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REVIEW ARTICLE

Radiation protection of the eye lens in medical workers—basis and impact of the ICRP recommendations

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ABSTRACT

The aim of this article was to explore the evidence for the revised European Union basic safety standard (BSS) radiation dose limits to the lens of the eye, in the context of medical occupational radiation exposures. Publications in the open literature have been reviewed in order to draw conclusions on the exposure profiles and doses received by medical radiation workers and to bring together the limited evidence for cataract development in medical occupationally exposed populations. The current status of relevant radiation-protection and monitoring practices and procedures is also considered. In conclusion, medical radiation workers do receive high doses in some circumstances, and thus working practices will be impacted by the new BSS. However, there is strong evidence to suggest that compliance with the new lower dose limits will be possible, although education and training of staff alongside effective use of personal protective equipment will be paramount. A number of suggested actions are given with the aim of assisting medical and associated radiation-protection professionals in understanding the requirements.

INTRODUCTION

In 2007, the International Commission on Radiological Protection (ICRP) report 103[1] was released, in which a detailed review of the epidemiological and (limited) mechanistic literature suggested that the lens of the eye may be more radiosensitive than previously thought. However, at the time, insufficient information was available from which to draw a firm conclusion on eye sensitivity. This has since been followed by the ICRP statement on tissue reactions[2] and report 118[3] that suggest an assumed absorbed dose threshold of 0.5 Gy for the lens of the eye and conclude with the recommendation to reduce the occupational equivalent dose limit for the lens from 150 mSv year^{-1} to 20 mSv in a year, averaged over defined periods of 5 years, with no single year exceeding 50 mSv. The revised dose limits have now been incorporated into the current European basic safety standard (BSS), which must be implemented by the European Union (EU) member states by February 2018.

The "paradigm shift" regarding lens radiosensitivity initiated in ICRP 103[1] and the subsequent radiation-protection recommendations have led to an increasing amount of research interest in the induction of cataract following exposure to ionizing radiation. In addition to several major epidemiological analyses and reanalyses, published studies have considered the type and extent of exposures, mechanisms of initiation of primary opacification and development through to clinically relevant cataracts and techniques and equipment to support improved lens protection.

Particularly important have been studies in occupational medical settings, where individuals receive readily measurable exposures, and thus decreased dose limits have the potential to genuinely impact individual working patterns. Probably the most common use of radiation within the medical setting is for diagnostic assessments. However, medical radiation procedures are becoming increasingly frequent and advances in treatments, especially over the last decade, have also led to increased complexity in both patient and medical staff exposure profiles. Those most likely to be affected by the new BSS lens exposure limits are interventional radiologists, cardiologists and individuals involved in nuclear medicine production, who are also mostly at risk of frequent exposure, depending on work load and patterns.[4–7]

This review considers studies where eye lens radiation doses have been assessed in cohorts of medical staff and occupationally exposed workers over a period of time. The recent evidence from the literature allows conclusions to be drawn regarding the likely spectrum of medical occupational exposure types and doses. Ultimately, the particular focus on studies of workers in the medical sector aims to help address questions surrounding ease of compliance with the revised BSS, including the UK Health & Safety Executive (HSE), and others.[8]

As previously highlighted in the literature, one particular challenge in medical occupational exposure settings is the availability of relevant radiation-protection tools.[9] Current methods of eye dosimetry need to be assessed to ensure that it will be possible to keep accurate records of eye lens doses—suitable and accurate dosimetry will be crucial for dose limit compliance. Current and new methods of lens dose monitoring will be discussed in this context.

Finally, in parallel with the issue of exposure, ICRP acknowledge that their conclusions regarding the increased radiosensitivity of the lens rely heavily on the weight of epidemiological evidence, while direct mechanistic evidence is somewhat lacking (ICRP 2012). Thus, it is highly relevant to consider new experimental studies, which can inform on mechanisms of cataract initiation and development, in order to strengthen current radiation-protection judgments. In particular, the question of whether radiation cataractogenesis should be viewed as a stochastic effect or a "tissue reaction" deterministic effect is still very much open. The mechanistic evidence is not reviewed in detail here; however, some important suggestions and conclusions from the literature are considered in various sections.

Direct evidence for radiation exposures in medical occupational settings

Epidemiological studies provide the key information source for evaluation of dose–effect relationships within radiation protection, not least for radiation-induced cataracts. ICRP had based previous recommendations regarding protection of the lens[1] on a number of historical studies, chiefly survivors of the Japanese A-bomb and some medical therapeutic exposures, indicating a threshold of approximately 2 Gy for acute exposures for induction of visual opacities.[1] However, a number of more recent studies and reanalyses of the existing cohorts have been carried out.

Prospective epidemiological studies take time to collate, but offer the most solid data on the incidence of cataracts amongst the occupationally exposed. This is because the exposure profiles can be recorded accurately (avoiding problems of recall) and the influence of radiation exposure can often be assessed during a substantial working period, increasing the likelihood of capturing the lengthy latency period for detectable cataract development. The most relevant epidemiological data for medical occupational exposures available to the ICRP reviewers were probably a 20-year study of this kind, published in 2008, based on almost 36,000 radiologic technologists in the USA.[10] An increased incidence of cataract was found in workers, of whom the majority received a cumulative dose lower than 500 mGy, supporting studies amongst survivors of the atomic bomb and other populations, and the conclusions were presented in ICRP 118 (2012).

