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Eye lens monitoring for interventional radiology personnel: dosemeters, calibration and practical aspects of $H_p(3)$ monitoring. A 2015 review

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Abstract

A thorough literature review about the current situation on the implementation of eye lens monitoring has been performed in order to provide recommendations regarding dosemeter types, calibration procedures and practical aspects of eye lens monitoring for interventional radiology personnel. Most relevant data and recommendations from about 100 papers have been analysed and classified in the following topics: challenges of today in eye lens monitoring; conversion coefficients, phantoms and calibration procedures for eye lens dose evaluation; correction factors and dosemeters for eye lens dose measurements; dosemeter position and influence of protective devices. The major findings of the review can be summarised as follows: the recommended operational quantity for the eye lens monitoring is $H_p(3)$. At present, several dosemeters are available for eye lens monitoring and calibration procedures are being developed. However, in practice, very often, alternative methods are used to assess the dose to the eye lens. A summary of correction factors found in the literature for the assessment of the eye lens dose is provided. These factors can give an estimation of the eye lens dose when alternative methods, such as the use of a whole body dosemeter, are used. A wide range of values is

found, thus indicating the large uncertainty associated with these simplified methods. Reduction factors from most common protective devices obtained experimentally and using Monte Carlo calculations are presented. The paper concludes that the use of a dosemeter placed at collar level outside the lead apron can provide a useful first estimate of the eye lens exposure. However, for workplaces with estimated annual equivalent dose to the eye lens close to the dose limit, specific eye lens monitoring should be performed. Finally, training of the involved medical staff on the risks of ionising radiation for the eye lens and on the correct use of protective systems is strongly recommended.

Keywords: eye lens monitoring, interventional radiology, calibration, $H_p(3)$ monitoring practical aspects

(Some figures may appear in colour only in the online journal)

1. Introduction

The radiosensitivity of the eye lens is a well-known phenomenon (ICRP 2007, UNSCEAR 2011). Radiation exposure can cause injuries in the eye lens that may progress in the loss of the eye lens function caused by the formation of lens opacities and cataract. The ICRP Report 103 (2007) recommended a review of the non-cancerous effects of ionising radiation on normal tissues in the low dose range. This triggered many epidemiological studies (Worgul *et al* 2007, Chodick *et al* 2008, Ciraj-Bjelac *et al* 2010, Rehani *et al* 2011, Vano *et al* 2010) which suggested that the threshold dose for the loss of the eye lens function could be lower than previously considered or that there is no threshold at all. For this reason ICRP report 118 (2012), set the threshold value for the absorbed dose to the eye lens at 0.5 Gy for acute or protracted exposures. Based on this, the ICRP have recommended that for occupational exposure a dose limit for the eye lens of 20 mSv in a year, averaged over defined periods of 5 years, should be applied, with no single year exceeding 50 mSv (ICRP 2011). The new limit is a substantial reduction of the previously recommended annual eye lens limit of 150 mSv. This raises serious questions and causes implications for workers occupationally exposed to radiation, especially in the medical field in the interventional personnel, since the number of fluoroscopically guided procedures has grown in the last decades (UNSCEAR 2010). In addition, this topic has become of concern for many national and international professional organisations which made an effort to analyse the implications and to provide an assessment of the impact of the implementation of the new dose limit (Bouffler *et al* 2012, Broughton *et al* 2013, Broughton *et al* 2015a). ICRP has already underlined the need for further collaboration, clarification and changes to working practices derived from this change (Boal and Pinak 2015, Bolch *et al* 2015, Broughton *et al* 2015b). Interventional cardiologists and radiologists, who are exposed to the scattered radiation from the patient, are among the professional groups that receive the highest doses to the eyes (Donadille *et al* 2011, Kim *et al* 2008).

Evidence on eye lens injuries associated with exposure to ionising radiation was firstly observed in the USA (Junk *et al* 2004), later in Latin America (Vano *et al* 2010) and Malaysia (Ciraj-Bjelac *et al* 2010). More recent studies were also performed in Finland (Mrena *et al* 2011), France (Jacob *et al* 2013) and in Latin America again (Vano *et al* 2013). Despite their methodological limitations, these studies demonstrated that interventional cardiologists and radiologists as well as nursing staff have an increased risk of lens opacities especially in cases where radiation protection tools are not in place or are not regulary used.

Before the reduction of the dose limit for the eye lens (ICRP 2011), eye lens dosimetry was seldom performed in practice for two reasons: firstly it was judged that, due to the high dose limit (150 mSv), whole body monitoring was sufficient to assure a reliable limitation of the eye lens in the case of most medical staff; and secondly, dedicated eye lens dosemeters calibrated in terms of the personal dose equivalent in depth of 3 mm, $H_p(3)$, were not commercially available.

To bridge the gap, many studies have explored alternative methods to assess the dose to the eye lens. Some of the approaches were based on the correlation between the eye lens doses with patient dose as it is recorded by the Kerma Area Product (KAP) values (Buls *et al* 2003, Vano *et al* 2009, Donadille *et al* 2011, Kim *et al* 2008, Efstathopoulos *et al* 2011, Bor *et al* 2009, Dauer *et al* 2010, Martin 2011, Antic *et al* 2013) in order to have a first estimation of the dose delivered to the eye lens of the operator without using an extra dosemeter. On the other hand, other researchers have tried to find a correlation between the eye lens dose and doses recorded by dosemeters worn on various parts of the body (Clerinx *et al* 2008, Martin 2009, Krim *et al* 2011, Sanchez *et al* 2010, Farah *et al* 2013). The idea was to use the whole body or even the extremity dosemeters to evaluate the eye lens dose. However, the practices concerning the number and position of the whole body dosemeters vary from country to country and from operator to operator.

Regardless the methodological approach, the aim of all the above mentioned studies was to focus on the professional groups who are at excess risk due to the increased eye lens doses as well as to contribute to the improvement of the radiation protection for these professional categories. Following the adoption of the new dose limit, a guidance for the IAEA Member States about implications of the new dose limit for the eye lens was developed (IAEA 2013).

The present paper provides a review of the current situation on the implementation of eye lens monitoring in the interventional radiology and cardiology (IC/IR) workplaces as well as operating rooms where fluoroscopy units are used, related to the available types of eye lens dosemeters and the respective calibration procedures including the operational quantities, the respective conversion coefficients and the phantoms that have been developed. Practical aspects on the eye lens monitoring arrangements are also given.

2. Challenges of today in eye lens monitoring

A very few studies have addressed the importance of eye lens monitoring since the early 90s (Janssen *et al* 1992). In 2000, ICRP in publication 85 (ICRP 2000) highlighted the risk of eye lens injuries to physicians and staff performing interventional procedures and recommended to wear an additional dosemeter at collar level, above the lead apron to have an indication of the head (eye) dose. The question of how to estimate the doses to the eye lens employing a single dosemeter was also investigated by Clerinx *et al* (2008). They proposed to use an unprotected collar dosemeter, calibrated in terms of $H_p(0.07)$, and then apply a correction factor of 0.75 to the evaluated dose so as to estimate the corresponding eye lens dose. A similar approach was followed by Martin and Magee (2013) for monitoring the exposed personnel, but they suggested using a head band dosemeter or a dosemeter attached to the protective eyewear to get more accurate results, in particular when the operator appears likely to reach the public dose limit of 15 mSv (European Commission 2014).

