitor eye lens doses in interventional environment. Phantom and routine clinical measurements were performed to compare the response of the above-mentioned dosemeters against that of a reference dosemeter based on thermoluminiscent (TL) technology. The relationship between the dose measured on chest over the apron and the dose measured at an eye level was also investigated.

MATERIALS AND METHODS

Dosemeters and calibration

The OSLD is a technology which now finds medical dosimetry applications in radiation dose measurement. Like thermoluminescent dosemeters (TLD), OSL material stores part of the energy imparted by radiation, trapping electrons between conduction and valence bands, but unlike thermoluminescent

†Part of the calibration results on the OSL dosemeters used was presented at the National Congress of Medical Physics and Radiation Protection held on June 2013 in Cáceres, Spain.

dosemeters, the stimulated light emission during the reading procedure is produced by a laser pulse instead of heat[13]. OSL dosemeters have proved to be linear up to 3 Gy, they have shown energy and angular dependence in diagnostic energies and therefore, special attention must be paid to potential inconveniences[14–16]. The OSL dosemeters were provided by Landauer, Inc. (http://www.landauer.com/) and consist of an active material Al_2O_3:C formulated as a powder mixed with a liquid binder, coated onto a base material and sealed with a transparent film tape. The type of OSL dosemeter used is the ‘nanodot’ that consists of a small disk (4 mm in diameter and ~0.3 mm thick) covered, when closed, in a 10 × 10 × 2 mm^3 light-tight plastic casing meant to prevent light exposure of the sensitive element. This format is suitable to measure point doses with high spatial resolution. The screened nanodots have individual sensitivity factors provided by the manufacturer with 2 % of uncertainty. To check the sensitivity factor, a sample of 20 nanodots with 1.76 mGy from a 81 kV_p, 3.37-mm Al of HVL X-ray beam were irradiated. The readings corrected by sensitivity were then compared.

Readouts of OSLDs were performed with a MicroStar reader (Landauer, Inc.) using a laser diode working in the continuous wave mode (CW)[13]. With the CW mode, stimulating laser beam and fluorescent emission coexist and OSL fluorescence has then to be discriminated using a set of filters coupled with a photomultiplier tube. The reading process is fast (~1 s) and as only a small portion of the traps is released (0.1–1 %), the same dosemeter can be read several times to verify anomalous readings or reduce uncertainty. The system reproducibility, when a dosemeter was read 20 times, resulted in 0.5 % (1 SD). This result is in agreement with Jursinic[15]. After irradiation, OSL dosemeters were erased on a source of white light of ~1500 cd·m^{-2}, coming from a conventional negatoscope. The set of nanodot OSL dosemeters selected presented a lower detection limit of 2.1 μSv. To remain within this lower detection limit, background (BG) readings were checked periodically. Dosemeters with anomalous BG readings (>20 % of average reading) were then rejected.

The electronic dosemeters used were the DoseAware [Philips Medical System, Best, The Netherlands (http://www.healthcare.philips.com/)]. They are silicon diode detectors of 45 × 45 × 10 mm^3 external dimensions specially designed to measure personal dose equivalent $H_p(10)$ at interventional environment and to provide cumulative dose and dose rate (averaged on a second)[17, 18]. Dosemeters are linked wireless to a base station, where the $H_p(10)$ dose rate is recorded every second if radiation is detected: their detection threshold is of a few tens of μSv·h^{-1}. Manufacturer ensures linearity from 40 μSv·h^{-1} up to 300 mSv·h^{-1}, 20 % variation in the energy response between N-40 and N-100 ISO standard beam qualities[19], and reports an angular dependence of >30 % for angles >50°.

LiF:Mg,Cu,P detectors manufactured by Conqueror Electronics Technology Co. Ltd., Beijing, China (http://www.cet-cns.com/index.htm) under the trade name TLD-2000C were used as reference dosemeters. LiF:Mg,Cu,P has been proved to have high sensitivity together with a good tissue equivalence[20, 21]. Chips of 4.5 mm diameter and 0.8 mm thickness packed in two different types of holders were used. The whole-body (WB) dosemeter consists of four chips, two of them located under 1 g·cm^{-2} and the other two under 7 mg·cm^{-2} polyvinyl chloride filters for the measurement of $H_p(10)$ and $H_p(0.07)$, respectively. The eye lens dosemeter includes two TL chips inside a 5-mg·cm^{-2} opaque polyethylene film.