A selection of very recent studies concerning those medically and occupationally exposed groups will be discussed here, an overview of which can be seen in Table 1. This table acts to highlight the varying exposure levels associated with different procedures occurring in different medical departments and across countries. Interventional cardiologists and radiologists make up one of the largest and most diverse group of occupationally exposed individuals within the medical setting. Procedures such as CT fluoroscopy—leading to mean whole-body doses of between 0.007 and 0.048 mSv for the radiologist[21]—are widespread throughout the world and are often conducted in dedicated large departments allowing high patient throughput required by these procedure types in modern medical care. Seals et al[5] (2015) reviewed the recent literature relating specifically to exposures of interventional radiologists and drew general conclusions regarding the risk of radiation-induced cataractogenesis in this occupational cohort. The study found that with current workloads and radiation-protective measures in place, there is potential for lens doses exceeding the recommended threshold of 20 mSv year^{-1}. There is a further suggestion that current data with regard to interventional radiologists (but likely to be relevant to any studied cohort) reflect an underestimation of actual exposure, given the possibility that studied individuals are likely to alter their behaviour to reduce dose, once they are aware of being a test subject.

Since the publication of ICRP 118 (2012), a number of relevant studies have been published. A recent 2013 study identified a significant increase in the development of specific posterior subcapsular (PSC) opacification amongst a large cohort of 106 interventional cardiologists from a range of centres across France, with a further 99 age-matched unexposed control subjects.[12] PSC opacifications are thought to be the most prevalent cataract type induced by radiation, although other types have been increasingly reported. It is also noteworthy that no difference was seen in other opacification types between the two groups. Interestingly, the risk of opacity increased with activity duration but not with workload. A summary of recent published assessments of interventional radiologists has been compiled[22] including the work of previously published clinical cohorts.[7,13] The concluding remarks from these studies reveal that using current monitoring techniques, workers are likely to exceed the new recommended occupational dose limits. A similar but larger retrospective study in Saudi Arabia analysed 34 staff including primary cardiologists and also assisting staff, based on thermoluminescent dosemeter (TLD) badges worn at the collar level.[14] Cardiologists received the highest doses as expected, but these were within the ICRP recommendations. There is substantial uncertainty using such a method, whereby conversion coefficients owing to different clinical setups and X-ray tube angulation may significantly affect exposure.

The ORAMED (Optimisation of Radiation Protection of Medical Staff) project was set up to investigate low-dose medical exposures and assess the risk and hazards these may pose, including those affecting the eye lens with a particular objective to

Table 1. Information from a selection of very recent studies of radiation dose specifically to the lens in medical scenarios

Study	Country	Procedure	Average lens dose/ procedure	Min/max lens dose/ procedure	Dosemeter
O'Connor et al[11]	Ireland	ECRP		0.01/0.09 mSv	EYE-D™
Jacob et al[12]	France	Various interventional cardiology		0.046/0.236 mSv	TLD
Vano et al[13]	Spain	Catheterizations		0.044/0.067 mSv	APD
Al-Haj et al[14]	Saudi Arabia	Cardiologists	0.02 mSv	0.005/0.08 mSv	TLD
Ainsbury et al[15]	UK	Various radiologists	0.03–0.05 mSv		Eye lens
Romanova et al[16]	Bulgaria	Fractura femoris	0.046 mSv	0.02/0.07 mSv	EDD30
		Fractura cruris	0.002 mSv (0.023 mSv with C-arm)	0.01/0.043 mSv	EDD30
Zagorska et al[17]	Bulgaria	ECRP	0.034–0.093 mSv		EDD30
Rathmann et al[18]	Germany	Radiologists	0.018 mSv	0.012/0.029 mSv	TLD
Khoury et al[19]	Brazil A	Hepatic chemoembolization	0.017 mSv	0.007/0.041 mSv	TLD
	Brazil B	Hepatic chemoembolization	0.02 mSv	0.016/0/025 mSv	TLD
	Brazil C	Hepatic chemoembolization	0.08 mSv	0.012/0.148 mSv	TLD
Cemusova et al[20]	Czech Republic	Radiologists		0.013/0.070 mSv	EYE-D™

APD, active personal dosemeters; ECRP, endoscopic retrograde cholangiopancreatography; EDD, educational direct dosemeter; TLD, thermoluminescent dosemeter.

optimize radiation protection in interventional cardiology and radiology settings,[23] following recent interest in the potential lowering of exposure thresholds by the ICRP. A number of studies were conducted monitoring eye lens dose using specific dosemeters and extrapolation to yearly doses received by workers covering 34 European hospitals and 1,300 procedures. Lens annual dose is likely to exceed the proposed 20 mSv year^{-1}, although there are some overestimations in these studies owing to TLD positioning, highlighting the importance of effective dosimetry monitoring and personal protective equipment (PPE). ORAMED since developed a more accurate monitor optimized for eye lens dosimetry, the EYE-D™ dosemeter dedicated to lens-specific exposure by incorporating Hp (3) measurements.[24] The EYE-D monitor was demonstrated in use in 2013[11] and indicated likelihood to exceed 20 mSv year^{-1} in gastroenterologists, although the study concludes that this could be remedied by a reconfiguration of equipment in order to stay within the revised limits of eye lens exposure.

Interestingly, the survey discussed previously by Carinou et al[25] found that of the respondents claiming to receive doses above the ICRP recommendations of 20 mSv annually, 40% of them based this assumption on eye lens dosemeters already being worn, and these (being non-specialist eye dosemeters) may lead to inaccurate exposure amounts.