The ideal situation in eye lens monitoring would be the assessment of the personal dose equivalent at depth 3 mm, $H_p(3)$, without seriously underestimating it. The definition of $H_p(3)$ is based on the assumption that the absorbed dose at depth 2.5–3.5 mm should give a reasonable measure of the mean dose for the variety of eye and irradiation geometries (Charles and

Brown 1975). The real challenge in the field is either to use an extra eye lens dosemeter properly calibrated in terms of $H_p(3)$, or to use the patient dose values or other personal dosemeters already worn by the operators and calibrated in other dosimetric quantities and estimate the eye lens dose using a correlation coefficient. Both of the solutions present problems that have to be solved. In the first situation, an extra dosemeter is not always practical for the medical staff who may already wear other dosemeters—whole body ones above and/or below the lead apron, extremity dosemeters, etc. Moreover, the eye lens dosemeter has to be worn as close as possible to the eye lens in order to reduce the inaccuracy of eye lens dose estimate. This may not be comfortable for the operator who usually wears eye lens glasses for protection. Another issue is where to position the dosemeter: outside or inside the lead glasses?

As regards the use of indirect measurements and a correlation coefficient, there are many studies which have already shown the poor correlation between the eye lens dose and the KAP values (Antic *et al* 2013). The relationship is situation dependent and therefore, no general rule can be drawn in order to have a standard procedure of estimating the eye lens dose via this dosimetric quantity. The estimation of the eye lens dose from the dosemeters worn on other parts of the body has also been studied (Farah *et al* 2013) but a high spread of the correlation coefficients was also found for the different setups that were investigated.

3. Operational quantities

According to ICRU (1992) $H_p(3)$ is the recommended operational quantity for eye lens dosimetry. The first definition appeared (with the name '*Individual Dose Equivalent, superficial* $H_s(3)$') in the 1980s in the ICRU report 39 (ICRU 1985) where the *Individual Dose Equivalent, superficial* $H_s(d)$ was introduced also for the eye lens. The same paragraph (3.2.2) contains also the origin of its subsequent disregard because it is mentioned that: *'In most exposure conditions, the dose equivalent limit for the lens of the eye will not be exceeded when the limits for the effective dose equivalent and the dose equivalent to the skin are not exceeded. Therefore, monitoring of* $H_s(3)$ *will be required only in unusual circumstances'*. That statement, probably, originated the belief that the dose limit for the eye can be exceeded '*only in unusual circumstances'* and radiation protection monitoring can be performed employing $H_p(10)$ and $H_s(0.07)$. The annual limit for the eye lens, 150 mSv versus the 50 mSv for the effective dose at that time (ICRP 1977) later reduced to 20 mSv (ICRP 2007), made those assumptions reliable, avoiding the need of a more accurate dosimetry for that tissue. As a result of that situation, no conversion coefficients were provided in ICRP or ICRU official documents for $H_p(3)$, with the only exception of those for electrons (ICRP 1996, ICRU 1998), because of the fact that electron tracks in tissue can be longer than 70 μm and therefore, they can deposit their energy further from the external surface.

The situation of the disregard of the personal dose equivalent, $H_p(3)$, was maintained as such in the 2007 recommendations of ICRP (2007).

The scene suddenly changed when a number of epidemiological studies (Ciraj-Bjelac *et al* 2010, Vano *et al* 2010, Rehani *et al* 2011, Chodick *et al* 2008, Worgul *et al* 2007) showed that the previously assumed 2 Gy threshold for cataract induction was probably too high. Consequently, in April 2011 the ICRP published a statement on tissue reactions (ICRP 2011) proposing to lower the limit in planned exposure situations for the eye lens. In the Publication 116 (ICRP 2010), inverting the previous approach, ICRP provided special considerations for assessing the absorbed dose to the eye lens and published a set of conversion coefficients, eye lens tissue absorbed dose per unit fluence, for photons, electrons and neutrons. A special analytical model reproducing the internal structure of the eye (Behrens and Dietze 2010) was used.

This was the only tissue/organ that ICRP decided to represent differently, since it was assumed that the voxel representation was inadequate to describe the internal structure of the eye.

A considerable discussion was initiated within the radiation protection community. A number of studies have been initiated in order to address the problem of eye lens dose evaluation. Appropriate dosemeters are being developed in order to measure the eye lens dose (Bilski *et al* 2011, Gilvin *et al* 2013) and studies have been performed on the use of extremity dosemeters calibrated on rod phantoms or dosemeters calibrated on the $H_p(0.07)$ quantity (Vanhavere *et al* 2011, Behrens *et al* 2012) considering that for photon beams, which is the case in interventional radiology, $H_p(10)$ and $H_p(0.07)$ can provide a conservative estimate of $H_p(3)$ (IAEA 2013).

The bottom line, however, is that, for the estimation of the eye lens doses the most appropriate quantity is the personal dose equivalent in the depth of 3 mm, $H_p(3)$. This is the quantity set by the scientific community for the limitation of the eye lens doses. When other quantities are used the overall uncertainty in the estimation of the eye lens dose may be higher than expected.

4. Conversion coefficients, phantoms and calibration procedures for eye lens dose evaluation

The above considerations gave a new motivation to study the conversion coefficients for $H_p(3)$ that were missing, and still are, apart for electrons, from the official ICRU and ICRP publications.

At present, conversion coefficients can be found in scientific literature, but not in the reports of the relevant international organisations. It was Grosswendt that originally calculated $H_p(3)$ per unit air kerma (Grosswendt 1990), for monoenergetic expanded and aligned beams, for four specific geometries: the ICRU cube of $30 \times 30 \times 30\,\mathrm{cm}^3$, 4 elements ICRU tissue, $1\,\mathrm{g\,cm}^{-3}$ density (later substituted by the slab of $30 \times 30 \times 15\,\mathrm{cm}^3$); the ICRU seminfinite slab of 30 cm thickness; the slab PMMA $30 \times 30 \times 15\,\mathrm{cm}^3$ and the PMMA semi infinite slab of 15 cm thickness. Grosswendt completed the series with angular evaluations (Grosswendt 1991) employing PMMA and ICRU tissue slab phantom ($30 \times 30 \times 15\,\mathrm{cm}^3$) and ISO x-ray series (Grosswendt 1992). A similar evaluation of the operational quantity $H_p(3)$, in the ICRU slab, was also performed by the group of Till *et al* (Till *et al* 1995). These sets of conversion coefficients were recently extended for high energy photons and electrons, up to1 GeV, by Veinot and Hertel (Veinot and Hertel 2011, Veinot and Hertel 2012, Veinot 2013).

ICRU considered a good approximation to employ a slab phantom of $30 \times 30 \times 15\,\mathrm{cm}^3$ for the representation of the human torso (ICRU 1992). ISO 12794 (ISO 2000), the actual reference for calibration of 'Individual thermoluminescence dosemeters for extremities and eyes', published in 2000, suggests the use of the conventional $30\mathrm{x}30\mathrm{x}15\,\mathrm{cm}^3$ water filled PMMA slab, already employed for the calibration of whole body dosemeters in terms of $H_p(10)$, in order to calibrate dosemeters in terms of $H_p(3)$. The more recent IEC 62387 standard (IEC 2012), that applies to all types of passive dosimetry systems used for the measurement of the personal dose equivalents and the ambient dose equivalent, $H^*(10)$, provides requirements for the $H_p(3)$ but does not recommend any specific calibration phantom.

However, the question that comes to the scene is whether the slab phantom can be used for the simulation of the head. From a general point of view, it should be underlined that a dosemeter calibrated in terms of $H_p(3)$ requires a proper calibration phantom able to reproduce the characteristics of the part of the body that the dosemeter is worn, i.e. human head in the case of eye lens dosemeters.

