Guidelines for Radiation Protection and Dosimetry of the Eye Lens

NEDERLANDSE COMMISSIE VOOR STRALINGSDOSIMETRIE

Report 31 of the Netherlands Commission on Radiation Dosimetry

May 2018

Netherlands Commission on Radiation Dosimetry
Subcommittee 'Protection and Dosimetry of the Eye Lens'
May 2018 DOI: 10.25030/ncs-031

Disclaimer regarding NCS reports

The NCS frequently publishes reports for fellow professionals in which recommendations are given for various quality control procedures or otherwise. The members of the NCS board and the members of the concerning subcommittee do not claim any authority exceeding that of their professional expertise. Responsibility on how the NCS recommendations are implemented lies with the user, taking into account the practice in his/her institution.

Terminology in this report

The following levels of recommendation are used throughout this report:

- “must” means there is a legal obligation according to Dutch and/or Belgian law;
- “should” indicates a strong recommendation. Not abiding to this recommendation needs to be motivated and documented, along with a description of an adequate alternative method to cope with the issue at hand;
- “recommend” or “advise” means a mere suggestion. This recommendation may be disregarded, keeping in mind that there is a reason for mentioning it in the report.
- “local protocol” means that there should be a clear, written protocol on how to check that particular item, including tolerance/action levels and the person responsible for performing the check(s).

The recommendations in NCS reports aim to optimise the treatment or diagnosis procedure by optimising QA procedures. Still, the reader should be aware that safety recommendations as described elsewhere, for instance by manufacturers, still need to be considered. In general, NCS and other recommendations should be taken seriously notwithstanding careful and thorough thought.

Disclosure of Potential Conflicts of Interest

In order to prepare a recommendation that has a widespread acceptance, the subcommittee consists of members from various professional organisations (NCS, NVKF, NVMBR, BVS, NVS, NVS-BGZ, NVvR, NVVC). To promote acceptance and application of this recommendation, the draft report has been submitted to representatives of several related professional groups (i-SZW, KINT, KNMvD, NVKF, NVMBR, NVNG, BVS, NVS, NVS-BGZ, NVT, NVvH, NVvR, NVVC). With respect to potential conflicts of interest, T.W.M. Grimbergen is working as a team manager for one of the approved dosimetry services in the Netherlands (NRG). L. Struelens (SCK-CEN) and R.P. Kollaard (NRG) are working on government funded research positions outside of the dosimetry services of their companies. The contribution of the chairman (R.P. Kollaard) to the committee was funded by the Dutch Ministry of Economic Affairs. A complete overview of the functions of the subcommittee members can be found on page v.

Preface

The Nederlandse Commissie voor Stralingsdosimetrie (NCS, Netherlands Commission on Radiation Dosimetry, http://www.radiationdosimetry.org) was officially established on 3rd September, 1982 with the aim of promoting the appropriate use of dosimetry of ionising radiation both for scientific research and for practical applications. The NCS is chaired by a board of scientists, made up via recommendations from the supporting societies, including the Nederlandse Vereniging voor Radiotherapie en Oncologie (Dutch Society for Radiotherapy and Oncology), the Nederlandse Vereniging voor Nucleaire Geneeskunde (Dutch Society of Nuclear Medicine), the Nederlandse Vereniging voor Klinische Fysica (Society for Medical Physics of the Netherlands), the Nederlandse Vereniging voor Radiobiologie (Netherlands Radiobiological Society), the Nederlandse Vereniging voor Stralingshygiëne (Netherlands Society for Radiological Protection), the Nederlandse Vereniging voor Medische Beeldvorming en Radiotherapie (Dutch Society for Medical Imaging and Radiotherapy), the Nederlandse Vereniging van Klinisch Fysisch Medewerkers (Dutch Society for Medical Physics Engineers), the Nederlandse Vereniging voor Radiologie (Radiological Society of the Netherlands) and the Belgische Vereniging voor Ziekenhuisfysici/Société Belge des Physiciens des Hôpitaux (Belgian Hospital Physicists Association) and expanded with a representative from the Dutch Metrology Institute VSL. To achieve its aims, the NCS carries out the following tasks: participation in dosimetry standardisation, promotion of mutual comparisons of dosimetry, drafting of dosimetry protocols and the collection and evaluation of physical data related to dosimetry. Furthermore, the commission shall establish or maintain links with national and international organisations concerned with ionising radiation and promulgate information on new developments in the field of radiation dosimetry.

Guidelines for Radiation Protection and Dosimetry of the Eye Lens

Members of the subcommittee:

R.P. Kollaard (*chairman*)[1]

D. Valk (*secretary*)[2]

M. Damen[3]

B. Goessens[4]

T.W.M. Grimbergen[5]

K.R. Henken[6]

J.P.C. Hoornstra[7]

W. Idema[8]

P.J.H. Kicken[9]

M.C.M. Lagerweij[10]

A.H. Maass[11]

L.J. Schultze Kool[12]

L. Struelens[13]

I.R. de Waard[14]

[1]RPE at Nuclear Research and Consultancy Group (NRG), Arnhem, The Netherlands

[2]RPE at National Institute for Public Health and the Environment (RIVM), Bilthoven, The Netherlands

[3]Medical Physics Trainee at Leiden University Medical Center, Leiden, The Netherlands

[4]Physician in occupational health and radiation protection at Radboud University Medical Center, Nijmegen, The Netherlands

[5]RPE at Nuclear Research and Consultancy Group (NRG), Arnhem, The Netherlands

[6]Medical Physics Trainee at St. Antonius Hospital, Nieuwegein, The Netherlands

[7]RPE at Universitair Medisch Centrum Utrecht, Utrecht, The Netherlands

[8]RPO at Academisch Medisch Centrum, Amsterdam, The Netherlands

[9]RPE at Astra Consultancy, Eindhoven, The Netherlands

[10]Medical Physicist at Isala Hospital, Zwolle, The Netherlands

[11]Cardiologist at University of Groningen, University Medical Center Groningen, Groningen, The Netherlands

[12]Interventional Radiologist at Radboud University Medical Center, Nijmegen, The Netherlands

[13]RPE at Belgian Nuclear Research Centre (SCK•CEN), Mol, Belgium

[14]RPE at National Institute for Public Health and the Environment (RIVM), Bilthoven, The Netherlands

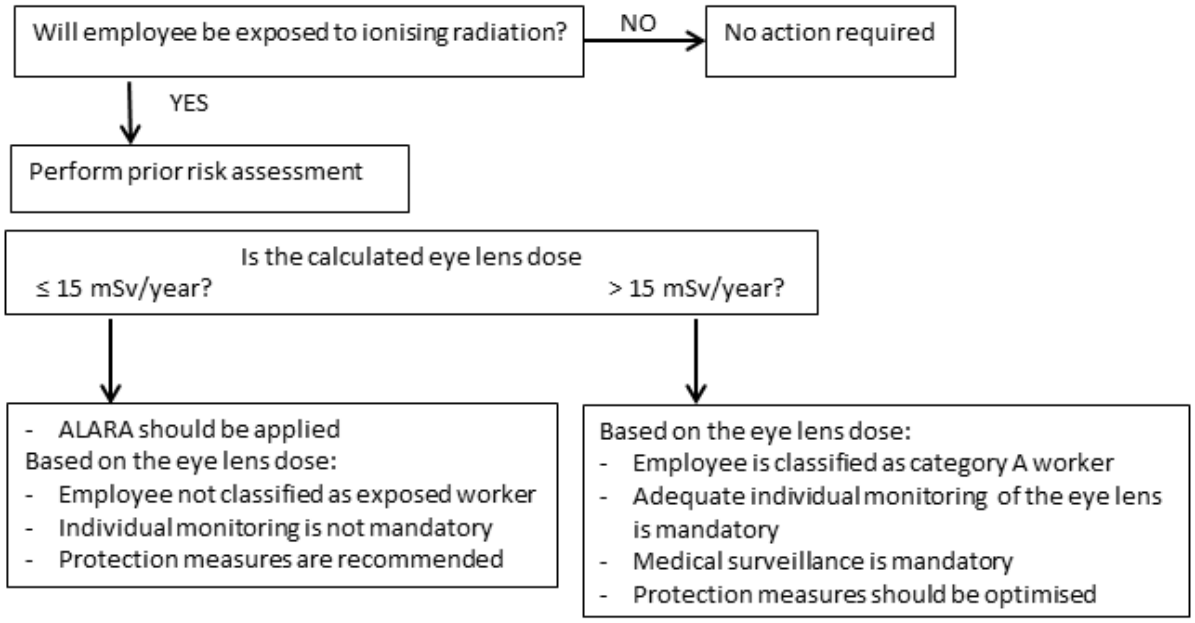
NCS, Delft, The Netherlands

For more information on NCS Reports, see http://radiationdosimetry.org

Summary

For years, the dose limit for occupational exposure of the eye lens to ionising radiation was rarely exceeded. Early 2018, this dose limit was reduced from 150 to 20 mSv per year. The reduction of this dose limit has significant implications for the protection of the eye lens. When category A workers are liable to receive significant exposures to the lens of the eye, an adequate system for monitoring shall be set up to ensure that the dose does not exceed the dose limit. The purpose of this NCS report is to support radiation protection experts in the Netherlands and Belgium with the implementation of the new legislation in their practice.

The following flow chart[1] can be used:



When the calculated eye lens dose in the risk assessment is higher than 15 mSv per year, a worker is to be classified as a category A worker. The largest group of involved workers is found in interventional radiology and cardiology. Incidentally, workers in other fluoroscopy-guided procedures, nuclear medicine, veterinary practice, non-destructive testing and isotope production can also be exposed to high dose levels. The adequate system for individual monitoring of the eye lens dose depends on exposure conditions. Where workers are exposed to a uniform photon beam, the whole body dosimeter can be expected to give a reasonable estimate for the eye lens dose. An example of this situation is found in non-

[1] This flow chart is based on the eye lens dose. Of course, workers can still be classified as category A workers based on their expected effective dose or their expected equivalent dose in other tissues, the skin or extremities.

destructive testing, where the distance is usually large and the radiation field is uniform. Due to aspects such as the short distance and the use of shielding, the situation for interventional procedures is more complex. Several studies show that in many of these exposure situations, the eye lens dose cannot be estimated adequately by the $H_p(10)$ measurement with the whole body dosimeter, positioned outside the lead apron (on the chest) or on the thyroid collar. In such situations, dedicated eye lens dosimetry should be applied for workers with an expected eye lens dose of more than 15 mSv per year, unless measurements over a long period show a constant ratio between $H_p(10)$ and $H_p(3)$ or a consistently higher measured whole body dose ($H_p(10)$).