It can be difficult to predict the likelihood of overexposure to the lens or have a general rule, as each medical centre will have varying levels of procedure throughput and radiation-protection approaches. In a recent multicentre study, during fluoroscopic procedures, it is estimated to take around 23.4 h of exposure time before the eye lens receives a dose of 20 mSv.[26]

Orthopaedic procedures pose an exposure risk to surgeons performing them. A recent Bulgarian study found average exposure per procedure to be 47.2 and 77.1 μSv for 3- and 5-min procedure durations, respectively.[16] Given the consistent workloads similar to those during the study period, compliance to the revised dose limits would be achievable; however, if the workloads and working patterns alter, this could result in overexposure and is likely to occur in medical centres with higher throughputs. Similarly in Bulgaria, the same monitoring was applied to medical workers during endoscopic retrograde cholangiopancreatography,[17] with eye lens doses ranging from 34.9 to 93.3 μSv per procedure. This study highlights the potential for particularly the primary gastroenterologist performing the procedure and the associated anaesthesiologist to exceed the revised annual dose limit, if protective equipment is not used.

The use of phantom models can have some limitations compared with human subjects in studies of eye lens exposure, but some useful data can be gathered on the positioning and quality of measurement tools. Such a model was used to estimate doses received to the eye lens, umbilicus and ankle of the interventional radiologist, whilst performing percutaneous biopsy, using modern C-arm CT system incorporating laser guidance.[18] Whilst the eye lens was not the most sensitive tissue during these procedures, a significant dose of 180 μSv can be delivered per procedure. C-arm CT systems are becoming increasingly attractive and are likely to be used more frequently in future, although current data do not suggest eye lens dose being exceeded initially, a significant throughput and increased use of such a system would require a high level of eye lens monitoring and sufficient shielding to reduce the potential of overexposure.

One study performed in Brazil[19] monitored a number of interventional radiologists during hepatic chemoembolization, a common non-surgical technique, where surgery is not an option. This multicentre investigation found mean exposure values to be between 17.6 and 80 μSv per procedure. Furthermore, the researchers used these data to calculate the number of procedures that could be performed each week, in order to keep within the revised annual dose limit of the lens, a novel approach which allows for workload and procedure throughput to be dictated by potential exposure.

As well as focusing on the exposure situations of cardiology and radiology, a significant but arguably smaller exposure scenarios occur in persons handling radionuclides working within nuclear medicine.[27] These situations have a variable degree of exposure and are likely less predictable than the working patterns and procedures of diagnostic and hospital-related procedures. Specifics regarding nuclides used and the working environment are extremely important in determining eye exposures.

Radiation exposure types

Radiology/radiotherapy departments provide an ever broader range of techniques and increasing throughput of patients, resulting in an increasing number of medical staff occupationally exposed to different types of radiation. The most common and well-known uses of radiation are those used during diagnostic procedures including X-ray and CT scans, but radiology also comprises a varying degree of interventional procedures as well as those used in dental practice and nuclear medicine.[28]

One of the key problems when identifying potential risks of such exposures is the lack of epidemiological data to support investigations into the influence of dose, dose rate and radiation quality. To date, information on these factors has been obtained from chiefly animal models and to a lesser extent, *in vitro* cellular models, where exposure conditions can be controlled. Animal models can provide a useful source of life span data following radiation exposures; however, the usefulness of the information for protection of humans is limited by differences between small rodents and humans.

The proposed new threshold limits do not take into account dose-rate effects largely because there is a lack of epidemiological data to support this.[29] The researchers also propose a hypothesis regarding the existence of a dose-rate effect in the lens: typically, tissue damage following radiation exposure leads to an initial accumulation of DNA damage, followed by some degree of cell death and turnover, thus reducing some of this accumulated damage burden. Dose rate and cellular turnover are both intrinsic in calculating the dose-rate effect. The lens is unique in that there is no cell death or degradation of cells, and early lens fibre cells are likely to be some of the oldest cells in the body. The dose-rate effect may not apply here. Rather than a dose-rate effect, it is proposed that a stationary or progressive cataract type develops, caused by the accumulation of DNA damage. The ICRP have highlighted the need for further information to inform current judgments on the dose and dose-rate effectiveness factor (DDREF) applicable to the eye lens.[30] DDREF values could be different for individual health end points, depending on the mechanisms that operate. DDREF as currently formulated by ICRP applies to the stochastic effects of cancer and heredity effects. The use of the DDREF remains a matter of some debate as to whether dose and dose rate should be pooled or considered as separately given potential differences in biological effects.

Another very important factor which will be particularly relevant to medical and occupational exposure is the type of radiation exposure. Different radiation qualities are effective to different degrees in terms of inducing damage or particular biological end points, including cataracts. Generally speaking, the relative biological effectiveness (RBE) of X-ray, gamma and beta radiation is similar, whereas alpha and neutron exposures have a broader, less well-defined, RBE. Most of what we know about the RBE values relevant for lens opacification is derived from epidemiological studies of human cohorts such as survivors of the atomic bomb and nuclear radiation workers. Given the radiosensitive nature of the lens as a tissue, the effects seen from neutron exposure within the cohort of survivors of the atomic bomb demonstrate a different threshold of effectiveness compared with cohorts involving other types of radiation exposure.[31] Mice exposed to neutron radiation[32] have shown an increased susceptibility to cataractogenesis compared with gamma radiation exposure, particularly at lower dose levels.[33] Heavy ions are a form of high linear energy transfer radiation quality found mainly in space but also encountered in heavy-ion beam therapy during medical procedures, although less common in recent years.