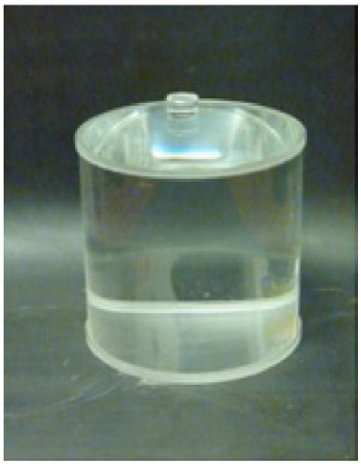

Figure 1. The phantom for the calibration of eye lens dosemeters proposed by the ORAMED project.

During the ORAMED project (Vanhavere *et al* 2012) a new calibration phantom, a cylinder 20 cm height, 20 cm diameter, water filled, with 0.5 cm PMMA walls (Gualdrini *et al* 2011, Bordy *et al* 2011a) was suggested (see figure 1). The same phantom has also been used for eye lens dosemeter calibration by other research groups (Gilvin *et al* 2013, Eakins *et al* 2014, Pirchio, 2014).

A conservative calibration approach was suggested by Behrens *et al* (2012) who investigated whether dosemeters designed for the quantity $H_p(0.07)$, calibrated on a rod phantom can also be worn on the head (close to the eyes) and provide adequate assessment of the eye lens dose. Different types of partial body dosemeters were irradiated at different photon energies on both a rod and a slab phantom. It turned out that their response values were within ±5%, independent of the phantom, if the quantity for the respective phantom is used. The authors concluded that extremity dosemeters designed for the quantity $H_p(0.07)$ and calibrated on a rod phantom may be worn on the head and used to monitor the eye lens dose from photon radiation, through the measurement of $H_p(0.07)$ on the head. It is important to highlight that these assumptions were drafted before ICRP published the new statement on eye lens tissue radiosensitivity and introduced the reduced dose limit (ICRP 2011).

On the basis of these evaluations, Behrens (2012a) investigated whether the quantity $H_p(3)$, when defined on slab or cylinder calibration phantom, can adequately represent the eye lens dose (or a conservative estimate of it). It was concluded that for photons both phantoms are well suited, except for angles higher than 75° for which cylinder phantom provides better results. Such effect, mainly geometrical, is obviously less important for electrons for which both phantoms behave in a similar way for the various irradiation angles (Ferrari and Gualdrini 2012).

In 2012, Behrens (2012b) published a set of conversion coefficients for $H_p(3)$, per unit air kerma, for the cylinder phantom for x- and gamma radiation qualities defined in ISO 4037 (ISO 1999) for the calibration of personal and area monitor dosemeters.

It should be mentioned that there is a draft ISO standard (ISO 15382), 'Radiological protection—Procedures for monitoring the dose to the lens of the eye, the skin and the extremities', dealing with the tasks of eye lens monitoring and which includes recommendations of calibration procedures (phantoms and conversion coefficients) and type testing.

To summarize the above considerations it has been demonstrated that for photon beams the use of the $H_p(0.07)$ quantity can be adequate when it is derived by the use of the rod phantom. In this case, an additional component to the overall uncertainty of dose measurement should be considered. However, since the conversion coefficients for $H_p(3)$ are now available in the literature (Behrens 2012b), the best estimate of eye lens can be performed by employing directly the measurement of a dosemeter calibrated for $H_p(3)$ on a slab, or even better, on a cylindrical phantom.

5. Dosemeters for eye lens dose measurements

For individual monitoring purposes the characteristics of a suitable eye lens dosemeter should be: the ability to measure the appropriate operational quantity, a suitable response with acceptable accuracy to a variety of angles and energies encountered in the scattered field of workplaces and finally being comfortable, as its position is usually as close as possible to the eye of the operator. Another factor that should be kept in mind is the use of the dosemeter in sterile environment, so the possibility of its sterilisation would be an advantage for its use in interventional rooms.

Nowadays, many services use eye lens dosemeters. The basic structure of the dosemeter is the same: a thermoluminescent detector, sufficient filtration and a holder to help the dosemeter to be placed as close as possible to the eye lens. The supports of the dosemeters vary a lot and depend on how convenient they are when worn by the operators. As the number of the different types of eye lens dosemeters is growing an intercomparison exercise was organized by EURADOS (Clairand *et al* 2015) in order to assess the capabilities of the eye lens dosemeters currently in use in Europe. In the exercise, 20 services participated from 15 European countries (figure 2). As it can be seen from the figure some of the services use a head band (no 4,5,6 and 7); other dosemeters can be clipped on the radiation protection or vision glasses (no 1 and 2); most of them use one detector, while others use two (no 3), or three detectors (no 7); finally some of them are extremity dosemeters which have been modified (no 4,8,9 and 10).

With regard to the type testing of the dosimetry systems based on passive dosimetry there are two international standards (IEC 2012, ISO 2000). Their use for the eye lens dosimetry systems is discussed by Bordy *et al* (2011b). It is important that dosemeters intended for the eye lens dose assessment in interventional workplaces are adequate in terms of detection threshold, energy and angle response.

Geber *et al* (2011) showed that the dosemeter should be attached as close as possible, to the eye because, if positioned further away, it could underestimate the eye lens dose as much as 45%. Moreover, it has been shown that the use of protective eyewear may provide a false sense of protection when radiation does not strike from the front direction, since scattered radiation can slip through the gap between the cheek and the eyewear (Geber *et al* 2011, McVey *et al* 2013, Koukorava *et al* 2014). Furthermore, the dimensions of an eye lens dosemeter should be as small as possible and the material should be, as close to soft tissue as possible.

The task of the design of a proper dosemeter was investigated within the ORAMED project (Vanhavere *et al* 2011). The result of that study was the first eye lens dosemeter (EYE D™ Radcard, Poland) especially dedicated to measurements of $H_p(3)$ (Bilski *et al* 2011). EYE D consists of a LiF : Mg,Cu,P thermoluminescent pellet and an optimised polyamide capsule. The dosemeter can undergo cold sterilisation. The test measurements and Monte Carlo calculations of the photon energy response and angular response produced very satisfactory results: all values are within about 20% around unity (with respect to Cs-137 beam quality).

Another case of passive eye lens dosemeter is the one used by the Public Health England's (PHE's) Centre for Radiation, Chemical and Enviromental Hazards (Gilvin *et al* 2013). The

Figure 2. Some of the dosemeters that participated in the EURADOS eye lens dosemeter intercomparison.

Personal Dosimetry Service (PDS) of PHE decided to use existing resources in order to monitor the eye lens doses. The dosemeter includes a polytetrafluoroethylene (PTFE) filter of 1.5 mm thickness. The filtration is equivalent to 3.3 mm of tissue, closely matched to the definition of $H_p(3)$ (ICRU 1993). The dosemeter element is the Harshaw EXTRAD™, as the one used in the PHE finger. The EXTRAD™ element and the PTFE filter are heat-sealed together in a polyvinyl chloride (PVC) pouch, which is part of a PVC head band. The PHE eye dosemeter was type tested and passed all the tests described in the relevant ISO standard (ISO 2000) and in the ORAMED recommendations (Bordy *et al* 2011b).

Similarly, ENEA, the Radiation Protection Institute in Bologna (Italy), considered the use of an extremity dosemeter to be worn on the forehead to measure $H_p(3)$ (Mariotti *et al* 2011). The extremity dosemeter used consists of a LiF : Mg,Cu,P thermoluminescent pellet (210 mg cm^{-2} thick) glued on a kapton strip identified by a bar code covered by a 0.1 mm thick protective layer. A first practical simple solution to modify the dosemeter filter is to wear the dosemeter on the reverse side so that the envelope thickness becomes 0.85 mm. The response of this converted dosemeter is within −30 and +20 % in the energy and angle range considered.