Before each irradiation, annealing was performed for 10 min at 240°C in a PTW-TLDO oven. Readout was carried out with a Thermo Scientific Harshaw 5500 hot gas reader. The heating procedure consisted of a pre-heating phase at 160°C for 10 s, followed by a linear heating rate of 4°C·s^{-1} for 26 s at a temperature up to 250°C. To improve the dosemeter accuracy, individual calibration coefficients were established for each detector, and stability checks were performed periodically with a ^{137}Cs beam. The lower detection limit is 1 μSv.

IEC standard 62387[22] recommends the use of ISO narrow spectra[19] for the calibration of passive dosemeters for personal monitoring. However, in the framework of this study, RQR IEC qualities[23] were also used with the aim to analyse the behaviour of OSLD in diagnostic X-ray beams. Conversion coefficients to relate air kerma K_{air} to personal dose equivalent $H_p(d)$ for the narrow spectrum series were taken from ISO 4037-3[19]. For the RQR qualities, these conversion coefficients are not available in the international standards. Therefore, for the RQR series, the conversion coefficients for the ICRU 4-element standard tissue slab phantom (30 × 30 × 15 cm^3) were calculated with the Monte Carlo code, PENELOPE[24], using a filtered X-ray spectra generated with the software XCOMP5R[25] and following a procedure that has been previously described[26]. The conversion coefficients are shown in Table 1.

Dosemeters were calibrated at the Institut de Tècniques Energètiques (Barcelona, Spain), a secondary laboratory licensed by the Spanish National Body for Accreditation. TLDs and OSLD were calibrated with ISO narrow spectrum qualities[19] and with RQR IEC qualities[23], with the corresponding experimental HVL values and the calculated[25] mean energies of the beams shown in Table 1. Calibration coefficients in terms of $H_p(0.07)$ and $H_p(10)$ were provided. The operational quantity recommended to monitor exposure to the lens of the eyes is the personal dose equivalent at a 3-mm depth $H_p(3)$[27]. However, in practice, this quantity has rarely been

Table 1. Conversion coefficients $H_p(0.07)/K_{air}$ and $H_p(10)/K_{air}$ from air kerma to personal dose equivalent for the beam qualities considered in OSL calibration.

Beam quality	kV	Mean energy (keV)	First HVL (mm Al)	$H_p(0.07)/K_{air}$ (Sv·Gy^{-1})	$H_p(10)/K_{air}$ (Sv·Gy^{-1})
RQR-4	60	36	2.15	1.29	1.10
RQR-6	80	44	3.07	1.36	1.30
RQR-9	120	56	4.98	1.50	1.52
N-60	60	48	5.77	1.55	1.65
N-150	150	119	16.4	1.61	1.73

Table 2. Beam qualities used on phantom irradiation.

Mode	Added filtration	kV	Mean energy (keV)	First HVL (mm Al)
Fluoroscopy low dose	0.9 mm Cu +1 mm Al	92	65	10.4
Fluoroscopy high dose	0.1 mm Cu +1 mm Al	79	49	5.48
Acquisition	No added filtration	80	44	3.97

used, Annex B of ICRP 103[28] suggests that the monitoring of the exposure to the eye lens is sufficiently reliable using other operational quantities, in particular, $H_p(0.07)$. Other authors[29] have confirmed the validity of this hypothesis for the photon energy range considered in this paper.