Radiation-protection impact of ICRP/BSS

Research into radiation-induced lens effects has been conducted for many decades, but the recent influx of studies relevant to low doses during occupational exposures is due to revisions made to the by ICRP on the recommended occupational eye lens dose limit and subsequently BSS regulations for working with radiation safely. The aims of the BSS are to ensure standardized safety procedures for those working with radiation occupationally and to a wider extent, the general public. As with ICRP (2012), the contributors to the BSS felt that given the increasing weight of evidence for induction of cataracts at doses lower than 2 Gy, the lower lens dose limit needed to be put in place, regardless of the remaining research uncertainties, in order to keep doses as low as reasonably practicable. This has always been the philosophy of radiation protection.

The focus in this review has been on individuals occupationally exposed to radiation exposure working within the medical sector around the world; unlike the majority of the general public and medical patients, these individuals are occupationally exposed to relatively low doses on a regular basis, making them particularly vulnerable to the regulatory changes introduced in the new BSS. Previously, these individuals have been working, in common with all radiation workers, to an eye dose limit of 150 mS vyr^{-1}, and much of the existing dosimetry and working patterns have been calculated on this basis. The new recommendations will require some form of change in practice to all those individuals at risk of exposure, ranging from small modifications to larger changes depending on country and medical procedure. The reduction in the dose limit to just 20 mSv in a single year (or 100 mSv in any 5 consecutive years subject to a maximum dose of 50 mSv in a single year) is large, but is judged to be necessary in light of both epidemiological and mechanistic evidence. Although not the main focus of this review, it is noteworthy that the lens dose limit for students and apprentices (aged between 16 and 18 years) and the general public is 15 mSv $year^{-1}$.

According to the revised BSS, workers with lens exposures likely to exceed 15 mSv $year^{-1}$ will be classified as category A workers. Category A workers are those working in areas where radiation exposure levels are higher, creating controlled areas with greater restrictions on access. The impact on radiation protection here would mean a very thorough and systematic process for regular monitoring of workers, with each person requiring individual dosimetry. This is likely to result in the introduction of new procedures and dosemeters, with a financial cost attached for both the product and additional service charges, in order to satisfy the new criteria for safety and monitoring. Indeed, this review, in common with other publications, highlights the need for effective eye lens dosimetry. This issue is discussed in further detail in the next sections.

Those individuals expected to receive a significant dose to the lens will, as a priority, require the best possible dosemeter specific for eye lens measurements. A relatively high frequency of recording will be essential for these workers, especially given the conclusions of some studies mentioned in this article that suggest that remaining under the new dose limits will be difficult and there are expected to be a number to workers exceeding the limit, notably in medical settings.

There will inevitably be a financial cost to introduction of new or modified dosimetry techniques, but these should be viewed in terms of the potential benefit to health, which can also be expected to bring some savings as a result in the long term. However, these are not easy to forecast currently and it will be a number of years before the full effects can be realized. It is thought that within the UK, the initial cost required to comply with new regulations would be around £8 million for both the medical occupational and nuclear worker settings. This is then estimated to equate to around £24 million over a 30-year period to implement (www.hse.gov.uk). The European Society of Radiology also recently published the "Summary of the European Directive 2013/59/Euratom: essentials for health professionals in radiology", which gives an overview of how radiology departments will specifically be impacted by the new BSS directive and the lower dose limits to be applied to lens exposures.

In response to the BSS and ICRP revisions on the recommendations for eye lens doses, the UK-based HSE compiled a report outlining the impacts on those affected, concerning costings and benefits of the changes. The document can be found at www.hse.gov.uk, which may also prove useful for countries performing similar assessments or planning to in the near future. To summarize some of the key findings relevant to the UK, the HSE predict a relatively small number of individuals to be at risk for significantly high lens doses, but there is also a warning that some work may become prohibited if persistent overexposure over the recommended dose limit occurs. The incorporation of further monitoring using optimized lens dosemeters could remedy this issue. Incorporation of the 2012 revised dose limit into the document "Implications for occupational radiation protection of the new dose limit for the lens of the eye" (TECDOC Number 1731), published by the International Atomic Energy Agency, have also helped to shape the guidance and impact notes by the HSE.

Education and training in the importance of radiation protection of the lens are also very important issues. Cataract surgery, the removal of opacification usually by laser, has become a common procedure across the world. Upon development of a visually impairing opacity, surgery can be performed to lase a hole through the opaque cells to allow light to pass through. This procedure is usually performed in less than 10 min and is relatively pain free, with patients expecting around a 2-h visit in total. The success rate of cataract removal is very high, but has some risks associated post surgery. Most commonly (affecting around a quarter of patients), the artificial lens inserted to replace the damaged lens can become cloudy with epithelial cells attempting to populate the lens once more, resulting in a posterior capsular opacity, which requires further treatment (www.visionaware.org). In the USA alone, Medicare estimates costs for cataract extraction in the region of \$3.6 billion per year, accounting for 60% of visually impairing disorders.[10]

Although the proposed lens dose limits have raised some concerns over the likelihood of compliance and the impact of workload and staffing, a recent survey found that 93% of medical physicists and radiation-protection officers were aware of the proposed reduction and a further 55% of those questioned were actively participating to some degree in monitoring of specific eye lens dose-monitoring studies.[25] Interventional radiologists and cardiologists, who typically receive the highest doses of radiation during their associated procedures, have been identified as most at risk of overexposure under the new dose limits.[34] Similarly, a study conducted by Public Health England[15] regarding UK workers across three radiology departments involving over 1000 individual procedures used optimized lens dosemeters available from Public Health England personal dosimetry services. Associated questionnaires were also included to assess the likelihood of compliance. In total, 68 persons took part in this pilot study; only 2 individuals received extrapolated doses of slightly more than 20 mSv $year^{-1}$, although these 2 individuals were not using protective lead glasses. Questionnaires revealed a high level of PPE awareness and usage, although these facilities had radiation protection operating at well-established high standards already. There are an increasing number of imaging techniques that require close personal contact between the operator and patient, especially in paediatric settings, and the risk of exceeding dose limits will be a potential hazard, as throughput and techniques improve. Eye lens monitoring, PPE availability and enforcement, in addition to education and training, are and will continue to be paramount to ensuring minimum number of workers are overexposed to radiation in the lens.[35]