Finally, another type of eye lens dosemeter described in the literature was designed and calibrated at the National Atomic Energy Commission of Argentina to evaluate $H_p(3)$ (Pirchio *et al* 2014). It consists of ^{7}LiF: Mg, Ti type thermoluminiscent detectors, with dimensions of 3.2 mm × 3.2 mm × 0.89 mm. A special PMMA holder is designed to contain the TLDs. The holder is 40 mm long and 10 mm wide. One end of the capsule has the chip inside, covered by a lid.

The thickness of the PMMA in front of the thermoluminescent pellet is equal to 3 mm of tissue. The detection limit dose is 0.1 mSv and the reading uncertainty is 10% with a coverage factor of 2.

Active dosemeters are mainly used to identify methodologies to improve radiation protection practices. At the moment no dedicated active dosemeters for the evaluation of the personal dose equivalent of $H_p(3)$ exist. The active personal dosemeters currently available have been used for the evaluation of the eye lens doses in some specific studies (Sanchez *et al* 2010) but not in routine basis mainly due to their size or extra cost. Furthermore, no specific standard exist for the type testing of active dosemeters in relation to the quantity $H_p(3)$. Previous studies highlighted the importance of checking their performance in interventional workplaces prior their use (Clairand *et al* 2011, Struelens *et al* 2011).

6. Dosemeter position

As it was shown in the ORAMED project (Carinou *et al* 2011) eye lens doses can be important in IC/IR and therefore monitoring is necessary to show compliance with the new eye lens dose limit of 20 mSv which is adopted by the IAEA Basic Safety Standards (IAEA 2014) and the European Council (European Commission 2014) and it is about to be transposed into legislation in every country, which is member of the European Union.

If a dedicated eye lens dosemeter is used then, following what has been discussed in the previous paragraphs, the best position of the eye lens dosemeter in routine monitoring is as close as possible to the eye lens, in the direction towards the x-ray tube. However, from the literature review it is evident that many measurements have been performed using the dosemeters in other locations such as above or between the eyes (McVey *et al* 2013, Vanhavere *et al* 2011). When lead glasses are worn it is expected to calculate the 'real' dose to the eye, so the eye lens dosemeter should be worn behind the glasses in order not to use reduction factors for dose calculation. However, this is not always practical, and for this reason, the dosemeter is often worn outside the lead glasses with either an appropriate filter that simulates the reduction of dose due to the lead glasses, or else, the dose is calculated by using a relevant reduction factor. Care should be taken so as not to underestimate the dose and to take into account all the relevant factors when the uncertainty is calculated.

As it is indicated in Carinou *et al* (2014) and Clerinx *et al* (2008), instead of the use of a specific dosemeter many workers use a whole body dosemeter worn on the collar and the eye lens dose can be assessed with a correlation coefficient. In table 1 the mean values of the ratios of the eye lens doses to the doses recorded on the unprotected thyroid or the chest region are shown for various interventional procedures encountered in the literature. These numbers refer to mono plane systems.

Table 1 indicates that in most of the cases the doses measured at the thyroid and chest region are higher than the eye lens doses. The cases where the ratios of eye lens to thyroid or chest doses are higher than 1 present some differences from the rest of the studies. In the case of Efstathopoulos *et al* (2006), the ratio is 1.86 but it refers to electrophysiology operators using bilateral femoral access. Moreover, the cases of Buls *et al* (2002) and Sulieman *et al* (2008) with correlation ratios of 1.22 and 1.46 respectively, refer to operators that use overcouch setups, so maybe this is a reason for indicating that the eye lens doses are higher than those measured at thyroid level. Furthermore, most of the results from Olgar *et al* (2009) with ratios of more than 1, refer to overcouch setups. Finally the ratio of 1.45 resulted from the measurements of Bor *et al* (2009) is calculated from measurements with high spread ranging from 0.5 to 2.8. This range is probably due to the fact that 6 out of 9 cardiologists participating in the study were assisting cardiologists, for whom the geometry setup is different due to

Table 1. Ratio of eye lens to thyroid doses for various interventional procedures encountered in the literature.

Ratio (eye lens/thyroid)	Procedure	Reference
0.87	Interventional cardiology and radiology procedures	Vañó *et al* (1998)
0.68	Interventional cardiology and radiology procedures	Häusler *et al* (2009)
0.73	Interventional cardiology and radiology procedures	Covens *et al* (2007)
0.44	Interventional cardiology and radiology procedures	Kicken *et al* (1999)
1.45	Interventional cardiology	Bor *et al* (2009)
0.49	Interventional cardiology pediatriac procedures	Li *et al* (1995)
0.54	Interventional cardiology procedures	Janssen *et al* (1992)
1.86	Electrophysiology procedures	Efstathopoulos *et al* (2006)
0.75	Interventional radiology, Monte Carlo simulations	Clerinx *et al* (2008)
1.22	ERCP (overcouch tube)	Buls *et al* (2002)
1.07	Orthopaedic procedures, ERCP	Olgar *et al* (2009)
0.54	Nephrolithotomy	Safak *et al* 2009
1.46	Hysterosalpingography (overcouch tube)	Sulieman *et al* 2008
0.38	Vertebroplasty	Harstall *et al* 2005
0.88	CT guided interventions	Nico Buls *et al* 2003
Ratio (eye lens/chest)	Procedure	Reference
0.52	Electrophysiology procedures	Efstathopoulos *et al* (2006)
0.75	Interventional cardiology	Lie *et al* (2008)
0.74–1.77	48 measurements for left and right eye and left middle and right position of the personal dosemeter	Farah *et al* (2013)

their possible shielding from the main operators. Finally the ratios indicated in the study of Farah *et al* (2013) also include values higher than 1, but in these cases no ceiling suspended shields were used. The study showed that eye lens dose presents the highest correlation with the personal dose equivalent in depth 10 mm, $H_p(10)$, measured on the left side of the phantom at the level of the collar, although this correlation implicates high spreads (41%).

The results summarized in table 1 support the recommendation proposed by Martin (2011) to use as indicator of the order of magnitude of the eye lens dose an unprotected dosemeter situated at the thyroid region, applying a factor of 0.75. This factor is consistent with the results from Monte Carlo simulations by Clerinx *et al* (2008). However, table 1 data also warn about the large variability of the ratios which may vary from 0.38 to 1.86. Moreover, table 1, as well as the review performed by Martin (2011), show that most of the available studies come from interventional cardiology procedures and that the knowledge from other types of studies is limited.

The use of dosemeters worn on other parts of the body such as the thyroid collar or at the chest level outside the lead apron can be a valuable tool for the estimation of the eye lens dose for investigative reasons or for retrospective calculations. However, the ratio of the eye lens dose to the dose at neck or chest level is extremely practice and position dependent and increases the uncertainty of dose assessment. Therefore, care should be taken if the dose calculated using this method reaches the investigation level or even the dose limit. At this point more accurate evaluations should be performed.

7. Correction factors

There are cases where the dosemeter is not worn close to the eye lens, or it is worn at the wrong side as regards the x-ray tube, or not worn behind the protection. For all these cases correction factors should be applied so as to convert the dose evaluated by the dosemeter to the real eye lens dose received by the operator. These correction factors can be obtained either by measurements or Monte Carlo calculations simulating the radiation setups of the interventional suites. Other factors that should be taken into account, by investigating the respective personnel, is the percentage of time using specific angulation, the time interval that the dosemeter had been worn in other positions than the one which was intended to, the thickness and shape of the eye lens protection used and the position of the operator respectively to the x-ray tube.