General (ALARA) principles can be applied to reduce the eye lens dose, such as limiting the exposure time, increasing distance and applying shielding of the source. The committee encourages focusing the protection measures primarily on these aspects. The use of personal protective equipment (typically radiation safety glasses) should be considered as a last step in this dose reduction and dose optimisation process. Another measure that plays a role in fluoroscopically-guided procedures is the optimal position of the monitors in the treatment room. It should be noted that the application of protection measures requires (additional) education and training of workers in the correct application of these measures. Medical surveillance plays a role in following up workers who are not able to limit their eye lens dose to less than or equal to 15 mSv per year.

This NCS subcommittee had its kick-off meeting at 14 July 2016.

DOI: 10.25030/ncs-031

Contents

Abbreviations and acronyms

ALARA	As Low As Reasonably Achievable
CI	Confidence Interval
Bbs	[Besluit basisveiligheidsnormen stralingsbescherming] Dutch legislation derived from the Basic Safety Standards
BVS	[Belgische Vereniging voor Stralingsbescherming] Belgian Society for Radiation Protection
EU BSS	Basic Safety Standards (Euratom)
CR	Computed Radiography
DR	Digital Radiography
DRF	Dose Reduction Factor
EU	European Union
EURALOC	EUropean epidemiological study on RAdiation-induced Lens Opacities among interventional Cardiologists
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units and measurements
IRPA	International Radiation Protection Association
ISO	International Organization for Standardization
i-SZW	[Inspectie van SZW] Inspection of SZW
KERMA	Kinetic Energy Released per unit MAss
KINT	[Nederlandse Vereniging voor Kwaliteitstoezicht, Inspectie en Niet-Destructieve Techniek] Dutch Society for Quality Surveillance, Inspection and Non-Destructive Testing
KNMvD	[Koninklijke Nederlandse Maatschappij voor Diergeneeskunde] Royal Netherlands Veterinary Association
LUMC	[Leids Universitair Medisch Centrum] Leiden University Medical Center
NCS	[Nederlandse Commissie voor Stralingsdosimetrie] Netherlands Commission on Radiation Dosimetry
NDRIS	[Nationaal Dosis Registratie en Informatie Systeem] National Dose Registry and Information System

NVKF	[Nederlandse Vereniging voor Klinische Fysica] Dutch Society for Medical Physics
NVMBR	[Nederlandse Vereniging Medische Beeldvorming en Radiotherapie] Dutch Society for Medical Imaging and Radiotherapy
NVNG	[Nederlandse Vereniging voor Nucleaire Geneeskunde] Dutch Society of Nuclear Medicine
NVS	[Nederlandse Vereniging voor Stralingshygiëne] Dutch Society for Radiation Protection
NVS-BGZ	[Afdeling Bedrijfs-GezondheidsZorg van de NVS] Section Occupational Healthcare of the NVS
NVT	[Nederlandse Vereniging voor Thoraxchirurgie] Netherlands Society for Thoracic Surgery
NVVC	[Nederlandse Vereniging voor Cardiologie] Netherlands Society of Cardiology
NVvH	[Nederlandse Verening voor Heelkunde] Dutch Association of Surgeons
NVvR	[Nederlandse Vereniging voor Radiologie] Radiological Society of the Netherlands
ORAMED	Optimization of RAdiation protection for MEDical staff
PAGO	Periodic occupational medical examination
PET	Positron Emission Tomography
PMMA	Acrylic glass
RIE-RAD	Risk assessment and evaluation for radiology
RIE-NG	Risk assessment and evaluation for nuclear medicine
RIVM	[RijksInstituut voor Volksgezondheid en Milieu] National Institute for Public Health and the Environment
SPECT	Single Photon Emission Computer Tomography
SZW	[Ministerie van Sociale Zaken en Werkgelegenheid] Dutch Ministry of Social Affairs and Employment
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation

List of symbols

E	Effective dose (limiting quantity)
H_{eye}	Eye lens equivalent dose (limiting quantity)
$H_p(d)$	Personal dose equivalent in soft tissue at depth d (in mm) (operational quantity)
$H_p(0.07)$	Personal dose equivalent in soft tissue at a depth of 0.07 mm, used as an estimator for the equivalent dose of the skin; also indicated as shallow dose or surface dose
$H_p(3)$	Personal dose equivalent in soft tissue at a depth of 3 mm, used as an estimator for the eye lens equivalent dose; also indicated as eye lens dose
$H_p(10)$	Personal dose equivalent in soft tissue at a depth of 10 mm, used as an estimator for the effective dose; also indicated as whole body dose or depth dose
H_T	Equivalent dose for tissue T

1 Introduction

1.1 Motivation

The sensitivity of the eye lens to ionising radiation has been gaining interest in the last decade. As a result of various investigations, the International Commission on Radiological Protection (ICRP) recommended in its statement on tissue reactions in 2011 a reduction of the equivalent dose limit for the lens of the eye for occupational exposure in planned exposure situations from 150 mSv to 20 mSv per year (averaged over a period of 5 years, with no annual dose in a single year exceeding 50 mSv).

Early 2018, this limit was implemented in the national legislation in all European member states[2]. When putting this legislation into practice, certain terminology requires interpretation and a number of issues need to be addressed in relation to the protection of the eye lens:

1) What level of exposure of the eye lens is considered to be “significant” and requires monitoring?
2) What is an “adequate system for monitoring”?
3) Which worker groups are expected to be involved?
4) How is the dose to the eye lens that a worker is “liable to receive” determined?
5) Which measures can be applied for protection of the eye lens?

The purpose of this report is to provide guidance and answers with respect to these questions.

1.2 Scope

The scope of this report is limited to protection and monitoring[3] of the lens of the eye for workers who are exposed to ionising radiation from external sources. Aspects related to the medical surveillance of the exposed worker are included as well.

This report does not cover other subjects, such as:

- radiation protection of the patient and their eye lens;
- considerations with respect to other organs at risk, such as the brain;
- radioactive contamination of the eye lens.

[2] Dutch legislation does not allow averaging of the occupational exposure over 5 years.

[3] The term (individual) monitoring is used in this report to describe the dosimetric evaluation of workers exposed to ionising radiation using personal dosimetry.

1.3 Content of this report

Chapter 2 provides background information about the radiation sensitivity of the eye lens and about the legal framework introduced to limit the dose to the eye lens. Chapter 3 comprises a flow chart to facilitate reading the other chapters of the report. Typical worker groups that may receive more than 15 mSv per year on the eye lens are listed in Chapter 4. Types of individual monitoring that are considered to be adequate for monitoring of the eye lens are explained in Chapter 5. Descriptions of the exposure conditions, expected doses, possible measures and proposals for adequate individual monitoring for relevant worker groups are provided in Chapter 6. Chapter 7 expands on the education and medical surveillance of the exposed workers. Chapter 8 contains a summary of the recommendations for protection, dosimetry and medical surveillance for the relevant worker groups.

2 Background

2.1 Scientific basis for the change in the dose limit

The International Commission on Radiological Protection (ICRP) recommends, develops and maintains the International System of Radiological Protection. This system is the basis for radiological protection standards, legislation, guidelines, programmes and practices.
The latest ICRP recommendations on dose limits were published in 2007 in Publication 103 [1]. In that publication, ICRP recommended the same numerical values for the dose limits, as in their earlier recommendations [2] and in the 1996 edition of the IAEA BSS [3]. For the eye lens dose limit, this meant an annual equivalent dose of 150 mSv for people who are occupationally exposed and 15 mSv for members of the public. Because of new data about the radiosensitivity of the lens of the eye and visual impairment, an ICRP Task Group was initiated to review these dose limits and evaluate the literature on the non-cancerous effect of ionising radiation on normal tissues.

ICRP Statement on Tissue Reactions

In 2011, the Task Group that reviewed the dose limits published the Statement on Tissue Reactions (prior to publication of the entire ICRP report). In that statement ICRP refers to the reviewed epidemiological evidence which suggests that there may be some tissue reaction effects, particularly those with very late manifestation, where threshold doses are or might be lower than previously considered. Therefore, ICRP state that the absorbed dose threshold for the lens of the eye is now considered to be 0.5 Gy. Furthermore, ICRP recommends for occupational exposure in planned exposure situations an equivalent dose limit for the lens of the eye of 20 mSv per year, averaged over defined periods of 5 years, with no single year to exceed 50 mSv.

This statement resulted in the new dose limit for the lens of the eye in the revised Basic Safety Standards of the European Union (BSS) of 2013.

ICRP-118

The recommendations of this ICRP Task Group were published in 2012 in ICRP publication 118 [4]. ICRP concluded that there was a well-documented history of publications about radiation-induced cataracts, but also that there still were considerable uncertainties about the relationship between dose and radiation induced cataracts. Various recent studies have suggested a higher risk for the development of cataracts in populations exposed to low

doses of ionising radiation below assumed thresholds (for example [5-7]). In these studies dose-related lens opacification has been reported at exposures significantly lower than 2 Gy for patients undergoing CT-scans, radiotherapy patients, astronauts, atomic bomb survivors, residents of contaminated buildings, victims of the Chernobyl Nuclear accident, radiological technologists and interventional cardiologists. According to ICRP, earlier studies had shorter follow-up periods, failed to consider the increasing latency period as dose decreases, did not have sufficient sensitivity to detect early lens changes, and had relatively few subjects with doses below a few Gy. It must be noted that, besides the studies that show a higher risk for radiation induced cataracts, there are also a few recent studies that do not show a lower threshold dose for radiation cataracts [8-10].

ICRP-118 reviewed and summarised various human epidemiological studies. These studies suggest that the former ICRP guidelines following exposures of dose thresholds of 5 Gy for opacities and 8 Gy for visual impairment may underestimate the risks. Furthermore, literature data on animal models have been reviewed. These studies offer the opportunity to examine the effects of precisely controlled radiation exposures on specific pathologies. New data from both human epidemiological studies and animal models suggest that lens opacities occur at doses far lower than those generally assumed to be cataractogenic. These observations are consistent with the presence of a small or non-existent dose threshold.

Table 2-1 shows the results of studies that have formally investigated an acute dose threshold for induction of opacities or cataracts. The studies of Nakashima et al. [11] and Neriishi et al. [12] were based on data of atomic bomb survivors. The study of Worgul et al. [7] was based on data of Chernobyl clean-up workers.

ICRP-118 summarises the results and conclusions of the studies on radiation-induced cataracts as follows:

(697) *Overall, the general consistency of the collective results for both early lens opacities and advanced cataracts makes a compelling 'weight of evidence' judgement that the recommended acute dose threshold for the purposes of radiation protection should be lowered from its current value to a nominal value of 0.50 Sv. This is subject to the caveats that the progressive nature of assessed opacities into cataracts, and the likely greater sensitivity of the lens in children compared with post-adolescents, requires further characterisation.*

Table 2-1 Recent epidemiological studies of cataract formation where formal estimates of threshold doses were made [4].