Furthermore, in support of the ICRP and BSS, implementation of the revised dose limits for the lens of the eye will also affect most radiation workers in a positive manner—whether that is through raising awareness and training or introducing new dosimetry and radiation-protection measures to ensure compliance. Recommendations will be relevant across Europe and also raise discussion internationally. It must be noted the HSE also raise the valid point that these new dose limits will not only potentially affect occupational medical exposures but also those working within the nuclear sector including reactor vessel entry, fuel dismantling and industrial radiography. On an individual level, if education, protection and monitoring do not succeed in reducing the lens limits, then alterations to work patterns may still be necessary.

Monitoring of eye lens doses

As discussed, there is evidence in the literature that with current working practices, lens doses received by interventional cardiologists, in particular, may be close to or exceeding the new eye lens dose limit of 20 mSv year^{-1}. To ensure accurate compliance monitoring, it is apparent that changes to current dosimetry practices may be required. The use of both medical personnel and phantoms are useful in providing data on exposure doses, but also for testing the suitability of monitoring techniques. Typically, the standard method of monitoring consists of a TLD worn around the chest area, giving a representation of whole-body dose but not specifically for the radiosensitive eye lens. This strategy has been discussed elsewhere;[20] here, details of available eye lens dose-monitoring techniques are presented, to inform on the selection of appropriate monitoring to ensure compliance going forward.

As mentioned, occupational doses received by radiation workers have traditionally been monitored using one or more TLD badges placed either on the body or at the extremities, depending on the nature of the work. The need for optimized dosemeters using an eye lens tissue-relevant measuring technique, namely Hp(3) tissue-equivalent dosimetry, is a concern that has been raised previously,[36] and dosemeters specifically developed and optimized for the eye lens are now beginning to become available. Of chief concern is the necessity to have a dosemeter than can account for the unique characteristics possessed by the lens, including the nature of the lens structure and tissue composition. The ORAMED project in conjunction with Radcard TLD Dosemeters (Krakow, Poland) has produced a potentially suitable eye dosemeter, the EYE-D. The EYE-D represents one of the first dosemeters specific for lens monitoring, which can be worn on a narrow headband that sits adjacent to the eye. With the lowest level of detection at 10 μSv, the device is one solution to achieving accurate lens exposure doses, whilst being practical to wear. The dosemeter had been tested and calibrated, and a recent study has become one of the first to demonstrate the use of the EYE-D in practice.[11] A total of 12 staff from two endoscopy departments in separate facilities in Ireland wore the dosemeters during endoscopic retrograde cholangiopancreatography procedures. The dosemeters were found to be a practical and effective means of monitoring eye lens dose. Mirion Technologies also now have made available an eye lens-specific dosemeter worn in a similar fashion to the EYE-D. A recent study also discussed specific eye lens dosemeters to be worn at the eye level as per the previous two products.[15,37] Produced by Public Health England in the UK, these demonstrate another example of dosemeter incorporating the Hp(3) dose-equivalent measurement method, further expanding the options for modified dosimetry in future.[37]

However, specific lens dosemeters are only indicated in cases when lens doses are likely to approach significant levels, as assessed by local radiation-protection professionals. Indeed, there may be circumstances when collars or other dosemeters are sufficient. However, it is important in these instances that a representative measurement of the relevant tissue is achieved, as dosemeters worn incorrectly can result in recorded doses several times lower than those of the area with maximum exposure.[8] A recently published investigation[22] makes the suggestion of using active personal dosemeters (APD), which are routinely used by a large number of clinical staff. This approach has several advantages stemming from the idea that the eye lens dose is extrapolated from the existing monitoring from the APD by applying a mathematical formula. This requires no additional or modified personal dosimetry, but slightly advanced analysis. Although this study is adapted from a single cardiologist and three further assisting nurses, the data suggests that this technique is very feasible practically and would increase the accuracy of estimated annual dose and has the additional benefit of flagging procedures where APD has been forgotten and so can give a platform for where and when additional training is required to staff. In any case, risk assessments should include guidance regarding the ideal positioning of the TLD when worn, ideally by placing the dosemeter to the side of the head or neck to give a representative eye lens exposure.

As well as pre-existing models for measured lens dosimetry, the incidence of reported and predicted cases of dose limit exceedances also indicate that not only eye dosimetry but novel approaches and updates to established methods of eye protection are needed. For instance, the risk of developing PSC opacities can be significantly decreased by regular use of protective lead glasses, as demonstrated amongst a large cohort of French interventional cardiologists, and modern glasses are much lighter, more comfortable and afford much better vision than earlier versions.[12] The use of radiation shielding over the eyes would further reduce the received lens dose. For instance, ceiling mounted face shielding using lead has been proven to significantly reduce lens dose using phantoms and humans.[11] It should be noted that whilst there has long been the recommendation for using protective eye wear such as leaded glasses to shield the lens; there are numerous studies that highlight the variability in dose reduction achieved through use of glasses of differing style and construction. A recent study[38] evaluated the efficiency of dose reduction by two of the most commonly used styles of lead glasses, and indicated that sports-style wrap-around glasses were significantly better at reducing dose. This supports the idea that one of the limiting factors when reducing dose using eyewear is the background scatter created by the forehead,[39] and so a product with a "tighter fit" would be beneficial. With eye protection even more crucial given the reduction in eye lens dose limits, a balance between the most effective protective measures and practicality of wear should be further investigated to ensure high levels of compliance.