Phantom measurements

An anthropomorphic phantom model Rando [The Phantom laboratory (http://www.phantomlab.com/), Salem, NY, USA] was located over the treatment couch of a Philips Allura (http://www.healthcare.philips.com/) FD-10/20 biplane C-arm unit, with the phantom centred at the isocentre. The phantom was irradiated with several X-ray beam qualities: two low-dose and low image quality fluoroscopic modes with added filtration and one acquisition mode without filtration, but with high dose rate and high image quality. Table 2 shows the values of HVL measured and the mean energy of the beams calculated[25]. The manufacturer provided information about the tube used for the calculation: MRC 200 0507 ROT 1004 X-ray tube assembly with an inherent filtration of 2.5 mm Al and 11° of anodic angle.. The phantom entrance surface air kerma was monitored with an ionisation chamber Radcal model 20x6-60E with the electrometer model 20x26C [Radcal (http://www.radcal.com/) corp. Monrovia, CA, USA]. The dosemeters tested were the OSL nanodot, the TLD eye lens dosemeter and the Doseaware electronic dosemeter. The first two were compared with $H_p(0.07)$ measurement with the TL WB dosemeter and the electronic reading with $H_p(10)$ measurement with the TL badge. The dosemeters were located 65 cm from isocentre towards feet and on a 30 × 30 × 15 cm^3 polymethyl methacrylate (PMMA) phantom as described in Figure 1, as close to each other as possible to minimise dose variations due to spatial inhomogeneity in scatter radiation fields. A direct reading electronic dosemeter Thermo model EPD [Thermo Scientific, Inc. (http://www.thermoscientific.com/), USA] was also located on the PMMA phantom to monitor in real time the scatter radiation (between 30 and 50 μSv, i.e. the minimum dose intended to be detected in typical clinical routine for single procedures) delivered to the dosemeters evaluated.

Measurements during interventional cardiology procedures

During routine interventional cardiology procedures at Hospital Clinico San Carlos, Madrid, Spain, both OSL nanodot and TLD eye lens dosemeters were located on the external left side of the cardiologist's goggles to estimate eye lens doses (Figure 2). The main interest of such measurements is to evaluate the proper use of the ceiling suspended screen and to assess the potential need for goggles in cardiac procedures (in addition to the ceiling suspended screen). An electronic DoseAware dosemeter was also placed on the left outer pocket of the cardiologist's lead apron at a chest level (Figure 2). Personal dose equivalent ($H_p(10)$) over the apron are used in some

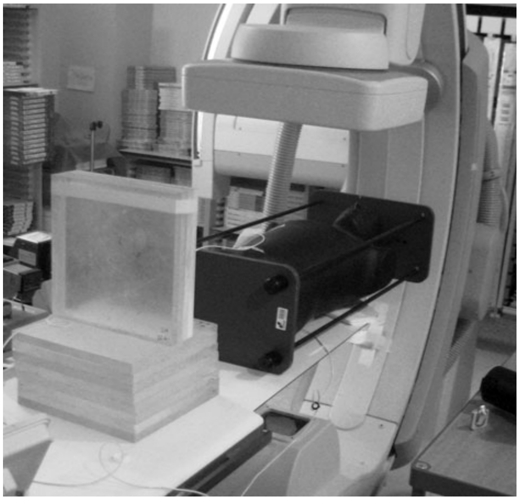

Figure 1. Arrangement for phantom measurements.

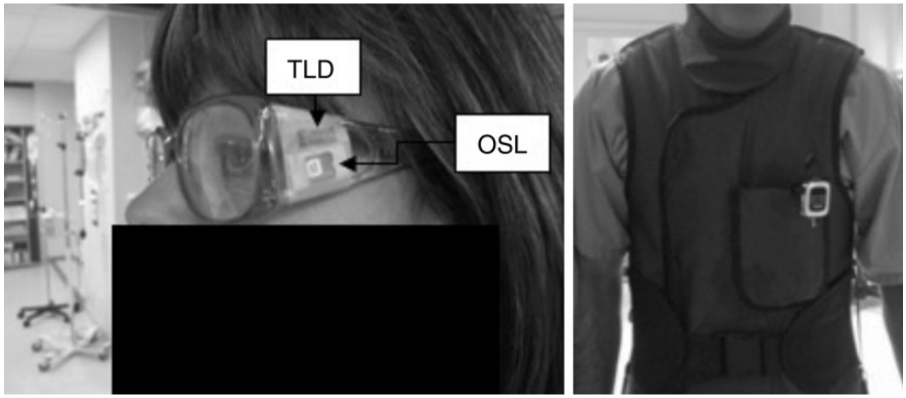

Figure 2. On the left, one OSL nanodot and one TL eye lens dosemeter on the goggles left side. An electronic DoseAware dosemeter over the apron (right).

cases (as recommended by ICRP) to estimate eye lens doses when no better alternative is available[11, 28]. Cardiologists have always used leaded apron and thyroid collar in the Centre. In most procedures, they also used protection ceiling suspended screen and goggles, but not always.