Study	Cataract type	Threshold dose	Confidence intervals	Reference
Atomic bomb survivors (acute exposure)	Cortical cataract	0.6 Sv	90%: <0–1.2 Sv	Nakashima et al. (2006)
	Posterior subcapsular opacity	0.7 Sv	90%: <0–2.8 Sv	
Atomic bomb survivors (acute exposure)	Postoperative cataract	0.1 Gy	95%: <0–0.8 Gy	Neriishi et al. (2007)
Chernobyl clean-up workers (fractionated protracted exposure)	Stage 1–5 cataract	0.50 Gy	95%: 0.17–0.65 Gy	Worgul et al. (2007)
	Stage 1 cataract	0.34 Gy	95%: 0.19–0.68 Gy	
	Stage 1 non-nuclear cataract	0.50 Gy	95%: 0.17–0.69 Gy	
		0.34 Gy	95%: 0.18–0.51 Gy	
	Stage 1 superficial cortical cataract	0.35 Gy	95%: 0.19–0.66 Gy	
	Stage 1 posterior subcapsular cataract			

Note. Reprinted with permission from ICRP: Ann. ICRP 41(1/2) [4], 2012.

(698) For fractionated and protracted exposures, the current epidemiological evidence indicates that the threshold is not greater than that for acute exposures, although animal data suggest that a higher value might be plausible. For chronic exposure over several to many years, much of the evidence refers to opacities rather than overt cataracts. The uncertainties about progression of opacities into cataracts, and the age-at-exposure problem mentioned above, make any judgement about dose thresholds for chronic exposures difficult.

(699) In addition, it is suggested that there is a genetic component to the radiosensitivity of cataractogenesis which may produce more cataracts in a few percent of exposed individuals. On the other hand, chemical agents that block lens cell proliferation might reduce cataract formation, although there are no established mitigating factors. Finally, although the lower 95% CI in some threshold calculations includes a zero dose, there is no direct evidence that a single damaged progenitor lens epithelial cell can produce a cataract and hence radiation-induced lens cataracts are still considered a tissue reaction (deterministic effect) with an albeit small dose threshold.

2.2 Legal context of eye lens protection

The 2013 revision of the BSS of the EU [13] sets the European framework for the protection of the eye lens against the danger arising from exposure to ionising radiation, including dose limits for members of the public and for exposed workers.

The relevant articles of BSS with respect to the eye lens are summarised as follows:

Article 9.3a: For occupational exposure, the limit on the equivalent dose for the lens of the eye shall be 20 mSv in a single year or 100 mSv in any five consecutive years subject to a maximum dose of 50 mSv in a single year, as specified in national legislation.

Article 12.3a: For public exposure, the limit on the equivalent dose for the lens of the eye shall be 15 mSv in a year.

Article 40.1a: Those exposed workers who are liable to receive an equivalent dose greater than 15 mSv per year for the lens of the eye shall be classified as a category A worker.

Article 41.1: Member States shall ensure that category A workers are systematically monitored, based on individual measurements performed by a dosimetry service. In cases where category A workers are liable to receive significant exposure of the lens of the eye, an adequate system for monitoring[4] shall be set up.

Article 41.2: Member States shall ensure that monitoring of category B workers is at least sufficient to demonstrate that such workers are correctly classified as category B. Member States may require individual monitoring and if necessary individual measurements performed by a dosimetry service for category B workers.

The European member states were required to implement this directive at a national level before 6th February 2018. The interpretation of these articles is covered in Chapters 3-6 of this report.

With regard to the eye lens, the Dutch implementation of the EU directive is restricted to the dose limit for the eye lens of 20 mSv in a single year.

[4] In Dutch 'passend persoonlijk dosiscontrolemiddel', Bbs art. 7.12

2.3 Quantities

This section summarises the system of quantities used for radiation protection in external exposure situations in general and, more specifically, for radiation protection of the eye lens.

In radiation protection, two types of quantities can be distinguished: limiting quantities and operational quantities. The limiting quantities are the tissue equivalent dose, H_T, and the effective dose, E. For both quantities the unit sievert (Sv), or more practically, millisievert (mSv), is used. Limiting quantities are used to set dose limits in legislation. Their definition is based on organ doses (in gray, Gy) and on radiation weighting factors so that tissue equivalent dose and effective dose values are suitable for limiting ionising radiation health risks independent of the type of radiation (photons, neutrons, etcetera). This simplifies legislation as there is no need for different dose limits for different types of ionising radiation. The effective dose is a combination of tissue equivalent doses to tissues of the human body, relevant with respect to health risks, and tissue weighting factors. In this way, the effective dose can be used to limit exposure to ionising radiation, irrespective of the type of radiation and the irradiation geometry, including partial body irradiation and internal exposure by intake of radionuclides. In the Netherlands and Belgium the effective dose is limited to 20 mSv per year for category A workers.

For exposures where the irradiation of the human body is very inhomogeneous, setting a limit for the effective dose may not provide sufficient protection for specific tissues. Therefore, separate limits for the equivalent dose for specific tissues have been set, e.g. for the eye lens equivalent dose H_{eye}. As already indicated in the previous section, the new limit for eye lens equivalent dose is set to 20 mSv per year for occupational exposures.

As limiting quantities are defined on organ doses, these quantities can be calculated by using theoretical models for irradiation conditions and anthropomorphic phantoms. However, limiting quantities are not measurable in practice. For the purposes of measuring occupational exposure to external radiation, ICRU introduced operational quantities. These operational quantities serve as measurable estimators for the limiting quantities. The personal dose equivalent, $H_p(d)$ in mSv, is defined as the dose equivalent in soft tissue at depth d (in mm) at a specified point on the body. Contrary to the limiting quantities, the personal dose equivalent is defined at a distinct point. The extent to which the personal dose equivalent is an accurate estimator for the effective dose or tissue equivalent depends on the choice of both depth d and the measuring point on the body.

Depth d is chosen such that the dose equivalent is measured at the most relevant depth, i.e. at the depth in tissue where the cells at risk are located. In practice, three distinct values of parameter d are in use. $H_p(10)$, also called the “depth dose”, is used to obtain an

estimation of the effective dose, E. For this purpose, normally the measuring position is on the trunk. $H_p(0.07)$, also called the “surface” or “shallow” dose, is used to obtain an estimation of the skin equivalent dose H_{skin}. When the measuring position is on the hands or fingers, $H_p(0.07)$ is also used as an estimate of the extremity equivalent dose. $H_p(3)$ is regarded as the best estimator for the eye lens equivalent dose, H_{eye}. The popular name for $H_p(3)$ is, therefore, the “eye lens dose”, although this name is used alternately as a shortened term for the eye lens equivalent dose, H_{eye}. In some cases this may lead to some confusion. Obviously, the choice of d is more critical when there is a strong depth-dose gradient. For strongly penetrating radiations, such as medium and high energy photons and neutrons, the choice of d is not critical. That implies that $H_p(0.07)$ and $H_p(10)$, although less accurate compared to $H_p(3)$, can give acceptable estimates of the eye lens equivalent dose. On the other hand, for weakly penetrating radiations such as (very) low energy photons and electrons (betas) dose gradients in the first few millimetres in tissue may be very strong, and values for $H_p(0.07)$, $H_p(3)$ and $H_p(10)$ in the same irradiation conditions may differ significantly.

Although the best choice for the measuring point on the body to measure the eye lens dose is on, or close to, the eye the position of the measuring point is only critical in inhomogeneous irradiation conditions. In the case of homogeneous irradiation conditions measurement of the personal dose equivalent at other positions of the body may be much more practical and can still give an acceptable estimate of the eye lens equivalent dose. It should be kept in mind however, that the personal dose equivalent does not only depend on the radiation field incident on the body, but also on backscattered radiation. This means that even in homogeneous incident irradiation fields, the personal dose equivalent on different positions of the body may differ because of differences in backscatter.

Personal dose equivalent dosimeters are designed to be worn on specific positions on the body. These dosimeters respond not only to the radiation directly occurring on the dosimeter, but most probably to backscattered radiation as well. For design, type testing and calibration purposes, personal dose equivalent dosimeters will be used in combination with specified phantoms. Practical dosimeters will be designed for specified radiations (e.g. photons only, or photons plus electrons) and need to be tested for specified ranges of energies and angles. The response of the dosimeter will be compared to reference values for the personal dose equivalent for the specified phantom, at the specified depth, d. Reference values of personal dose equivalents can be calculated from physical quantities (e.g. air kerma for photons) by applying appropriate conversion coefficients. The choice of the phantom depends on the intended wearing position of the dosimeter. For dosimeters

designed to be worn on the trunk, wrist or ankle, and finger, standard phantoms have been defined by the International Organization for Standardization (ISO). Together with the specifications of these phantoms, ISO provides conversion coefficients for different irradiations, energies and angles [14]. For a wearing position close to the eye (i.e. on the head) no specific phantom with associated conversion coefficients has been defined by ISO yet. However, the cylindrical phantom proposed by the ORAMED project (www.oramed-fp7.eu) seems to be well accepted and conversion coefficients can be found in literature [15, 16].

3 Process for protection of the eye lens

3.1 Introduction

Depending on the level of the eye lens exposure, different steps need to be taken.
A flow chart that describes these steps is presented in Figure 3-1. The flow chart will be explained in more details in the following sections. This flow chart is based on the eye lens dose. It goes without saying that workers can also be classified as category A workers based on their expected effective dose or equivalent dose to the skin or extremities.