On a practical level, the cost of new/modified personal dosimetry, protective equipment and education can be substantial—however, such costs cannot be avoided as all employers of radiation workers will be legally required to comply with the new BSS (Directive 2013/59/Euratom) following implementation in national legislation.

Furthermore, eye dosemeters must be wearable, which it seems is not always the case. From a survey of interventional radiology and nuclear medicine workers, around 50% did not feel the current eye lens dosemeters used were comfortable to wear.[25] TLDs and other similar dosemeters tend to have strong compliance of use, as they are easily clipped on to external overalls or other PPE, but a specific eye lens monitor[37] may present a challenge and require additional training on the importance of correct use.

Specialized eye lens dosimetry would appear to be the most reliable method of effectively monitoring the radiation dose received by the eye lens. If existing whole-body monitoring systems are already in place,[20] eye lens dose can potentially be extrapolated, reducing the burden and cost of introducing eye lens-specific tools. However, this may only be a feasible option for workers with a predictably low risk of eye lens exposure.

It is worth noting that in order to obtain the full benefit of the increased investment in eye lens monitoring and improvement in protective measures, large population studies of affected workers are very important to assess impact. This will also be helpful in the future, as more research is conducted to understand the impact of low-dose radiation on the induction of radiation-induced cataract.

DISCUSSION AND CONCLUSION

The increasing number and quality of human studies demonstrating that doses of radiation <2 Gy can induce clinically relevant cataracts prompted the ICRP to review and subsequently reduce their recommendations for occupational eye lens dose limits. The new limits are based on a new threshold of 0.5 Gy; however, the ICRP specifically do not rule out the possibility of a no-threshold model. In line with ICRP 118 (2012), recent literature suggests that medical radiation workers may develop cataracts, as a result of occupational exposures. Furthermore, the data in this review indicate that eye lens doses to individuals who are occupationally exposed in the medical sector may in some cases currently exceed 20 mSv annually, especially for interventional radiologists and cardiologists. Workers within the medical sector are thus likely to be at risk of failure to comply with the new regulatory dose limits in the EU/ICRP recommendations, if these are implemented elsewhere.

The epidemiological evidence is supported by a small number of animal studies investigating early lens changes, for example.

Table 2. Provides an "at-a-glance" overview of raised issues and suggested actions as a result of this review

Issue	Action
Reduction of lens dose limits	Monitor eye doses received over extended periods of time to evaluate impact
May impact working schedules	Increased use of protective dose-reduction measures should negate the need to reduce working hours
Effective monitoring of eye lens dose	Trained radiation-protection practitioners should advise
	Provide model for regular monitoring and record keeping
	Particular emphasis on workers routinely receiving >15 mSv in 1 year
Personal protective equipment	May require modification
	Thorough reassessment of appropriate PPE
	Must be worn effectively and routinely
Personnel training and awareness	Training to ensure workers are aware of the importance of protective lens (legal and health basis)
	Training regarding importance of protective eyewear and compliance of use
	Awareness of consequences of cataract development
Effects of low doses of radiation and dose rate?	Magnitude of lose-dose/dose-rate effects
	Worker cohorts followed up in future years

PPE, personal protective equipment.

However, although there have been recent advances in our understanding of specific steps in radiation cataract initiation and development, it is still very difficult to draw conclusions on the relevant issues such as whether radiation cataractogenesis may most appropriately be viewed as a stochastic or deterministic effect of radiation-protection purposes. The authors can only echo the ICRP in stating that more research needs to be conducted to investigate initial low-dose effects and progression to clinically relevant opacities, taking into account the long latency period and potential impact of genetic background.

In practical terms, EU member states must now comply with the ICRP recommendations, which have now been incorporated in the revised BSS, and in the rest of the world, consideration of the issues are currently under way. Strategies for effective reduction, protection, monitoring and dosimetry are available, in order to support compliance with the BSS/ICRP recommendations—including eye lens dosemeters for workers who might approach the action levels. However, eye lens dose-monitoring techniques still need to be refined and possibly standardized, to ensure compliance and to give reliable data on annual doses received to support prospective epidemiological studies.

Attention should be paid to education and training of medical radiation workers, particularly in terms of the need for protection and monitoring and the consequences of cataract development—the ease of use of PPE and the costs and post-surgical risks for cataract treatment. However, one of the most positive outcomes of the ICRP review and recommendation process has been the increased awareness of the importance of lens exposures within the radiation-protection and medical communities. This is reflected by the increased number of eye dose-monitoring and related published studies since 2011.

Other issues reviewed in detail elsewhere are how best to resolve the knowledge gaps regarding mechanisms and how human studies should be directed towards solving the remaining research questions.[29] Standardization of cataract-reporting methodologies should be a high priority here. The latency period between initiating damage and cataract manifestation is also not well understood.

In summary, compliance of medically exposed radiation workers with the revised BSS is expected in all EU member states by February 2018. This appears likely within the EU, if appropriate dosimetry and protection are applied. Information in this review may be of use in other countries looking at the ICRP recommendations (2012), in order to define their own legal basis for radiation protection. Over the coming years, further studies and results are expected to help answer the questions raised in this review and others about the initiation of radiation damage, with a focus on low-dose exposures and how early mechanistic changes influence the latency and progression of opacities to manifestation as full cataracts. An overview of the scientific and practical issues raised by this and other recent articles is presented in Table 2, along with suggestions and recommendations for actions, as highlighted within this text.