8. Influence of protective devices: measurements and simulations

The protection devices that are used for reducing the upper body irradiation of the operator are the shielding suspended screens, the lead drapes, the use of lead glasses or head mask, the patient protection pad, the mobile protection shields where the operator can stand behind it and the radiation protection cabine. Most of the literature findings that refer to the eye lens dose reduction and, more specifically, to the use of eye lead glasses and ceiling suspended shield as well as the combination of them have been summarised in table 2. As it can be seen from the Table there is a wide range in the reduction factors that had been calculated by the various researchers; this may be due to the fact that these factors are influenced by other parameters such as the distance of the operator from the patient, the orientation of the operator's head (determined by the position of the screens in the room), the distance of the image detector from the patient, the beam collimation, the tube configuration, the tube voltage and filtration, the height of the operators, the complexity of the procedure. It should also be stressed here that the way of the calculation of these factors (either simulations or measurements on phantoms or operators) affects the results. The simulations and the measurements performed on phantoms are static and take into account a standard geometry whereas the measurements on operators can include other factors, such as the fact that the protection measures are not properly used. Moreover, when the eye lens goggles do not have side protection then radiation slips from the side of glasses in the gap between the glasses and the head and therefore the protection is not the most suitable.

The three major components of radiation that reach the eye lens when lead glasses are worn are: the radiation that penetrates the radioprotective material, the radiation that reaches the eye lens from the partly uncovered parts and the photons that are back scattered to the eye lens from the operator's head. Therefore, the main aim of the use of the lead glasses is to reduce the first two components by using the appropriate thickness and shape. From table 2 it is seen that the eye lens glasses can reduce the eye lens dose from 5 to 33 times with the most frequent range between 8 and 10. Moreover, Sturchio *et al* (2013) underlined the influence of the head orientation towards the radiation source as well as the importance of the proper fit of the eyewear glasses to the face shape. The efficacy of the lead glasses depends on this factor as well. Van Rooijen *et al* (2014) also stressed the importance of the orientation of the operator's head to the x-ray tube in the eye lens dose reduction. As the operator's head orientation depends on the position of the monitors in the x-ray room, this consideration should be taken when decision on position of the monitors in the interventional suite is made. Furthermore, Koukorava *et al* (2014) highlighted the importance of how the protective equipment is used. The study suggests the medical staff involved in interventional procedures to select their protective

Table 2. Reduction factors for various factors affecting the eye lens dose.

Factor affecting the eye lens dose	Reduction factor	Remark	Way of calculation	Reference
Lead glasses	5		Measurements on phantom and simulations	McVey *et al* (2013)
Lead glasses	8–10	Depending on the orientation of the operator's head and type of glasses	Measurements on phantom	Van Rooijen *et al* (2014)
Lead glasses	5–10	Depending on the position of the operator and beam angulation.	Measurements on phantom	Thornton *et al* (2010)
Lead glasses	8		Measurements	Moore *et al* (1980)
Lead glasses	8–10		Measurements	Vanhavere *et al* (2011)
Lead glasses	33	Fluoroscopy, cine cardiac imaging and digital subtraction angiography	Measurements with phantoms	Vano *et al* (2008)
Lead glasses	10	Various thicknesses of glasses, and positions of the operator	Simulations	Koukorava *et al* (2014)
Ceiling suspended screen	5.7		Measurements on phantom	van Rooijen *et al* (2014)
Ceiling suspended screen	2.3	Average of 25 setups	Simulations	Koukorava *et al* (2014)
Ceiling suspended screen	3		Measurements on operators	Vañó *et al* (1998)
Ceiling suspended screen	1.3–14	Depending on beam angle and position of the shield	Simulations	Koukorava *et al* (2011)
Ceiling suspended screen	30	Depending on tube orientation	Measurements with phantoms	Galster *et al* (2013)
Ceiling suspended screen	33	With the assumption that the screen is not always used throughout the procedure	Measurements with phantoms	Vano *et al* (2008)
Ceiling suspended screen	20	Depending on angle of incidence and body height	Measurements (Scatter entrance skin air kerma to the operator position)	Kuon *et al* (2003)
Ceiling suspended screen	1.5–4		Measurements	Vanhavere *et al* (2011)
Ceiling suspended screen	2–7		Measurements and simulations	Carinou *et al* (2011)
Lead drapes	5–25		Measurements on phantoms	Thornton *et al* (2010)
Combination of lens glasses and lead drapes	25–143		Measurements on phantoms	Thornton *et al* (2010)

eyewear individually, based on how well they fit their face in order to minimise the air gaps between the face and the eyewear, since a large amount of scattered radiation reaches both eyes through these gaps.

The ceiling suspended screen can lower the dose from 1.2 to 33 times with the most frequent range between 3 and 11 as already stressed in the review by Martin (2009). Finally the lead drapes placed between the patient and the operator—taking care so as not to be inside the primary beam- can reduce the eye lens dose as much as 25 times, whereas the combination of glasses and lead drapes can really reduce doses of 2 orders of magnitude (Thornton 2010).

One of the parameters that affects the eye lens dose can be the proper use of radiation protection equipment. The interventional staff should be aware of the risks and the proper use of radiation protection equipment via specific training programmes (Broughton *et al* 2013). However, awareness on eye lens protection methods and related risks is usual raised in the framework of dedicated measurements (Carinou *et al* 2014).

In summary, the influence of the eye lead glasses and the ceiling suspended screen is very important in reducing the doses. However, there is a wide range of reduction factors in the literature which show that there are also other influence parameters that affect the eye lens doses. When trying to assess the eye lens dose for retrospective or designing reasons, the most conservative value should be used, unless the whole setup is known and fully described in the literature. In such a case the reduction factor calculated by previous researchers can be used. Emphasis should be given in the analysis of the uncertainty.

9. Conclusions

There is a variety of eye lens dose measurements in the literature that has been triggered from the reduction of the eye lens dose limit. The present study aimed to underline specific practical aspects of eye lens dosimetry concerning the topics of the calibration of the eye lens dosemeters, the dosemeter position and the eye lens radiation protection measures.

The appropriate operational quantity for the eye lens monitoring is $H_p(3)$ and, even when a different quantity is used to make an estimate of this value—such as the case of the use of a whole body dosemeter situated on the thyroid collar, calibrated in terms of $H_p(10)$– the results of the eye lens monitoring should be expressed in terms of $H_p(3)$. Dosemeters are now available and, probably, new dosemeters will be produced soon, depending on market issues. Calibration can be performed using the conventional slab phantom, if large irradiation angle can *a priori* be excluded; otherwise, the cylinder phantom of 20 cm in diameter and 20 cm high should be preferred.

When a decision to perform routine eye lens monitoring has been made, a specific eye lens dosemeter should be chosen and positioned as close as possible to the eye, and at the side of the operator that is closest to the x-ray tube. Specific correction factors should be applied when the eye lens dosemeter is not worn behind the glasses, or on the most exposed side of the head. Care should be taken so as to ensure that the dosemeter is comfortable for the operator and that it does not draw his/her attention from his/her tasks.