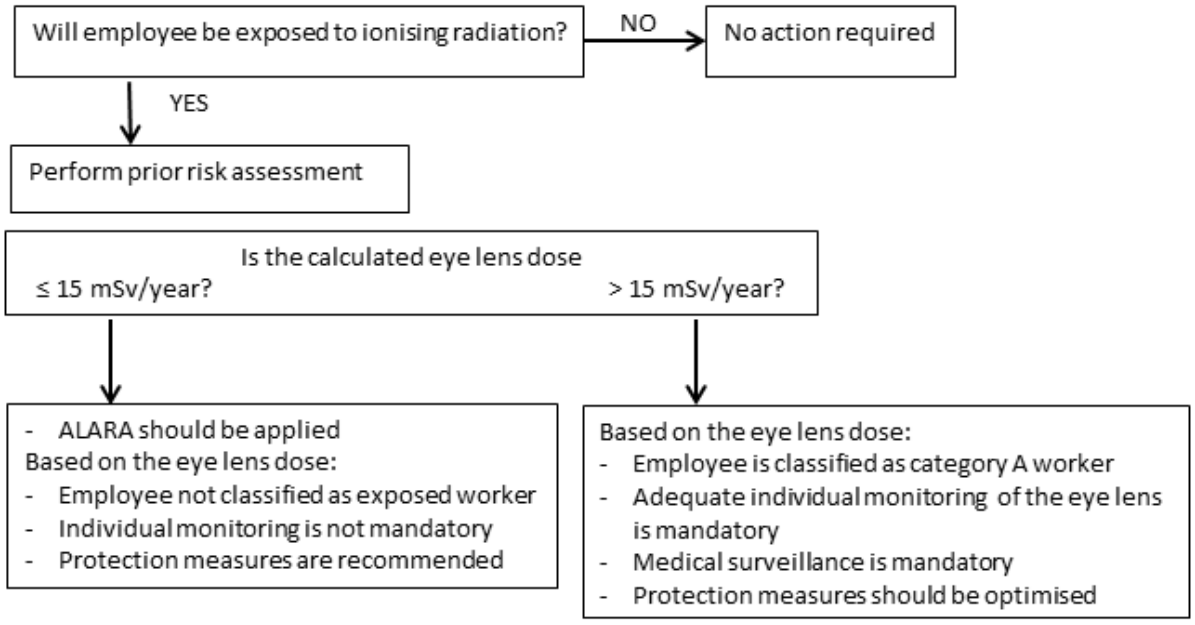


Figure 3-1 Flow chart about the protection of the eye lens

3.2 Prior risk assessment

A prior risk assessment should be performed for all employees who are exposed to ionising radiation (EU BSS, art. 32). The risk assessment should result in an estimate of the dose that an individual worker is liable to receive, including the equivalent eye lens dose. In this assessment contributions from regular and potential exposures of the worker should be taken into account.

Templates for risk assessments for several medical applications are available in Dutch at the NCS website (look for RIE-RAD and RIE-NG at http://radiationdosimetry.org). Currently, specific calculations for the eye lens dose have not been implemented. When calculating eye lens doses of workers, some basic assumptions should be considered for situations where

these workers are positioned close to the radiation source. The distance from the radiation source to the eye lens may differ from the source-trunk distance and the angle of the primary radiation beam and/or scattered radiation to the eye may differ from the angle of the radiation to the trunk. In these situations, the eye lens dose may differ significantly from the dose to the trunk (or the whole body dose).

It should be noted that according to Dutch legislation the protective effect of personal protective equipment should not be taken into account in the classification of the worker. Examples of personal protective equipment are lead aprons, radiation safety glasses and lead gloves [17]. In the Dutch radiation protection system, the requirements for categorisation of the worker (and need for dosimetry) depend on the dose level outside the personal protective equipment.

3.3 Classification of workers

Employees who are liable to receive exposures exceeding the dose limits for public exposure should be classified as exposed workers (EU BSS, art. 4). When the prior risk assessment results in an eye lens dose of more than 15 mSv per year, the employee must be classified as a category A worker. It is noted that this dose level is equal to the eye lens dose limit for members of the public (art.12). Typical worker groups that may receive more than 15 mSv per year on the eye lens are listed in Chapter 4. According to articles 41 and 45 of the EU BSS, systematic individual monitoring and yearly medical examinations are required for category A workers.

3.4 Individual monitoring

Types of individual monitoring that are considered to be adequate for monitoring of the eye lens are explained in Chapter 5. Whether the whole body dosimeter is considered to be adequate depends on various factors such as radiation quality, homogeneity of the field etc.

This section addresses the level of exposure to the eye lens (per year) that is considered to be “significant”. According to article 41.4 from the EU BSS, an adequate system for monitoring shall be set up where category A workers are liable to receive “significant” exposure of the lens of the eye. Several interpretations of the term “significant” are possible. Publications from IAEA [18], ISO [19] and IRPA [20] recommend routine monitoring above 5 or 6 mSv per year (see Table 3-1). As the (equivalent) dose limit for the eye lens is set to 15 mSv per year for the public, the NCS committee proposes to consider eye lens doses that

exceed 15 mSv per year as a “significant” exposure. Below this level, there is no legal requirement for routine individual eye lens monitoring. In accordance with article 41 of the EU BSS, the committee recommends carrying out a survey for workers for who the assessed (calculated) equivalent dose to the eye lens varies between 10 and 15 mSv per year. This survey is needed to demonstrate that the 15 mSv dose level is not exceeded, as expected. This survey should be performed adequately, based on the methods described in Chapter 5 to mimic the routine measurements. The situation during the survey should represent normal work circumstances within a year. It should be performed for at least three consecutive months since the intention of the survey is to have a representative sample of the annual doses. If the activities are very irregular (large fluctuations from month to month), longer periods of monitoring may be appropriate [19]. It is recommended that the results of individual monitoring are used to verify the assumptions used in the prior risk assessment.

Table 3-1 Recommended action levels per year for monitoring of the eye lens

Recommendation by	Survey	Routine monitoring
IAEA TECDOC 1731 [18]	-	> 5 mSv
ISO-15382 [19]	Not specified	> 15 mSv (single year) or > 6 mSv (consecutive years)
IRPA guidance [20]	1-6 mSv	> 6 mSv
This report	10-15 mSv	> 15 mSv

3.5 Protection measures

In order to limit the dose to the eye lens, several protection measures can be applied and taken into account in the risk assessment. Specific work situations may require a dedicated approach, although some general (ALARA) protection principles such as decreasing the strength of the radiation source, decreasing the exposure time and increasing the distance to the source apply to all work situations. Descriptions of the exposure conditions, expected doses, possible measures and proposals for adequate individual monitoring for relevant worker groups are provided in Chapter 6. Chapter 7 expands on the education and medical surveillance of the exposed workers.

4 Overview of exposed worker groups

4.1 Introduction

This chapter contains an overview of groups of workers whose eyes are or may be exposed to ionising radiation. Exact calculations of the expected eye lens dose are not relevant for workers who only receive a low dose. As the exposure of the worker increases, the dose to the eye lens needs to be assessed with more precise calculations or measurements. This chapter aims to provide a first estimate of the eye lens dose, based on information in:

- the Dutch national dose registry;
- UNSCEAR publication “Sources and effects of ionizing radiation” from 2008 [21].

These sources of information contain only the $H_p(10)$ dose, measured with whole body dosimeters. As little or no eye lens dose measurements are available for the entire “population” being exposed to ionising radiation, the whole body dose is used as a surrogate of the eye lens dose.

4.2 Population overview based on data from the Dutch national dose registry

In the Netherlands, labels for source type, work[5] and employer category are assigned during the registration process of personal dosimeters. This allows for retrospective analysis of the recorded data associated with registered dosimeters. Anonymised $H_p(10)$ data for the year 2015 from the Dutch national dose registry (NDRIS) and the NRG dosimetry service were collected. The NRG dosimetry service is the largest dosimetry service in the Netherlands. The standard NRG whole body dosimeter measures both $H_p(10)$ and $H_p(0.07)$ at the same wearing position. Therefore, $H_p(0.07)$ data from the NRG database were added to this overview to obtain additional insight into influences of different measurement depths.

An overview of the number of workers as a function of different dose groups and work categories is presented in Table 4-1. Data are sorted as a function of the number of workers in the highest dose category. This does not necessarily mean that these work categories have the highest risks on a significant dose; some work categories with high risks only contain a limited number of workers. The number of workers in the different databases with annual doses higher than 15 mSv is presented in Figure 4-1. It should be noted that some of the database entries may be deceptive. For example, due to the high quality of radiation protection in Dutch and Belgian radiotherapy departments, occupational exposures higher

[5] Different work categories may occur at the same employer.

than 6 mSv per year are not to be expected, unless incidents occur. Most probably, the high dose entry reported in Table 4-1 (>10 mSv) can be attributed to a dosimeter that was left in the treatment room during irradiation of a patient or phantom.

Table 4-1 Number of workers in different work categories as a function of $H_p(10)$ values in the Dutch national dose registry and as a function of $H_p(0.07)$ in the NRG database for the year 2015.

	$H_p(10)$ NDRIS (in mSv)						$H_p(0.07)$ NRG (in mSv)		
Work category	≥ 0	> 1	> 6	> 10	> 15	> 20	≥ 0	> 15	Relevant source types
Radiology	10323	824	175	94	53	34	10017	70	X-ray
Interventional proc., MD	3694	1084	262	135	67	30	3385	89	X-ray
Other industrial applications	1261	81	5	4	3	2	846	4	Several
Other applications	1001	50	14	3	3	2	591		Unknown
Industrial radiography (mobile equipment)	990	164	6	3	3	2	563	2	Sealed sources
Interventional proc., other	840	121	18	7	3		840	5	X-ray
Veterinary medicine	4762	192	23	7	1		4754	5	X-ray
Industrial irradiation	608	19	5	3			546		Cyclotron
Isotope production	374	99	4	1			374	1	Cyclotron
Radiotherapy	1549	6	3	1			1336		Accelerator
Other medical applications	642	30	1	1			589	1	Several
Nuclear medicine (excl. PET)	1458	118	2				1355		Several
Education, R&D	1451	15	1				506		Several
Transport (excl. nuclear fuel)	78	2	1				78		Several
Aircrew	14462	12157					n/a		Natural
Nuclear energy	1045	73					n/a		Reactor
PET applications	402	53					402		Several
Maintenance and repair	686	10					604		X-ray
Transport of nuclear fuel	346	10					343		Several
Nuclear fuel enrichment	189	2					189		Several
Waste treatment and storage	30	2					30		Unknown
Dental radiology	2030	1					2030		X-ray
Security, Safety & Inspection	269	1					241		Several
Industrial radiography (fixed)	208						205		Several
Other nuclear applications	47						47		Several
Mining, oil & gas extraction	32						32		Several
Automatic control engineering	14						14		Several
Decommissioning	5						5		Several
Total	47721	15111	520	259	133	70	29922	177	

Based on this overview, the following observations can be made:

- The largest group of workers receiving a high dose is found in fluoroscopically-guided interventional procedures. These workers usually wear their dosimeter on the collar when using a lead apron. The dose values presented here are measured outside the lead apron.

- Small groups with high dose values are found in veterinary medicine, isotope production, industrial radiography and other applications.
- Some workers in industrial applications with high doses work with cyclotrons (see right column of the table).