REFERENCES

1. ICRP. Early and late effects of radiation in normal tissues and organs—threshold doses for tissue reactions in a radiation protection context. *Ann ICRP* 2007.
2. ICRP. ICRP statement on tissue reactions. *Ann ICRP* 2011.
3. ICRP. ICRP Publication 103. *Ann ICRP* 2012.
4. Frey D. Radiation cataracts: new data and new recommendations. *AJR Am J Roentgenol* 2014; **203**: W345–6. doi: http://dx.doi.org/10.2214/AJR.13.11242
5. Seals KF, Lee EW, Cagnon CH, Al-Hakim RA, Kee ST. Radiation-induced cataractogenesis: a critical literature review for the interventional radiologist. *Cardiovasc Interv Radiol* 2016; **39**: 151–60.
6. Bitarafan Rajabi A, Noohi F, Hashemi H, Haghjoo M, Miraftab M, Yaghoobi N, et al. Ionizing radiation-induced cataract in interventional cardiology staff. *Res Cardiovasc Med* 2015; **4**: e25148. doi: http://dx.doi.org/10.5812/cardiovascmed.25148
7. Ciraj-Bjelac O, Rehani M, Minamoto A, Sim KH, Liew HB, Vano E. Radiation-induced eye lens changes and risk for cataract in interventional cardiology. *Cardiology* 2012; **123**: 168–71. doi: http://dx.doi.org/10.1159/000342458
8. Martin CJ. A 20mSv dose limit for the eye: sense or no sense? *J Radiol Prot* 2011; **31**: 385–7. doi: http://dx.doi.org/10.1088/0952-4746/31/4/E03
9. Bouffler S, Ainsbury E, Gilvin P, Harrison J. 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* 2012; **32**: 479–88. doi: http://dx.doi.org/10.1088/0952-4746/32/4/479
10. Chodick G, Bekiroglu N, Hauptmann M, Alexander BH, Freedman DM, Doody MM, et al. Risk of cataract after exposure to low doses of ionizing radiation: a 20-year prospective cohort study among US radiologic technologists. *Am J Epedimiol* 2008; **168**: 620–31. doi: http://dx.doi.org/10.1093/aje/kwn171
11. O'Connor U, Gallagher A, Malone L, O'Reilly G. Occupational radiation dose to eyes from endoscopic retrograde cholangiopancreatography procedures in light of the revised eye lens dose limit from the International Commission on Radiological Protection. *Br J Radiol* 2013; **86**: 20120289. doi: http://dx.doi.org/10.1259/bjr.20120289
12. Jacob S, Boveda S, Bar O, Brézin A, Maccia C, Laurier D, et al. Interventional cardiologists and risk of radiation-induced cataract: results of a French multicenter observational study. *Int J Cardiol* 2013; **167**: 1843–7. doi: http://dx.doi.org/10.1016/j.ijcard.2012.04.124
13. Vano E, Sanchez RM, Fernandez JM. Estimation of staff lens doses during interventional procedures. Comparing cardiology, neuroradiology and interventional radiology. *Radiat Prot Dosimetry* 2015; **165**: 279–83. doi: http://dx.doi.org/10.1093/rpd/ncv049
14. Al-Haj AN, Lobriguito AM, Al-Gain I. Staff eye doses in a large medical centre in Saudi Arabia: are they meeting the new ICRP recommendations? *Radiat Prot Dosimetry* 2015; **165**: 294–8. doi: http://dx.doi.org/10.1093/rpd/ncv073
15. Ainsbury EA, Bouffler S, Cocker M, Gilvin P, Holt E, Peters S, et al. Public Health England survey of eye lens doses in the UK medical sector. *J Radiol Prot* 2014; **34**: 15–29. doi: http://dx.doi.org/10.1088/0952-4746/34/1/15