Uncertainties

The expanded uncertainty (2 SD) for TLD dosemeters, both WB and eye lens dose measurements, is 5 % in well-known laboratory conditions and 10 % in workplace fields.

The energy and angular dependence are the main sources of uncertainties for OSL measurements. Al-Senan and Hatab[16] have estimated a variation in OSL nanodot response of 10–15 % for 45° incidence angle and 80 kV_p. In the case of phantom measurements, angular dependence was avoided and the overall uncertainty was of 20 % (2 SD). In the case of clinical measurements, uncertainties were higher, but they are more difficult to assess as wider range of beam qualities and angular incidences can appear.

RESULTS

Calibration and phantom measurements

Figure 3 shows the calibration coefficients $N_{cal}(E)$ in terms of $H_p(0.07)$ for the OSL dosemeters and the beam qualities (E) considered in this work normalised to RQR-4 quality. It reveals an important difference in response between the high-filtered high kV beam N-150 and the RQR qualities as reported by the manufacturer. For the diagnostic beam qualities of interest in this experiment (RQR-4 to RQR-9 and N-60), there was a difference of 20 % for $H_p(0.07)$ calibration coefficients. The readings corrected by sensitivity for the sample of dosemeters investigated

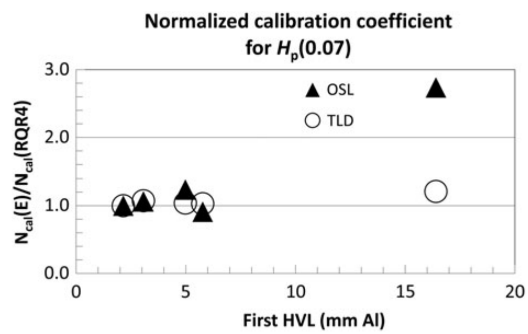

Figure 3. OSL and TLD calibration coefficients in terms of $H_p(0.07)$; values normalised to RQR-4 beam quality.

had a standard deviation of 1.8 %, with a minimum value of sensitivity of 0.95 and a maximum of 1.03, showing an accurate estimation of sensitivity factors.

In phantom measurements, the ratio of the $H_p(10)$ and $H_p(0.07)$ readings evaluated with the WB TL dosemeter provided an estimation of the mean energy of the scatter radiation fields, which seemed to be close to RQR-6 for the acquisition and fluoroscopic high-dose modes (low-filtered X-ray beams), and close to RQR-9 for the low-dose fluoroscopy mode (high-filtered beam). As shown in Tables 1 and 2, the mean energy of the RQR-6 beam is 44 keV, i.e. quite similar to the mean energy of the beams for the acquisition and fluoroscopic modes, 44 and 49 keV, respectively. For the high filtered beam, its mean energy is 65 keV and RQR-9 is the closest RQR beam quality, with a mean energy of 56 keV.

Table 3 presents the personal dose equivalent, $H_p(10)$ and $H_p(0.07)$, measured with the WB TL personal dosemeter for the three beams tested. Table 4 shows the ratio of the readings of the different dosemeters against the WB dosemeter reading for the three different beams. For the TL eye lens and OSL nanodot, $H_p(0.07)$ was compared. The quantity under study was $H_p(10)$ for the electronic DoseAware and Thermo. On average, OSL nanodot underestimated H_p (0.07) by 15 %, while electronic dosemeters had better response on average, although in some cases deviations of 22 or 12 % in $H_p(10)$ were observed.

Measurements during interventional cardiology procedures

Individual dose measurements of lens doses were performed during 33 clinical procedures with dosemeters located on cardiologists' goggles (left side).

In most procedures (although not always), the acquisition with unfiltered beams contributes mainly to patient dose area product. Therefore, for clinical measurements, the RQR-6 calibration coefficient was used in the dose assessment.

The average $H_p(0.07)$ per procedure measured with TLD was 80 μSv, with a maximum value of 697 μSv in a single procedure. Differences between OSL nanodot and TLD chips are shown in Figures 4 and 5. Figure 4 shows the histogram for the relative difference between OSL and TLD when TLD readings were ≥20 μSv. An average difference of −9 % was obtained. Figure 5 shows the absolute difference recorded in procedures with eye lens dose <20 μSv and higher than the lower detection limit. An average difference of 2 μSv was observed.