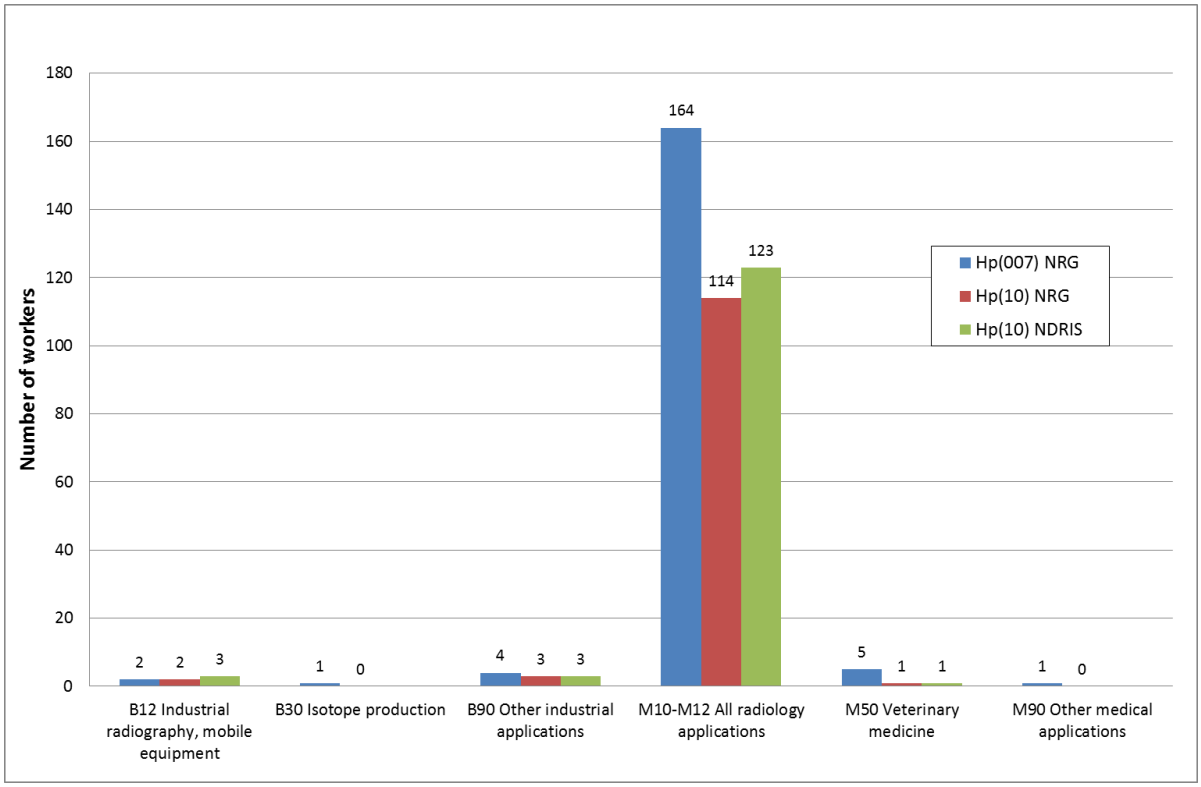


Figure 4-1 Number of workers with a measured dose of more than 15 mSv (data for 2015).

4.3 Population overview based on other publications

The UNSCEAR publication “Sources and effects of ionizing radiation” from 2008 [21] gives an extensive overview of the exposed worker groups. According to this publication, the largest groups with high (whole body) doses are found in nuclear power plants, industrial radiography, diagnostic radiology, radioisotope production and uranium mining. One group that was not found in the Dutch national dose registry is the group of workers exposed in workplaces other than mines due to radon in building materials. Because the dose of workers in diagnostic radiology seems to be reported under the apron, the use of this publication for estimation of the eye lens dose is limited.

IAEA TECDOC 1731 [18], the technical information sheets provided by the French Radiological Protection Society [22] and publications by the IRPA task group [20, 23] list

various worker groups who may receive significant eye lens doses. Examples mentioned in these publications are:

For Pu, Am and beta emitters:

- glove box work and related maintenance [24]
- those handling plutonium or depleted uranium

For ^{60}Co and ^{58}Co (primarily activation products):

- nuclear facility modification works (e.g. work on steam generators, work on vessel closure thermocouples, welding on hot spot)
- dismantling operations (e.g. waste sorting or waste package filling)
- changing targets and maintenance works on accelerators or cyclotrons

4.4 Risk categories for exposed workers groups

Based on the previous sections and input from professionals involved, the following three risk categories are proposed:

1. Significant eye lens doses to be expected (highlighted red in Table 4-1)
   Staff working in close proximity to patients in:
   - fluoroscopically-guided procedures (including interventional cardiology, interventional radiology, other interventional fluoroscopically-guided procedures)
   - CT-guided interventions
2. Moderate eye lens doses to be expected (highlighted orange in Table 4-1)
   Staff working in:
   - nuclear medicine (typically those preparing radiopharmaceuticals)
   - veterinary medicine (especially those involved in imaging of horses, both by X-ray and by scintigraphy)
   - industrial radiography (performing non-destructive testing with sealed sources)
   - nuclear industry and isotope production (replacement of cyclotron targets)

   Workers handling beta sources require special attention, because the measured $H_p(10)$ whole body dose may underestimate the eye lens dose.
3. Only limited eye lens doses to be expected

   In general, the groups marked in green in Table 4-1 and some of the categories marked in orange are expected to receive limited eye lens dose. This category comprises aircrew, staff involved in radiation therapy (manual brachytherapy with high energetic sources is very rare nowadays) and workers involved in veterinary medicine applications for pets, including scintigraphy.

5 Recommendations for measurement of the eye lens dose

5.1 Introduction

Where the flow chart in Chapter 3 and/or the risk analysis, as described in Chapter 4, indicates that eye lens dose monitoring is recommended or mandatory, this section gives guidance on the type of dosimeter to be used, the dose quantity and the position of the dosimeter on the body. The appropriate operational dose quantity for the eye lens dose assessment is $H_p(3)$. Therefore, eye lens dosimeters should in principle be calibrated in terms of this quantity. However, as described in the work of Behrens et al. [25, 26] and in Chapter 2.3 of this report, dosimeters calibrated in terms of other quantities, i.e. $H_p(0.07)$ and $H_p(10)$ may be used as well, depending on the exposure conditions.
The radiation field parameters that should be taken into account are:

- the type of radiation;
- the energy and angle of incidence of the radiation;
- the geometry of the radiation field;
- the protection measures.

It should be noted that, irrespective of the quantity used, the dosimeter should be calibrated by the dosimetry service on an appropriate phantom, i.e. the phantom should mimic the backscatter radiation from the head. As a representative mode for the head, a cylindrical phantom has been developed in the ORAMED project [16]. Studies by Behrens have shown that the widely used slab phantom can be used for calibration as an alternative for the cylindrical phantom, provided that the incidence angles for the radiation are smaller than 75 degrees [27]. Since the ORAMED project several types of eye lens dosimeters have become available and intercomparisons have been performed, including many of the available eye lens dosimeters [28, 29].

5.2 Eye lens dose measurements for different exposure situations

Workers who might routinely receive significant doses to the lens of the eye can be classified in three exposure categories [18]:

1. Workers exposed to a relatively uniform whole-body (penetrating) radiation field;

The expected dose to the eyes of workers in this category is comparable to the expected dose at other positions, such as chest or neck, as long as the distances of the body locations to the radiation source are comparable. For these workers, the expected eye lens dose can

easily be derived from the measurement results of the whole body dosimeter of these workers.

2. Workers exposed to highly non-uniform radiation fields, in which the lens of the eye may be preferentially exposed, including:

- those whose trunks may be shielded by protection measures but not the head;
- those whose heads are close to a source of penetrating radiation;
- those who are exposed to beta radiation.

For workers of this category, estimation of the expected eye lens dose (based on a measurement elsewhere) is more complicated.

3. Workers exposed to a homogeneous exposure of weakly penetrating radiation, such as beta particles or photons of low energies (below about 15 keV), significantly contributing to the eye lens dose but not to the effective dose.

This category may be of a theoretical nature to some degree, but is mentioned for the sake of completeness and will be included in the schemes in the following sections.

In general, it should be considered that the exposure conditions for the two eyes can be different. For example, when the radiation source is positioned to one side of the body of the worker, the exposure to the eye on that side is higher than to the other eye. When the exposure conditions are expected to be different, monitoring should be carried near the most exposed eye.

5.3 Choice of dose quantity and dosimeter position with respect to the radiation field

Since different types of dosimeters can be used in different radiation field conditions, guidance is given on the use of the appropriate dose quantity and appropriate dosimeter position for exposed workers that potentially need dedicated eye lens dosimetry. While the choice of the adequate dose quantity ($H_p(10)$, $H_p(0.07)$ or $H_p(3)$) is determined by the energy and angle of incidence of the radiation field to which the worker is exposed (Section 2.3), the position of the dosimeter is determined by the geometry of the radiation field (i.e. degree of homogeneity) and the type of protection measures used.

Table 5-1, Table 5-2 and Table 5-3 schematically show a decision tree for photon, electron and neutron fields, respectively. These tables are adapted from the work of Behrens et al. [25]; it is noted that similar results have been summarised in IAEA TECDOC 1731 [18].

In Chapter 6, specific exposure conditions are described for different groups of exposed workers with an expected significant radiation dose to the eye. Adequate monitoring of eye

lens dose will be described for each of these worker groups, based on the exposure conditions presented in Table 5-1 to Table 5-3.

5.3.1 Photon radiation fields

Table 5-1 provides guidance for eye lens dosimetry with respect to photon radiation field characteristics, such as the energy and angle of incidence of the radiation beam, the radiation field geometry and the applicability of radiation protection measures. This type of radiation is used very frequently in medical applications (Sections 6.1 and 6.2), veterinary medicine (Section 6.3), and also in industrial radiography (Section 6.4)

Table 5-1 Guidance on the use of dose quantity and dosimeter position to measure eye lens dose with respect to photon radiation field characteristics, adapted from IAEA TECDOC 1731 page 17, © IAEA, 2013 [18].

<table>
<tr><th>Field characteristics</th><th colspan="3">Guidance</th></tr>
<tr><td rowspan="3">Energy and angle of incidence</td><td colspan="3">Is the mean photon energy below about 40 keV?</td></tr>
<tr><td>If yes
↓
$H_p(3)$ or $H_p(0.07)$ may be used,
but not $H_p(10)$</td><td colspan="2">If no
↓
Is the radiation coming mainly from the front or is the person moving within the radiation field?</td></tr>
<tr><td>If radiation from the front
↓
$H_p(3)$, $H_p(0.07)$ or $H_p(10)$ may be used</td><td>If moving within the radiation field
↓
$H_p(3)$ or $H_p(0.07)$ may be used,
but not $H_p(10)$</td></tr>
<tr><td rowspan="2">Radiation field geometry</td><td colspan="3">Is the worker exposed to a homogeneous radiation field?</td></tr>
<tr><td>If yes
↓
Monitoring of the trunk may be used to estimate the eye lens dose</td><td colspan="2">If no
↓
Monitoring near the eyes is necessary</td></tr>
<tr><td rowspan="2">Protective equipment</td><td colspan="3">Is protective equipment used (personal protective equipment or room protective equipment)?</td></tr>
<tr><td>If used to protect the eye
↓
Monitoring near the eyes and the effect of shielding should be considered (Section 5.4)</td><td colspan="2">If used for the trunk only (e.g. lead apron)
↓
If the worker is exposed to a homogeneous field, but the whole body dosimeter on the trunk is shielded, separate monitoring near the eyes is necessary</td></tr>
</table>

5.3.2 Beta radiation fields

In analogy with Table 5-1, Table 5-2 provides guidance for eye lens dosimetry with respect to beta radiation fields. This type of radiation is used in e.g. nuclear medicine (e.g. Y-90, Lu-177 therapy, Section 6.2), in brachytherapy and in the nuclear industry (Section 6.5)

Table 5-2 Guidance on the use of dose quantity and dosimeter position to measure eye lens dose with respect to beta radiation field characteristics, adapted from IAEA TECDOC 1731 page 18, © IAEA, 2013 [18].