In the case that an eye lens dosemeter is not worn and the eye lens dose is needed to be estimated, then the dosemeter worn outside the thyroid collar or the lead apron can be used. When, as recommended by ICRP (2000), the effective dose is estimated by the use of the so-called ‘double dosimetry’, using one dosemeter below and another over the lead apron, the unprotected dosemeter can provide a first estimation of the eye lens dose. However, attention should be drawn to ensure that the worker does not mix up the dosemeters. There is a wide range of correlation coefficients for the estimation of the eye lens dose from the values of the thyroid and chest dosemeter depending on the setup of the radiological procedure and the exact position of the dosemeter. The value of 0.75 (thyroid to eye lens dose correlation coefficient) seems adequate. However, due to the observed wide range of values, specific workplace

or individual values should be calculated for a better estimation of the eye lens dose. In particular, this should be considered when estimated annual doses are close to the dose limit.

More important than the monitoring is the use of protective means that can reduce the eye lens dose significantly. According to the literature findings the eye lens glasses can reduce the eye lens dose from 8 to 10 times (most frequent range) while the ceiling suspended screen from 3 to 11 times (most frequent range). The use of ceiling suspended screen should be preferred since it can also protect the upper part of the body. However, there are cases, such as many electrophysiology procedures, where the screen cannot be used; in these cases the eye lens glasses are recommended and offer the desired eye lens protection. The use of lead drapes that reach the patient are also very effective. As radiation dose to the eye lens depends on the operator's head orientation with respect to the radiation sources and the latter is determined by the position of the monitors in the room, the overall layout of the interventional theatre should be carefully designed in order to maximize efficiency of the available protection tools, both in terms of design and position during interventional procedures.

In conclusion, the medical staff in IC/IR who are in a programme of eye lens monitoring should preferably wear specific eye lens dosemeters, properly calibrated and placed in the nearest possible position to the eye lens. On the basis of protection, all the necessary measures should be taken in order to reduce the eye lens doses. Finally, specific training on the radiation risks and the proper use of the various radiation protection measures especially for the eye lens are highly encouraged. It is of utmost importance to communicate to the interventional medical staff the challenges in the nowadays eye lens radiation protection.

References

Antic V, Ciraj-Bjelac O, Rehani M, Aleksandric S, Arandjic D and Ostojic M 2013 Eye lens dosimetry in interventional cardiology: results of staff dose measurements and link to patient dose levels *Radiat. Prot. Dosim.* **154** 276–84

Behrens R 2012a On the operational quantity $H_p(3)$ for eye lens dosimetry *J. Radiol. Prot.* **32** 455–64

Behrens R 2012b Air kerma to $H_p(3)$ conversion coefficients for a new cylinder phantom for photon reference radiation qualities *Radiat. Prot. Dosim.* **151** 450–5

Behrens R and Dietze G 2010 Monitoring the eye lens: which dose quantity is adequate? *Phys. Med. Biol.* **55** 4047–62

Behrens R, Engelhardt J, Figel M, Hupe O, Jordan M and Seifert R 2012 $H_p(0.07)$ photon dosemeters for eye lens dosimetry: calibration on a rod versus a slab phantom *Radiat. Prot. Dosim.* **148** 139–42

Bilski P *et al* 2011 The new eye-DTM dosemeter for measurements of $H_p(3)$ for medical staff *Radiat. Meas.* **46** 1239–42

Boal T J and Pinak M 2015 Dose limits to the lens of the eye: international basic safety standards and related guidance *Ann. ICRP* **44** 112–7

Bolch W E, Dietze G, Petoussi-Henss N and Zankl M 2015 Dosimetric models of the eye and lens of the eye and their use in assessing dose coefficients for ocular exposures *Ann. ICRP* **44** 91–111

Bor D, Olgar T, Onal E, Caglan A and Toklu T 2009 Assessment of radiation doses to cardiologists during interventional examinations *Med. Phys.* **36** 3730–6

Bordy J M, Gualdrini G, Daures J and Mariotti F 2011a Principles for the design and calibration of radiation protection dosemeters for operational and protection quantities for eye lens dosimetry *Radiat. Prot. Dosim.* **144** 257–61

Bordy J M, Daures J, Denozière M, Gualdrini G, Ginjaume M, Carinou E and Vanhavere F 2011b Proposals for the type tests criteria and calibration conditions of passive eye lens dosemeters to be used in interventional cardiology and radiology workplaces *Radiat. Meas.* **46** 1235–8

Bouffler S, Ainsbury E, Gilvin P and Harrison J 2012 Radiation-induced cataracts: the health protection agency's response to the ICRP statement on tissue reactions and recommendation on the dose limit for the eye lens *J. Radiol. Prot.* **32** 479–88

Broughton J, Cantone M C, Ginjaume M and Shah B 2013 Report of task group on the implications of the implementation of the ICRP recommendations for a revised dose limit to the lens of the eye *J. Radiol. Prot.* **33** 855–68

Broughton J, Cantone M C, Ginjaume M and Shah B 2015a Implications of the implementation of the revised dose limit to the lens of the eye: the view of IRPA professionals *Ann. ICRP* **44** 138–43

Broughton J, Cantone M C, Ginjaume M, Shah B and Czarwinski R 2015b Implications in dosimetry of the implementation of the revised dose limit to the lens of the eye *Radiat. Prot. Dosim.* **164** 70–4

Buls N, Pagés J, de Mey J and Osteaux M 2003 Evaluation of patient and staff doses during various CT fluoroscopy guided interventions *Health Phys.* **85** 165–73

Buls N, Pages J, Mana F and Osteaux M 2002 Patient and staff exposure during endoscopic retrograde cholangiopancreatography *Br. J. Radiol.* **75** 435–43

Carinou E *et al* 2011 Recommendations to reduce extremity and eye lens doses in interventional radiology and cardiology *Radiat. Meas.* **46** 1324–29

Carinou E, Ginjaume M, O'Connor U, Kopec R and Sans Merce M 2014 Status of eye lens radiation dose monitoring in European hospitals *J. Radiol. Prot.* **34** 729–39

Charles M W and Brown N 1975 Dimensions of the human eye relevant to radiation protection *Phys. Med. Biol.* **20** 202–18

Chodick G *et al* 2008 Risk of cataract after exposure to low doses of ionizing radiation: a 20 year prospective cohort study among us radiologic technologists *Am. J. Epidemiol.* **168** 620–31

Ciraj-Bjelac O, Rehani M M, Sim K H, Liew H B, Vano E and Kleiman N J 2010 Risk for radiation-induced cataract for staff in interventional cardiology: is there reason for concern? *Catheter. Cardiovasc. Interv.* **76** 826–34

Clairand I *et al* 2011 Use of active personal dosemeters in interventional radiology and cardiology: tests in laboratory conditions and recommendations—ORAMED project *Radiat. Meas.* **46** 1252–7

Clairand I, Ginjaume M, Vanhavere F, Carinou E, Daures J, Denoziere M, Honorio da Silva E, Principi S and Van Rycheghem L 2015 First EURADOS intercomparison exersice of eye lens dosemeters for medical applications *Radical Prot. Dosim.* (doi:10.1093/rpd/ncv368)

Clerinx P, Buls N, Bosmans H and de Mey J 2008 Double-dosimetry algorithm for workers in interventional radiology *Radiat. Prot. Dosim.* **129** 321–7

Covens P, Berus D, Buls N, Clerinx P and Vanhavere F 2007 Personal dose monitoring in hospitals: global assessment, critical applications and future needs *Radiat. Prot. Dosim.* **124** 250–9

Dauer L T, Thornton R H, Solomon S B and St Germain J 2010 Unprotected operator eye lens doses in oncologic interventional radiology are clinically significant: estimation from patient kerma-area-product data *J. Vasc. Interv. Radiol.* **21** 1859–61