16. Romanova K, Vassileva J, Alyakov M. Radiation exposure to the eye lens of orthopaedic surgeons during various orthopaedic procedures. *Radiat Prot Dosimetry* 2015; **165**: 310–3. doi: http://dx.doi.org/10.1093/rpd/ncv122
17. Zagorska A, Romanova K, Hristova-Popova J, Vassileva J, Katzarov K. Eye lens exposure to medical staff during endoscopic retrograde cholangiopancreatography. *Phys Med* 2015; **31**: 781–4. doi: http://dx.doi.org/10.1016/j.ejmp.2015.03.011
18. Rathmann N, Kostrzewa M, Kara K, Bartling S, Haubenreisser H, Schoenberg SO, et al. Radiation exposure of the interventional radiologist during percutaneous biopsy using a multiaxis interventional C-arm CT system with 3D laser guidance: a phantom study. *Br J Radiol* 2015; **88**: 20150151. doi: http://dx.doi.org/10.1259/bjr.20150151
19. Khoury HJ, Garzon WJ, Andrade G, Lunelli N, Kramer R, de Barros VS, et al. Radiation exposure to patients and medical staff in hepatic chemoembolization interventional procedrues in Recife, Brazil. *Radiat Prot Dosimetry* 2015; **165**: 263–7. doi: http://dx.doi.org/10.1093/rpd/ncv075
20. Cemusova Z, Ekendahl D, Judas L. Assessment of eye lens doses in interventional radiology: a simulation in laboratory conditions. *Radiat Prot Dosimetry* Jul 2015. Epub ahead of print.
21. Paulson E, Cheafor D, Enterline D, McAdams P, Yoshizumi T. CT fluoroscopy-guided interventional procedures: techniques and radiation dose to radiologists. *Vasc Interv Radiol* 2001; **220**: 161–7.
22. Omar A, Marteinsdottir M, Kadesjö N, Fransson A. On the feasibility of utilizing active personal dosimeters worn on the chest to estimate occupational eye lens dose in X-ray angiography. *J Radiol Prot* 2015; **35**: 271–84. doi: http://dx.doi.org/10.1088/0952-4746/35/2/271
23. Vanhavere F, Carinou E, Domienik J, Donadille L, Ginjaume M, Gualdrini G, et al. Measurements of the eye lens doses in interventional radiology and cardiology: final results of the ORAMED project. *Radiat Measurements* 2015; **46**: 1243–47. doi: http://dx.doi.org/10.1016/j.radmeas.2011.08.013
24. Bilski P, Bordy JM, Daures J, Denoziere M, Fantuzzi E, Ferrari P, et al. The new EYE-D™ dosemeter for measurements of Hp(3) for medical staff. *Radiat Measurements* 2011; **46**: 1239–42. doi: http://dx.doi.org/10.1016/j.radmeas.2011.04.031
25. Carinou E, Ginjaume M, O'Connor U, Kopec R, Sans Merce M. Status of eye lens radiation dose monitoring in European hospitals. *J Radiol Prot* 2014; **34**: 729–39. doi: http://dx.doi.org/10.1088/0952-4746/34/4/729
26. Attigah N, Oikonomou K, Hinz U, Knoch T, Demirel S, Verhoeven E, et al. Radiation exposure to eye lens and operator hands during endovascular procedures in hybrid operating rooms. *J Vasc Surg* 2016; **63**: 198–203. doi: http://dx.doi.org/10.1016/j.jvs.2015.08.051
27. Bruchmann I, Szermerski B, Behrens R, Geworski L. Impact of radiation protections means on the dose to the lens of the eye while handling radionuclides in nuclear medicine. *Z Med Phys* 2015; S0939–3889(15)00099–9. doi: http://dx.doi.org/10.1016/j.zemedi.2015.07.002
28. Mettler FA Jr, Huda W, Yoshizumi TT, Mahesh M. Effective doses in radiology and diagnostic nuclear medicine: a catalog. *Radiology* 2008; **248**: 254–63. doi: http://dx.doi.org/10.1148/radiol.2481071451
29. Hamada N, Fujimichi Y, Iwasaki T, Fujii N, Furuhashi M, Kubo E, et al. Emerging issues in radiogenic cataracts and cardiovascular disease. *J Radiat Res* 2014; **55**: 831–46. doi: http://dx.doi.org/10.1093/jrr/rru036
30. Rühm W, Woloschak GE, Shore RE, Azizova TV, Grosche B, Niwa O, et al. Dose and dose-rate effects of ionizing radiation: a discussion in the light of radiological protection. *Radiat Environ Biophys* 2015; **54**: 379–401. doi: http://dx.doi.org/10.1007/s00411-015-0613-6
31. Otake M, Schull WJ. Radiation-related posterior lenticular opacities in Hiroshima and Nagasaki atomic bomb survivors based on the DS86 dosimetry system. *Radiat Res* 1990; **121**: 3–13. doi: http://dx.doi.org/10.2307/3577557
32. Di Paola M, Bianchi M, Baarli J. Lens opacification in mice exposed to 14-MeV neutrons. *Radiat Res* 1978; **73**: 340–50. doi: http://dx.doi.org/10.2307/3574825
33. Medvedovsky C, Worgul BV, Huang Y, Brenner DJ, Tao F, Miller J, et al. The influence of dose, dose-rate and particle fragmentation on cataract induction by energetic iron ions. *Adv Space Res* 1994; **14**: 475–82. doi: http://dx.doi.org/10.1016/0273-1177(94)90502-9
34. Broughton J, Cantone MC, Ginjaume M, Shah B. 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* 2013; **33**: 855–68. doi: http://dx.doi.org/10.1088/0952-4746/33/4/855
35. Le Heron J, Padovani R, Smith I, Czarwinski R. Radiation protection of medical staff. *Eur J Radiol* 2010; **76**: 20–3. doi: http://dx.doi.org/10.1016/j.ejrad.2010.06.034
36. Behrens R. Monitoring the eye lens: how do the international organisations react? *Radiat Prot Dosimetry* 2015; **164**: 75–8. doi: http://dx.doi.org/10.1093/rpd/ncu277
37. Gilvin PJ, Baker ST, Gibbens NJ, Roberts GH, Tanner RJ, Eakins JS, et al. Type testing of a head band dosemeter for measuring eye lens dose in terms of H(P)(3). *Radiat Prot Dosimetry* 2013; **157**: 430–6. doi: http://dx.doi.org/10.1093/rpd/nct144
38. Koukorava C, Farah J, Struelens L, Clairand I, Donadille L, Vanhavere F, et al. Efficiency of radiation protection equipment in interventional radiology: a systematic Monte Carlo study of eye lens and whole body doses. *J Radiol Prot* 2014; **34**: 509–28. doi: http://dx.doi.org/10.1088/0952-4746/34/3/509
39. McVey S, Sandison A, Sutton DG. An assessment of lead eyewear in interventional radiology. *J Radiol Prot* 2013; **33**: 647–59. doi: http://dx.doi.org/10.1088/0952-4746/33/3/647