<table>
<tr><th>Field characteristics</th><th colspan="2">Guidance</th></tr>
<tr><td rowspan="2">Energy and angle of incidence</td><td colspan="2">Is the maximum beta energy above about 0.7 MeV?</td></tr>
<tr><td>If no
↓
No monitoring due to beta radiation is necessary as it does not penetrate to the lens of the eye.</td><td>If yes
↓
Monitoring is necessary as described according to the geometry of the radiation field and protection used</td></tr>
<tr><td>Radiation field geometry</td><td colspan="2">As beta radiation fields are usually rather inhomogeneous, monitoring of the dose to the lens of the eye is necessary with the dosimeter placed near the eyes. However, it may not be needed if a thick shield is used, see field characteristic below.</td></tr>
<tr><td rowspan="2">Protective equipment</td><td colspan="2">Is protective equipment used that is thick enough to absorb the beta radiation in use?</td></tr>
<tr><td>If used for the eye
↓
Consider only ‘photon radiation’ (Table 5-1) as the beta radiation is completely absorbed by the shielding. The production of bremsstrahlung must be taken into account – contributions produced outside and inside the shielding</td><td>If not used for the eye
↓
$H_p(3)$ is the only appropriate quantity</td></tr>
</table>

5.3.3 Neutron radiation fields

Table 5-3 gives guidance for eye lens dosimetry with respect to neutron radiation field characteristics. Neutron radiation is mainly used in the nuclear industry (Section 6.5).

Table 5-3 Guidance on the dosimeter position to measure eye lens dose due to neutron radiation fields, adapted from IAEA TECDOC 1731 page 16, © IAEA, 2013 [18].

<table>
<tr><th>Field characteristics</th><th colspan="2">Guidance</th></tr>
<tr><td>Energy and angle of incidence</td><td colspan="2">For certain energies and angles of incidence of neutrons, whole body monitoring is not likely to be conservative with respect to the dose to the lens of the eye [30], therefore, neutron dosimetry of the lens of the eye may become necessary in some workplace situations [30]. However, this needs further investigation</td></tr>
<tr><td rowspan="2">Radiation field geometry</td><td colspan="2">Are homogeneous radiation fields present?</td></tr>
<tr><td>If yes
↓
Monitoring of the trunk ($H_p(10)$-dosimeter) may be used as a surrogate of eye lens dose</td><td>If no
↓
Monitoring near the eyes is necessary with $H_p(3)$-dosimeter</td></tr>
<tr><td>Protective equipment</td><td colspan="2">Any personal protective equipment in use may not be adequately protective for neutron radiation</td></tr>
</table>

5.3.4 Mixed radiation fields

In case of exposure to mixed radiation fields, monitoring should be done for all types of radiation contributing more than 2.5 mSv in a year[6]. Guidance on the use of dosimeters in cases of mixed radiation fields is given in Table 5-4. Regarding the type and position of the dosimeters, guidance in Table 5-1 to Table 5-3 applies.

[6] For mixed radiation fields, IAEA recommends specific monitoring for those radiation types contributing more than 1 mSv per year [18]. The same document also recommends eye lens dose monitoring above 6 mSv per year. As this document proposes eye lens dose monitoring from 15 mSv per year, monitoring for mixed radiation fields is recalculated accordingly.

Table 5-4 Guidance on the choice of dosimeter types to monitor the dose to the lens of the eye in mixed radiation fields, adapted from IAEA TECDOC 1731 page 19, © IAEA, 2013 [18].

Radiation in the field			Necessary types of dosimeters
Neutron	**Photon**	**Beta above 0.7 MeV**	
x			See Table 5-3
	x		See Table 5-1
		x	See Table 5-2
x	x		Separate monitoring for neutron field (Table 5-3) and photon field (Table 5-1)
x		x	Separate monitoring for neutron field (Table 5-3) and beta field (Table 5-2)
	x	x	One $H_p(3)$-dosimeter for photon and beta fields positioned near the eyes
x	x	x	Separate monitoring for neutron field (Table 5-3) and one $H_p(3)$-dosimeter for photon and beta fields positioned near the eyes

5.4 General recommendations regarding dosimeter position

Guidance on the position of the dosimeter for specific radiation field characteristics is given in Table 5-1, Table 5-2, Table 5-3 and Table 5-4. In general, eye lens dosimeters should be positioned as close as possible to the most exposed eye, in contact with the skin and facing the radiation source [19]. When room or source protection tools are used, such as lead (suspended) shields, lead cabins or shielding for radioactive vials and syringes, the protection efficiency is usually included in the dose measurement. However, when personal protective equipment such as radiation safety glasses are used, it could be very difficult to position the dosimeter in such a way that the exposure characteristics of the dosimeter are equal to those of the eye lens. In this case, it is recommended to position the dosimeter above or next to the eye protection and apply an appropriate dose reduction factor (see Chapter 6).

6 Eye lens exposure and protection in practice

This chapter aims to transpose the legal and theoretical context of eye lens protection into a practical implementation for different worker groups. These groups, which include worker groups that are prone to a significant or moderate eye lens exposure, are:

- staff performing fluoroscopically-guided procedures (interventional cardiologists and radiologists, vascular surgeons and neurosurgeons);
- staff involved in the preparation and administration of isotopes for nuclear medicine;
- veterinary medicine professionals involved in imaging of horses, both by X-ray and by scintigraphy;
- staff performing industrial radiography;
- staff involved in isotope production or working in the nuclear industry.

Each section of this chapter addresses the exposure conditions, the expected eye lens dose and the protection measures per worker group. The content is based on the input from experts in the field, literature and measurements. In the description of the exposure conditions, the focus is on exposure of the eye lens and on the differences with other body parts. The description of the protections measures includes the conditions in use, effectiveness and costs.

Depending on the expected eye lens dose, additional measures can be useful to protect the lens of the eye. The preferred approach would be to reduce the source strength or shield the source itself, to decrease the exposure time, to increase the distance to the source (with or without tools) and to use room protective measures. The last step in the optimisation process (when the eye lens dose reduction is still not satisfactory) would be to make use of personal protective equipment such as radiation safety glasses [17]. For all measures, the effectiveness depends heavily on proper use. Education and training of workers is extremely important.

6.1 Fluoroscopically-guided procedures

The largest group of category A workers based on their expected eye lens dose are those involved in fluoroscopically-guided procedures. This section contains information on the exposure conditions, the expected eye lens dose, protection measures, and individual monitoring for these workers. A practical guide for workers involved in fluoroscopically-guided procedures is added in Appendix 1.

6.1.1 Exposure conditions in fluoroscopically-guided procedures

In this report, fluoroscopically-guided interventional procedures comprise interventional cardiology, interventional radiology, CT-guided interventions, and other applications of fluoroscopically-guided interventional X-ray procedures, for example in traumatology, vascular and maxillofacial surgery, orthopaedics, urology and neurology. Of these procedures, interventional cardiology and radiology usually produce the highest exposure levels.

Usually, these applications are performed in catheterisation rooms, interventional radiology rooms or operating rooms. During the majority of these applications, the operator or medical specialist is standing next to the patient table, close to the C-arm or fluoroscopy machine (Figure 6-1). Interventional procedures usually involve fluoroscopic imaging. Movements of the X-ray beam carrier, rotation, and angulation of the X-ray tube housing and movement of the patient table are carried out by means of a control panel fixed at the patient table or manually. Fluoroscopic images are shown on a movable ceiling-mounted display unit. The display unit may be positioned opposite the operator, diagonally opposite the operator, near the distal end or over the distal end of the patient table. The second operator or assistant and circulating assistant are usually positioned further away from the patient and radiation source.

Factors that contribute to the eye lens dose include the following:

- the distance of the operator to the patient (primary radiation field) and angle of the radiation source (i.e. the patient scattering the primary beam);
- the position of the display unit, which determines the orientation of the (head of the) operator with regard to the scattered field;
- type and position of protection measures.

Note that the dose to the left eye can differ from the right eye, depending on the position and orientation of the head of the operator [31]. This is of particular importance in exposure situations where the radiation source is not positioned in the sagittal plane of the patient body.

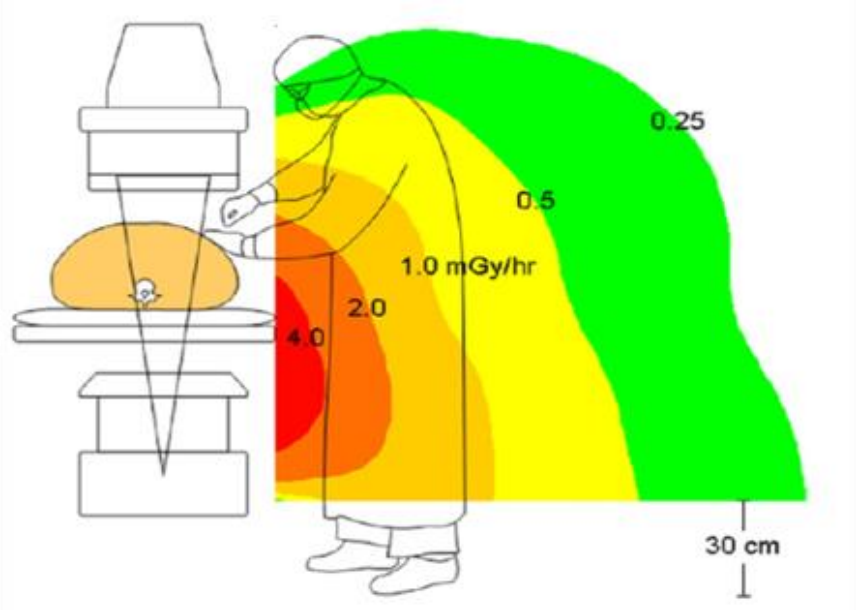


Figure 6-1 Schematic view of the set up in fluoroscopically-guided procedures with an under-couch tube position.

Reprinted with permission from The Radiological Society of North America: RadioGraphics [32], 2006.