In 30 out of the 33 procedures mentioned previously, the cardiologist also wore an electronic dosemeter at a chest level over the apron. The Pearson correlation coefficient between $H_p(10)$ on chest over the apron vs. $H_p(0.07)$ on goggles resulted in 0.17. In this particular set of measurements, the electronic personal dosemeter worn on the left side of the chest overestimated the dose at eye lens with an average of 3.5 factor.

Table 3. Personal dose equivalent, $H_p(10)$ and $H_p(0.07)$ measured with the reference dosemeter (TLD_{WB}) for the three tested clinical procedures.

TLD_{WB}	Fluoroscopy low dose	Fluoroscopy high dose	Acquisition
$H_p(10)$ (μSv)	36	32	48
$H_p(0.07)$ (μSv)	38	31	51

DISCUSSION

The differences found in phantom measurements show an acceptable underestimation (15 %) of OSL vs. TLD for the typical range of occupational doses and radiation beam qualities used in the cardiology laboratories of this study. These differences are similar to those obtained with other electronic dosemeters and seem to be independent of the beam qualities tested in this work. They may be related to the low doses measured (few tens of μSv). For the electronic dosemeters, differences of 20 % versus reference TLD can also be found. In the case of OSL dosemeters, the underestimation seems to be systematic (13–18 %) for all the beam qualities tested in this experiment. This could imply that the calibration coefficient for OSL is still to be improved.

The personal dose measurements carried out on cardiologists' goggles during routine procedures were analyzed: for cases with TLD doses >20 μSv, an average underestimation of −9 % versus TLD was obtained, in agreement with phantom measurements, but higher dispersion was observed in some individual cases as shown in Figures 4 and 5. Further investigations are needed to explain the increase in dispersion in clinical measurements. However, it is believed that these differences could be partly related to the fact that, in some procedures, most of the radiation measured was highly filtered by the protection ceiling suspended screen (0.5 mm Pb equivalent), and that the OSL response varies significantly in these fields as shown in Figure 3. It can be assumed that measurements >100 μSv corresponded to a non-optimised geometry or a lack of use of the ceiling suspended screen, therefore the contribution of radiation filtered by the protection screen was less important

Table 4. $H_p(d)_{\text{Tested dosemeter}}/H_p(d)_{\text{TLD WB}}$ for the different dosemeters and for the three beams qualities tested.

Tested dosemeter	$H_p(d)_{\text{Tested dosemeter}}/H_p(d)_{\text{TLD WB}}$ ($d = 0.07$ for TL and OSL and $d = 10$ for electronic dosemeters)			
	Fluoroscopy low dose	Fluoroscopy high dose	Acquisition	Average ± SD
$TL_{\text{eye lens}}$	1.00	1.00	1.04	1.01 ± 0.02
OSL_{nanodot}	0.87	0.87	0.82	0.85 ± 0.03
DoseAware	1.08	1.22	1.02	1.11 ± 0.10
Thermo EPD	0.97	0.88	1.04	0.96 ± 0.08

In the right column, the average ratio ± standard deviation for each dosemeter is shown.

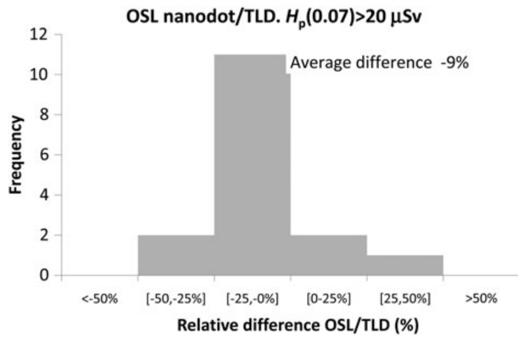

Figure 4. Relative differences of OSL nanodot/TL eye lens dosemeter carried at cardiologist protection goggles (left side) for the procedures with measured $H_p(0.07) \geq 20$ µSv.