Donadille L *et al* 2011 Staff eye lens and extremity exposure in interventional cardiology: results of the ORAMED project *Radiat. Meas.* **46** 1203–9

Eakins J S, Baker S T, Gibbens N J, Gilvin P J, Hager L G and Tanner R J 2014 Monte Carlo modelling of 90Sr/90Y and 85Kr Beta Fields for $H_p(3)$ measurements *Radiat. Prot. Dosim.* **158** 115–21

Efstathopoulos E P, Katritsis D G, Kottou S, Kalivas N, Tzanalaridou E, Giazitzoglou E, Korovesis S and Faulkner K 2006 Patient and staff radiation dosimetry during cardiac electrophysiology studies and catheter ablation procedures: a comprehensive analysis *Europace* **8** 443–8

Efstathopoulos E P, Pantos I, Andreou M, Gkatzis A, Carinou E, Koukorava C, Kelekis N L and Brountzos E 2011 Occupational radiation doses to the extremities and the eyes in interventional radiology and cardiology procedures *Br. J. Radiol.* **84** 70–7

European Commission 2014 Council Directive 2013/59/Euratom of 5 December 2013 Laying down Basic Safety Standards for Protection against the Dangers Arising from Exposure to Ionising Radiation, and Repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom 13 1–73

Farah J, Struelens L, Dabin J, Koukorava C, Donadille L, Jacob S, Schnelzer M, Auvinen A, Vanhavere F and Clairand I 2013 A correlation study of eye lens dose and personal dose equivalent for interventional cardiologists *Radiat. Prot. Dosim*. **157** 561–9

Ferrari P and Gualdrini G 2012 Eye lens dosimetry for electrons: $H_p(3)$ per unit fluence conversion coefficients for electrons from 800 keV to 10 MeV based on MCNPX simulations on a cylindrical phantom *ENEA Technical Report* RT/2012/6/ENEA

Galster M, Guhl C, Uder M and Adamus R 2013 Exposition of the operator's eye lens and efficacy of radiation shielding in fluoroscopically guided interventions *RöFo* **185** 474–81

Geber T, Gunnarsson M and Mattsson S 2011 Eye lens dosimetry for interventional procedures—relation between the absorbed dose to the lens and dose at measurement positions *Radiat. Meas*. **46** 1248–51

Gilvin P J, Baker S T, Gibbens N J, Roberts G H, Tanner R J, Eakins J S, Hager L G and Daniels T J 2013 Type testing of a head band dosemeter for measuring eye lens dose in terms of $H_p(3)$ *Radiat. Prot. Dosim.* **157** 430–6

Grosswendt B 1990 Conversion coefficients for calibrating individual photon dosemeters in terms of dose equivalents defined in an ICRU tissue cube and PMMA slabs *Radiat. Prot. Dosim.* **32** 219–31
Grosswendt B 1991 The angular dependence and irradiation geometry factor for the dose equivalent for photons in slab phantoms of tissue-equivalent material and PMMA *Radiat. Prot. Dosim.* **35** 221–35
Grosswendt B 1992 Coefficients for the conversion of air collision kerma to dose equivalent for the calibration of individual dosemeters in x-ray fields *Radiat. Prot. Dosim.* **40** 169–84
Gualdrini G, Mariotti F, Wach S, Bilski P, Denoziere M, Daures J, Bordy J-M, Ferrari P, Monteventi F and Fantuzzi E 2011 Eye lens dosimetry: task 2 within the ORAMED project *Radiat. Prot. Dosim.* **144** 473–77
Harstall R, Heini P F, Mini R L and Orler R 2005 Radiation exposure to the surgeon during fluoroscopically assisted percutaneous vertebroplasty: a prospective study *Spine* **30** 1893–98
Häusler U, Czarwinski R and Brix G 2009 Radiation exposure of medical staff from interventional x-ray procedures: a multicentre study *Eur. Radiol.* **19** 2000–8
IAEA 2013 *Implications for Occupational Radiation Protection of the New Dose Limit for the Lens of the Eye* (*Tecdoc-1731*) (Vienna: IAEA)
IAEA 2014 *Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards* (*General Safety Requirements Part 3, No. GSR Part 3*) (Vienna: IAEA)
ICRP 1977 Recommendations of the ICRP. *ICRP Publication 26 Ann. ICRP 1*
ICRP 1996 Conversion coefficients for use in radiological protection against external radiation *Publication 74 26: (3–4)* (Oxford: Pergamon)
ICRP 2000 Avoidance of radiation injuries from medical interventional procedures *Publication 85 30: (2)* (Oxford: Pergamon)
ICRP 2007 The 2007 recommendations of the International Commission on Radiological Protection *Publication 103 ICRP 37: (2–4)* (London: Elsevier)
ICRP 2010 Conversion coefficients for radiological protection quantities for external radiation exposures *Publication 116 40 (2–5)* (London: Elsevier)
ICRP 2011 Statement on tissue reactions (www.icrp.org/docs/icrp%20statement%20on%20tissue%20reactions.pdf)
ICRP 2012 *ICRP*Statement on tissue reactions / early and late effects of radiation in normal tissues and organs threshold doses for tissue reactions in a radiation protection context *Publication 118 ICRP 41: (1/2)*
ICRU 1985 *Determination of Dose Equivalents Resulting from External Radiation Sources* (*Report* 39) (Bethesda, MD: ICRU Publications)
ICRU 1992 *Measurement of Dose Equivalents from External Photon and Electron Radiations* (*Report* 47) (Bethesda, MD: ICRU Publications)
ICRU 1993 *Quantities and Units in Radiation Protection Dosimetry* (*Report 51*) (Bethesda, MD: ICRU Publications)
ICRU 1998 *Conversion Coefficients for Use in Radiological Protection Against External Radiation* (*Report 57*) (Bethesda, MD: ICRU Publications)
IEC 2012 *Radiation Protection Instrumentation—Passive integrating dosimetry systems for personal and environmental monitoring of photon and beta radiation* (Geneva: IEC)
ISO 1999 *ISO 4037-3. X and Gamma Reference Radiation for Calibrating Dosemeters and Doserate Meters and for Determining their Response as a Function of Photon energy—Part 3: Calibration of Area and Personal Dosemeters and the Measurement of their Response as a Function of Energy and Angle of Incidence* (Geneva: ISO)
ISO 2000 *ISO 12794 Nuclear Energy—Radiation Protection—Individual Thermoluminescence Dosemeters for Extremities and Eyes* (Geneva: ISO)
Jacob S, Boveda S, Bar O, Brézin A, Maccia C, Laurier D and Bernier M-O 2013 Interventional cardiologists and risk of radiation-induced cataract: results of a french multicenter observational study *Int. J. Cardiol.* **167** 1843–47
Janssen R J J N, Hadders R H, Henkelman M S and Bos A J J 1992 Exposure to operating staff during cardiac catheterisation measured by thermoluminescence dosimetry *Radiat. Prot. Dosim.* **43** 175–77
Junk A K, Haskal Z and Worgul B V 2004 Cataract in interventional radiology—an occupational hazard? *Invest Ophthalmol. Visual Sci. E-Abstr.* **45** 388
Kicken P J H, Kemerink G J and van EngelshovenJ M A 1999 Dosimetry of occupationally exposed persons in diagnostic and interventional arteriography. Part 1: assessment of entrance doses *Radiat. Prot. Dosim.* **82** 93–103