6.1.2 Expected eye lens dose in fluoroscopically-guided procedures

Literature

The expected occupational eye lens dose may be estimated based on measurement results reported in literature. Therefore, this section aims to provide an overview of eye lens doses for fluoroscopically-guided procedures reported in literature[7].

The following characteristics are extracted from publications:

- role of the exposed person – operator and assistant;
- medical procedure – the procedure is copied from the publications and sorted according to the following types: cardiac angiography, cardiac interventions, CT-guided interventions, radiological intervention, radiology, fluoroscopically-guided surgery, urology;
- eye lens dose per procedure – the range (minimum and maximum) of a measured dose is included.

Publications show a large variety in aim, method and reported eye lens dose (see Table 6-1). Various positions and orientations of exposed persons, radiation sources, imaging

[7] The PubMed database has been searched using the following search string: Radiation Protection Dosimetry, Health Physics and Journal of Radiological Protection searched for "eye lens" and "dose" and searched for "eye lens" "protection", with and without "radiation". The same search strings are used for a general internet search. Some of the references listed in the papers found were also included.

equipment, monitors and protective measures, etc. have been found. The reported eye lens dose was obtained in clinical conditions, experimental set-ups and Monte Carlo simulations.

The doses reported in these publications varied from approximately 10 µSv to tens of mSv per procedure. The mean eye lens dose per procedure is shown in Figure 6-2. The range of values for the eye lens dose of fluoroscopically-guided procedures is presented in Table 6-1. The highest values are associated with the over-couch X-ray tube geometry and the absence of ceiling-suspended screens and protective eyewear.

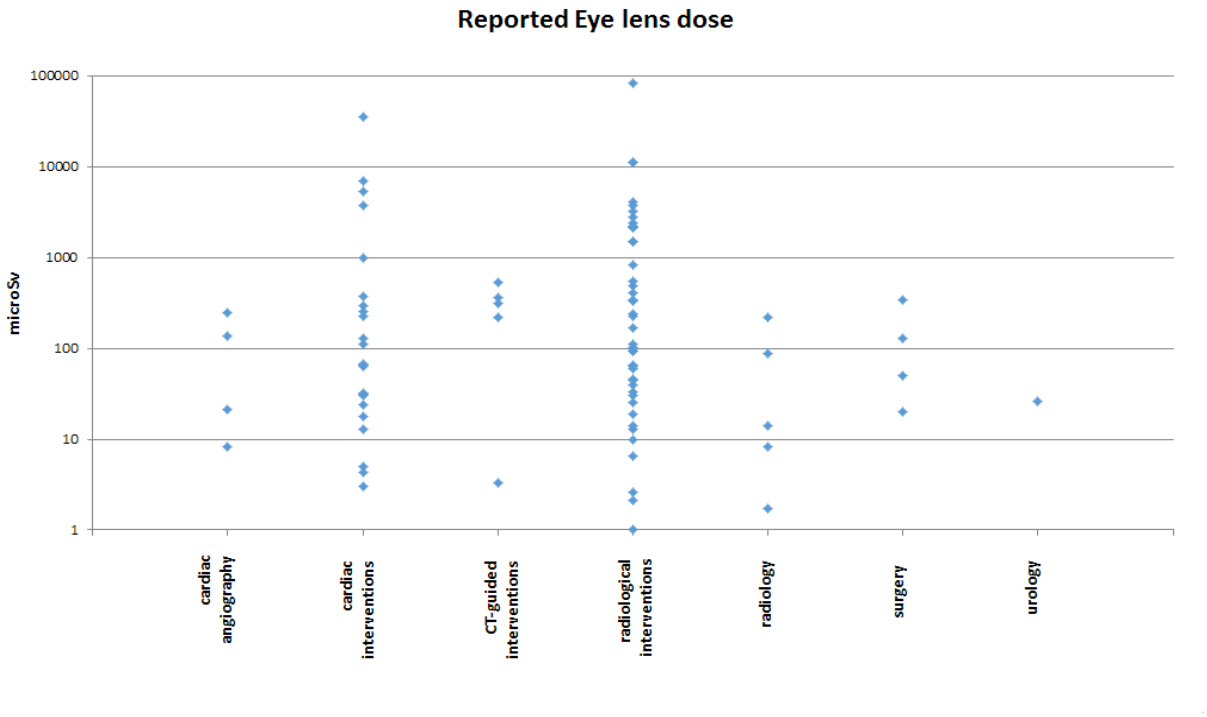


Figure 6-2 Reported eye lens doses per type of procedure reported in various publications.

A large number of publications provide references for the expected eye lens dose of professionals in the field of interventional radiology but the range of the reported doses is very large. As summarised in the UNSCEAR report 2008, annex B [21], various publications showed that measured occupational doses related to fluoroscopically-guided procedures were highly dependent on several parameters, including: the type of intervention performed; operator training; quality assurance; dose rate gradients in the vicinity of the beam orientation; the technique selected (kV, mA or mA-s per pulse); differences in beam filtration; field size; TV-monitor position; intensifier size; operational modes (continuous or pulsed fluoroscopy); the number of frames; dose rates; locations inside the room; patient weight and

size; design and maintenance of the facility and the existence and use of protective tools, especially radiation safety glasses and ceiling-suspended screens [33-38].

An excellent literature overview of the measured ratio between the eye lens to thyroid dose for various interventional procedures is found in the work by Carinou et al. [39]. The reported ratios vary between 0.38 and 1.86, where part of the ratios larger than 1 are found for over-couch X-ray tube geometries.

Table 6-1 Range of reported eye lens doses for various medical categories.

Medical category	**Reported eye lens dose (µSv)**		
	Min	**Max**	**Number of procedure types**
Cardiac angiography	1	250	2 [40, 41]
Cardiac intervention	1.2	35000	< 8 [18, 40, 42-48]
CT-guided interventions	3.3	530	5 [18, 49, 50]
Radiological intervention	1	81900	< 18 [18, 40, 44, 45, 51-61]
Radiology	1.74	220	2 [18, 45, 56]
Surgery	20	340	4 [18, 62, 63]
Urology	26	26	1 [18, 45]

Measurements in proximity of the eye lens

The following section aims to provide insight in the type of information that can be obtained from measurements in proximity of the eye lens. In the Netherlands, it is common practice to wear a personal whole body dosimeter outside the lead apron during fluoroscopically-guided procedures [64]. These measurements can give an indication of the eye lens dose, in clinical routine.

In two Dutch hospitals (LUMC and Isala) pilot measurements were performed with whole body dosimeters (NRG) and eye lens dosimeters (PHE and RadPro). The whole body dosimeter was attached either to the thyroid collar or to a breast pocket. Eye lens dosimeters were positioned on the left and/or right orbita as close to the eye lens as possible.

In Isala hospital, the dose of the left eye lens of four operators was measured during interventional fluoroscopic procedures. In the LUMC, eye lens doses of the right and left eye of eight operators were measured during interventional fluoroscopic procedures and of four operators during CT-guided interventional procedures.

The ratio between the eye lens dose and the whole body dose is shown in Figure 6-3 for the left and right eye, respectively. This figure also contains data from similar measurements performed in different European countries within the framework of the European EURALOC project [65]. All measurements have been performed over longer measurement periods, going from several weeks up to 2 months, to register the dose over a longer time.

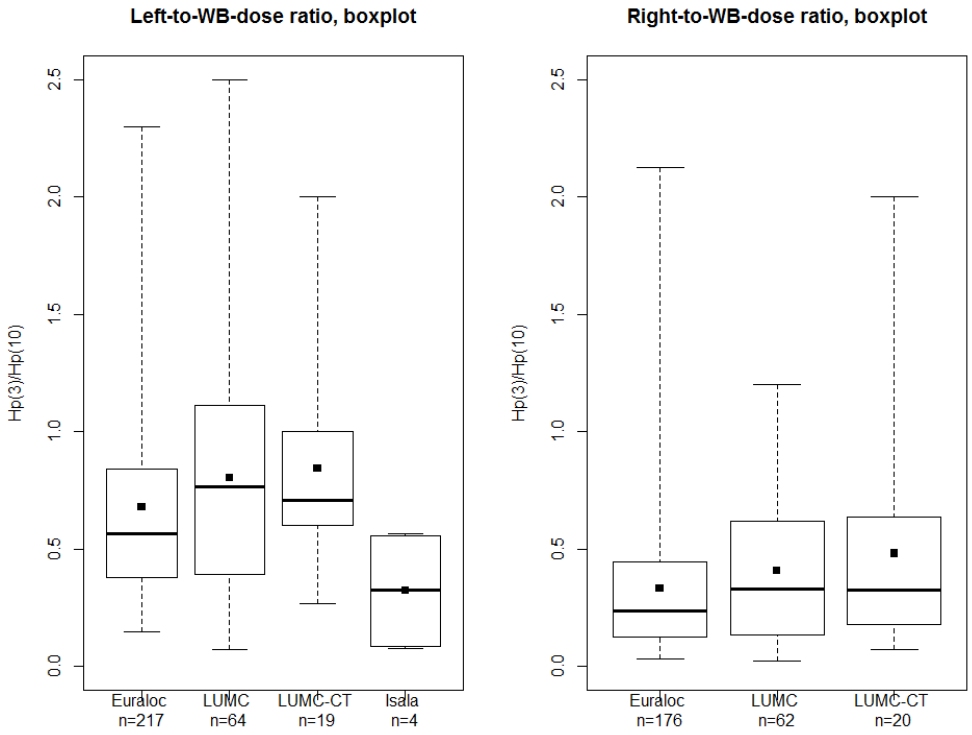


Figure 6-3 Ratio between eye lens dose ($H_p(3)$) and whole body dose ($H_p(10)$) for the left eye (left) and right eye (right), for n measurement periods. The mean is indicated with a dot, the median with a horizontal line. The box contains 50% of the data points and the error bars indicate the minimum and maximum of the data set.

The ratio of the dose to left eye lens and the personal dose equivalent is, in most cases, less than unity. But a wide range ratios is observed, including large outliers in few cases. In most procedures, the left eye is the more exposed, depending on the position of the exposed person relative to the X-ray system. In the current dataset, the eye lens dose ($H_p(3)$) will not exceed the dose limit of 20 mSv per year when the personal dose equivalent ($H_p(10)$), measured outside the lead apron, is less than 10 mSv per year, with only a few exceptions. In 90% of the measurements, the eye lens dose did not exceed the value of 15 mSv per year when the personal dose equivalent was lower than 10 mSv per year.