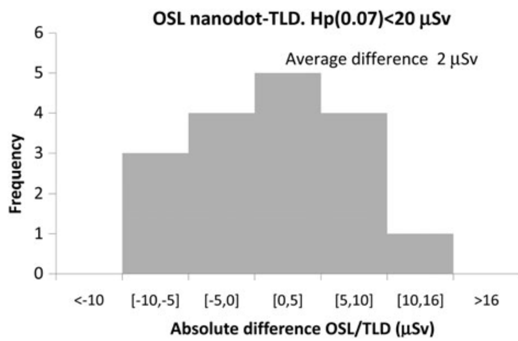

Figure 5. Absolute differences of OSL nanodot and TL eye lens dosemeter for procedures with personal dose equivalents <20 µSv.

and differences between OSL and TLD remained within ±20 %, like in the phantom measurements. On the contrary, when TLD $H_p(0.07)$ measurements were below 20 µSv, physicians were well protected by the protective suspended screen, and thus the major contribution to the personal dose equivalent came from filtered radiation.

As for measurements of personal dose equivalent with electronic dosemeters worn on chest over the lead apron to estimate dose at eye lens, the higher differences were estimated to derive mainly from geometrical changes (operator's position, C-arm angulations and position of the ceiling suspended screen). The poor correlation observed (0.17) between the electronic dosemeter $H_p(10)$ doses versus the reference TLD $H_p(0.07)$ shows that the dose measured on the chest over the apron can, in some cases, be quite different from the dose received by the eye when individual procedures are measured. In general, in the measurements used here, the over-apron dosemeter overestimated the real doses received by the lens of the eyes. Many factors could account for these differences; therefore, a conservative approach should be adopted such as values of the over-apron dosemeters as potential doses received at the lens, to recommend more protective actions (e.g. the use of goggles) for some complex procedures or operators with high workload. The fact that in some cases the dose measured by the passive dosemeters worn on the side of the goggles is much lower than the value measured by the electronic dosemeters should not be considered as a general rule by all the operators and in all the procedures. High differences (up to a factor of 15) may result from the angular dependence of the electronic dosemeter, from some particular C-arm angulations and from partial protection when only one of the two dosemeters—TLD or electronic—worn by the cardiologist happen to be covered by the ceiling suspended screen. This high dispersion found between doses on chest and goggles measuring single procedures could be reduced if monthly doses, resulting from dozens of procedures were accumulated in one measurement. Other authors have found better correlation (r^2=0.7) measuring several procedures in one dosemeter[9].

The absolute values of personal doses measured at cardiologists' goggles in the 33 procedures with an average of 80 µSv per procedure and maximum doses of almost 700 µSv in two cases are worth mentioning. The average value decreases to 40 µSv per procedure if the two highest values are removed. These average and maximum values are of the same order of magnitude than those reported in other studies[5–10]. With an average workload of 400 procedures per year, the new limit of 20 mSv·y^{-1} to the eye lens recommended for these professionals can be exceeded if the use of the ceiling suspended screen is not improved or if protection goggles are not used. Although professionals declare to always use the protection screen, they may in some cases use it partially or incorrectly. The average dose could be lower if the protection screen was always used correctly during the full procedure. The maximum doses of 685 and 697 µSv measured with TLD (621 and 627 µSv with OSL), i.e. 6 % of the sample in this experience, were recorded in two complex procedures with dose area products of 550 and 249 Gy·cm^2, respectively. In both cases, complications in patient access did not permit to use the protection screen during the full procedure, and some cardiologists did not use goggles. These high-dose values are indicative of the magnitude of the doses that can be received at the lens of the eyes when protective screens are not being used during procedures. The use of goggles should be strongly recommended in such cases.

CONCLUSIONS

In this survey, OSL material has been proved to be appropriate for measurements of eye lens dose in single procedures in cardiac catheterisation laboratories. OSL offers advantages such as easy manipulation and reduced costs, but as its response has a strong dependence with radiation quality, in particular its response to highly filtered beams, a specific calibration coefficient for the specific energy range and work environment is needed.

The DoseAware and Thermo EPD electronic dosemeters provided satisfactory measurements of $H_p(10)$ over the lead apron, comparable to passive estimates. However, a poor correlation was observed when comparing chest dose measurements with eye lens doses during clinical procedures. Further investigations are needed.

In addition, the study highlights the potential risk of high eye lens doses run by interventional cardiologists unless they strictly follow radiation protection rules and use protection means properly. If both dose mean values and the use of ceiling suspended screens cannot be improved, goggles should be recommended, in particular for high workloads (several hundreds of procedures per year).

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