Kim K P, Miller D L, Balter S, Kleinerman R A, Linet M S, Kwon D and Simon S L 2008 Occupational radiation doses to operators performing cardiac catheterization procedures *Health Phys.* **94** 211–27
Koukorava C, Carinou E, Ferrari P, Krim S and Struelens L 2011 Study of the parameters affecting operator doses in interventional radiology using monte carlo simulations *Radiat. Meas.* **46** 1216–22
Koukorava C, Farah J, Struelens L, Clairand I, Donadille L, Vanhavere F and Dimitriou P 2014 Efficiency of radiation protection equipment in interventional radiology: a systematic Monte Carlo study of eye lens and whole body doses *J. Radiol. Prot.* **34** 509
Krim S *et al* 2011 Extremity doses of medical staff involved in interventional radiology and cardiology: correlations and annual doses (hands and legs) *Radiat. Meas.* **46** 1223–7
Kuon E, Birkel J, Schmitt M and Dahm J B 2003 Radiation exposure benefit of a lead cap in invasive cardiology *Heart* **89** 1205–10
Li L B, Kai M, Takano K, Ikeda S, Matsuura M and Kusama T 1995 Occupational exposure in pediatric cardiac catheterization *Health Phys.* **69** 261–4
Lie Ø Ø, Paulsen G U and Wøhni T 2008 Assessment of effective dose and dose to the lens of the eye for the interventional cardiologist *Radiat. Prot. Dosim.* **132** 313–8
Mariotti F, Fantuzzi E, Morelli B, Gualdrini G, Botta M C, Uleri G, Bordy J M and Denoziere M 2011 ENEA extremity dosemeter based on LiF(Mg,Cu,P) to evaluate H_p(3,alpha) *Radiat. Prot. Dosim.* **144** 187–91
Martin C J 2009 A review of radiology staff doses and dose monitoring requirements *Radiat. Prot. Dosim.* **136** 140–57
Martin C J 2011 Personal dosimetry for interventional operators: when and how should monitoring be done? *Br. J. Radiol.* **84** 639–48
Martin C J and Magee J S 2013 Assessment of eye and body dose for interventional radiologists, cardiologists, and other interventional staff *J. Radiol. Prot.* **33** 445–60
McVey S, Sandison A and Sutton D G 2013 An assessment of lead eyewear in interventional radiology *J. Radiol. Prot.* **33** 647–59
Moore W E, Ferguson G and Rohrmann C 1980 Physical factors determining the utility of radiation safety glasses *Med. Phys.* **7** 8–12
Mrena S, Kivelä T, Kurttio P and Auvinen A 2011 Lens opacities among physicians occupationally exposed to ionizing radiation—a pilot study in Finland *Scand. J. Work Environ. Health* **37** 237–43
Olgar T, Bor D, Berkmen G and Yazar T 2009 Patient and staff doses for some complex x-ray examinations *J. Radiol. Prot.* **29** 393–407
Pirchio R, Sánchez H and Domazet W 2014 Dosimetric studies of the eye lens using a new dosemeter—surveys in interventional radiology departments *Radiat. Meas.* **63** 12–7
Rehani M M, Vano E, Ciraj-Bjelac O and Kleiman N J 2011 Radiation and cataract *Radiat. Prot. Dosim.* **147** 300–4
Safak M, Olgar T, Bor D, Berkmen G and Gogus C 2009 Radiation doses of patients and urologists during percutaneous nephrolithotomy *J. Radiol. Prot.* **29** 409–15
Sanchez R, Vano E, Fernandez J M and Gallego J J 2010 Staff radiation doses in a real-time display inside the angiography room *Cardiovasc. Interv. Radiol.* **33** 1210–4
Struelens L, Carinou E, Clairand I, Donadille L, Ginjaume M, Koukorava C, Krim S, Mol H, Sans-Merce M and Vanhavere F 2011 Use of active personal dosemeters in interventional radiology and cardiology: tests in hospitals—ORAMED project *Radiat. Meas.* **46** 1258–61
Sturchio G M, Newcomb R D, Molella R, Varkey P, Hagen P T and Schueler B A 2013 Protective eyewear selection for interventional fluoroscopy *Health Phys.* **104** S11–6
Sulieman A, Theodorou K, Vlychou M, Topaltzikis T, Roundas C, Fezoulidis I and Kappas C 2008 Radiation dose optimisation and risk estimation to patients and staff during hysterosalpingography *Radiat. Prot. Dosim.* **128** 217–26
Thornton R H, Dauer L T, Altamirano J P, Alvarado K J, St Germain J and Solomon S B 2010 Comparing strategies for operator eye protection in the interventional radiology suite *J. Vasc. Interv. Radiol.* **21** 1703–7
Till E, Zankl M and Drexler G 1995 Angular dependence of depth doses in a tissue slab irradiated with monoenergetic photons GFS-report 27 (Neuherberg GmbH, Oberschleissheim: GSF—Forschungszentrum fuer Umwelt und Gesundheit)
UNSCEAR 2010 *Sources and Effects of Ionizing Radiation Vol. UNSCEAR 2008 Report: Volume I: Sources—Report to the General Assembly Scientific Annexes A and B* (New York: United Nations)
UNSCEAR 2011 *Summary of Low-Dose Radiation Effects on Health UNSCEAR 2010 Report. Vol. Report of the United Nations Scientific Committee on the Effects of Atomic Radiation* (New York: United Nations)

Vanhavere F *et al* 2011 Measurements of eye lens doses in interventional radiology and cardiology: final results of the ORAMED project *Radiat. Meas.* **46** 1243–47
Vanhavere F *et al* 2012 *ORAMED: Optimization of Radiation Protection of Medical Staff* (Braunschweig: European Radiation Dosimetry Group e. V)
Vano E, Gonzalez L, Fernández J M and Haskal Z J 2008 Eye lens exposure to radiation in interventional suites: caution is warranted *Radiology* **248** 945–53
Vañó E, González L, Guibelalde E, Fernández J M and Ten J I 1998 Radiation exposure to medical staff in interventional and cardiac radiology *Br. J. Radiol.* **71** 954–60
Vano E, Kleiman N J, Duran A l, Rehani M M, Echeverri D and Cabrera M 2010 Radiation cataract risk in interventional cardiology personnel *Radiat. Res.* **174** 490–95
Vano E, Kleiman N J, Duran A L, Romano-Miller M and Rehani M M 2013 Radiation-associated lens opacities in catheterization personnel: results of a survey and direct assessments *J. Vasc. Interv. Radiol.* **24** 197–204
Vano E, Ubeda C, Leyton F, Miranda P and Gonzalez L 2009 Staff radiation doses in interventional cardiology: correlation with patient exposure *Pediatr. Cardiol.* **30** 409–13
Van Rooijen, B D, de Haan M W, Das M, Arnoldussen C W, de Graaf R, van Zwam W H, Backes W H and Jeukens C 2014 Efficacy of radiation safety glasses in interventional radiology *Cardiovasc. Intervent. Radiol.* **37** 1149–55
Veinot K G 2013 Personal dose equivalent angular response factors for photons with energies up to 1 GeV *Radiat. Prot. Dosim.* **154** 250–61
Veinot K G and Hertel N E 2011 Personal dose equivalent conversion coefficients for photons to 1 GeV *Radiat. Prot. Dosim.* **145** 28–35
Veinot K G and Hertel N E 2012 Personal dose equivalent conversion coefficients for electrons to 1 GeV *Radiat. Prot. Dosim*. **149** 347–52
Worgul B V *et al* 2007 Cataracts among Chernobyl clean-up workers: implications regarding permissible eye exposures *Radiat. Res.* **167** 233–43