The differences in eye lens dose and personal dose equivalent, observed in Figure 6-3, are mainly attributed to differences in wearing positions of the dosimeter. At LUMC, an additional eye lens dosimeter was positioned next to the whole body dosimeter during the measurement campaign. An average ratio $H_p(10)/H_p(3)$ of 0.86 was observed with a standard error of 0.19 (results not shown). The higher $H_p(3)$ dosimeter response can probably be attributed to the dose contribution of the scattered photons with a low energy. This difference in response between a $H_p(10)$ and $H_p(3)$ dosimeter is not taken into account in Figure 6-3.

Use of this ratio can be considered for the prospective risk analysis, but should be regarded with care. Due to large variation in observed ratios this is not recommended for most fluoroscopically guided procedures. For recommended eye lens dose monitoring, the reader is referred to Section 6.1.4.

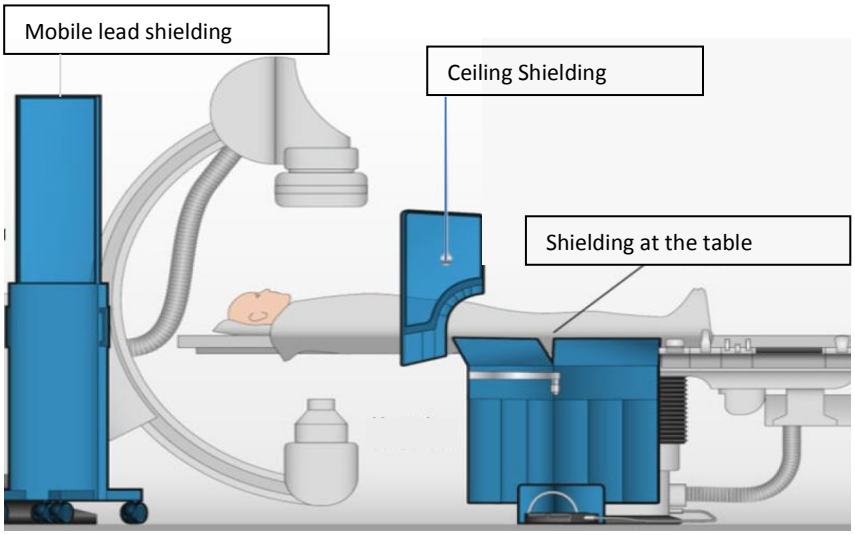


Figure 6-4 Overview of the available protection measures for fluoroscopically-guided procedures.

Reprinted with permission from Springer Berlin Heidelberg: Der Kardiologe [66], 2015.

6.1.3 Protection measures for fluoroscopically-guided procedures

An overview of the available protection measures for fluoroscopically-guided procedures is provided in Figure 6-4. The dose reduction strategy for fluoroscopy guided procedures consists of three parts:

1. Apply dose reduction options on the X-ray system:
    - the use of dose reduction software and hardware;
    - optimisation of the protocol;
    - minimising the gap between patient and detector;

- minimising the field size (diaphragm);
- applying an under-couch tube position;
- reducing the frame rate when image quality is less relevant.

2. Apply protection measures in the radiation field near the table and patient (Figure 6-5 to Figure 6-7):
   - *Position of the display* – Preferably, the display is positioned at operator eye-level, so that back tilting of the head is avoided. Back tilting (in case the displays are positioned at increased height) has a negative influence on the eye lens dose where scattered radiation can reach the eye through the gap between the glasses and the head [67].
   - *Ceiling-suspended shields and table mounted shields (upwards and downwards)* – Ceiling suspended shields should be positioned as close to the patient as possible to minimise the gap between shield and the source of scattered radiation. Moreover, scattered radiation is shielded more easily if the shield is positioned close to where the scattered radiation is created, therefore the shield should be positioned close to the image detector (and not next to the operator). The effect of the ceiling-suspended shield on the eye lens dose is reported in [67, 68]. In practice a Dose Reduction Factor (DRF) of 5 is typically applied for ceiling-suspended shields.

Figure 6-5 Ceiling suspended shield

Figure 6-6 Table mounted shields

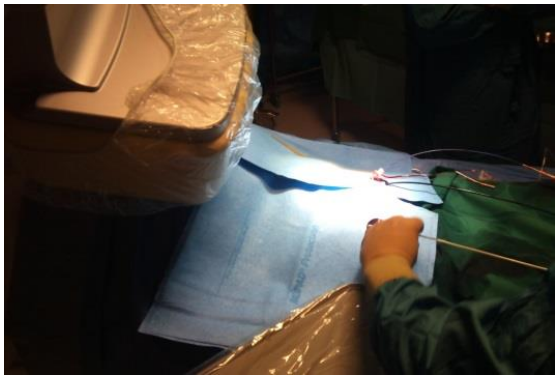


Figure 6-7 Flexible drapes

- *Disposable/reusable flexible drapes* – in procedures where the use of a ceiling-suspended lead shield is not possible, a disposable or reusable flexible drape can reduce scattered radiation to some extent. Drapes crossing the primary X-ray beam should be avoided, because the automatic exposure control increases the dose rate to compensate for the added attenuation. The effect of application of the drapes on the eye lens dose is studied in [68, 69]. A DRF of 2 may be a conservative approach.

3. Personal protective equipment
   - *Radiation safety glasses* - Wearing radiation safety glasses can be an effective way of protecting the eye lens if ceiling-suspended shields cannot be used. Radiation safety glasses are effective when the exposure is frontal or, put differently, when the wearer is looking through the glasses to the scattering object. An important prerequisite is that the glasses are adapted to the geometry of the face, where contact between the nose and cheeks and side shielding are of great importance. The effectiveness of wearing radiation safety glasses was studied in multiple studies [59, 68, 71-73], by means of phantom studies and measurements in clinical settings. A DRF of 2 may be considered a conservative approach if the glasses are applied effectively. Higher DRF's may be achieved, but ICRP-139 [72] states that the DRF that is applied should not be greater than 4.

Figure 6-8 Radiation safety glasses.

Figure 6-9 Radiation safety mask.
Reprinted by permission from SAFETY FIRST SALES [70], 2016.

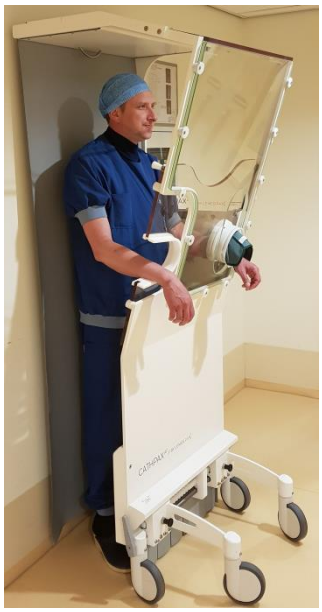


Figure 6-10 Lead cabinet.

   - *Radiation safety mask* - Radiation safety masks (or face masks or lead acrylic visors) are of a significant lower lead equivalence than lead glasses, being regularly only 0.1 mm. Full face masks have the benefit of covering a larger area than radiation safety glasses, thus reducing the exposure not only to the eyes, but also to other regions of the head that would make a significant contribution to the

dose to the eye lenses from backscatter. A review by Martin et al. reports a DRF varying between 2 and 4 [68]. This suggests that using a DRF of 2 would be a conservative approach.

- *Lead cabinet* - In some situations the use of a lead protective cabinet can be considered, especially for operators with physical problems and thus not able to wear a lead apron. The cabinet will protect the operator, but its use could physically obstruct the use of other protective measures and therefore increase the dose for other staff. Further information on performance of lead cabins can be found in [74-77]. The DRF can be in the order of 100 [78].

An indication of the costs of these measures is provided in Table 6-2. An indication of the dose reduction factors (DRFs) of the measures is provided in Table 6-3. These DRFs are dependent on the technical radiation parameters and clinical work method used.

Correct application of shielding materials is essential to ensure their efficacy. Additionally, adequate staff training and advice is important to ensure effective radiation protection. Also, minimising patient exposure and maintaining distance are vital. Bear in mind that workers positioned further away from the radiation source may not necessarily benefit from (individual) protection measures for operators.

Table 6-2 Estimated costs of protection measures for fluoroscopically-guided procedures (€ = € 0-100, €€ = €100-1000, €€€ = €1000-10.000, €€€€ = > €10.000).

Protective measure	**Costs**
Table shields	€€€
Ceiling-suspended glass	€€€
Disposable protective drapes	€ (a piece)
Radiation safety glasses	€€
Prescription radiation safety glasses	€€€
Lead head shield	€€
Lead cabinet	€€€€

Table 6-3 Indication of dose reduction factors (DRFs) for various protective measures.

Protective measure	Lead thickness (mm)	DRF in literature	Typical DRF
Radiation safety glasses	0.3-0.75	2.1 [67], 1.1-9.0 [71], 3-6 [72], 1.4-5.2 [73], 2.5-4.5 [68]	2
Radiation safety mask	0.10	4.0 [73], 2-4 [68]	2
Ceiling-suspended shield	0.5	5.7 [67], 2-20 [68]	5
Disposable protective drapes	Bismuth	2-4.5 [68], 1.6 [69]	2
Lead cabinet	1.8	54 [74], 68-390 [75], 28 [76], 100 [78]	100

6.1.4 Individual monitoring of the eye lens dose

If the risk analysis (Chapter 4) indicates a possible eye lens dose higher than 15 mSv per year, individual monitoring of the eye lens dose is mandatory. ICRP-139 contains a number of valuable recommendations for measures in interventional procedures [72]. When monitoring the eye lens the following five aspects are relevant.

1. The dosimeter should be positioned next to the eyes

Because of the close proximity to the radiation field and a possible use of protective shielding in fluoroscopically-guided procedures, the operator is usually not exposed to a homogeneous radiation field. According to Table 5-1, the eye lens dose should be monitored by means of a dosimeter positioned next to the eyes. This is in accordance with the ICRP-139 publication [72], which mentions that above a certain value (e.g. 10 mSv), it may be advisable to improve the accuracy of assessment by wearing an eye lens dosimeter adjacent to the most exposed eye. An example of the use of such an eye lens dosimeter is given in Figure 6-11.

Figure 6-11 Illustration of the use of an eye lens dosimeter near the most exposed eye in interventional radiology.

2. Recommended dose quantity for dosimeter calibration is $H_p(0.07)$ or $H_p(3)$

Medical staff performing interventional fluoroscopically-guided procedures is exposed to photon radiation scattered from the patient. Typical scattered X-ray spectra vary between mean energies from 20 keV to 120 keV [79]. The main operator does not move in the room, but the X-ray tube rotates during the procedure and produces a scattered photon field that incidences the operator usually obliquely from below. Based on these typical exposure conditions and regarding energy and angle of incidence, it is recommended to use dosimeters calibrated in terms of the dose quantities $H_p(0.07)$ or $H_p(3)$ (see Table 5-1).

3. Monitoring near the collar or on the chest may prove to be adequate for assessment of the eye lens dose

Evaluation of measured dose near the eye lens and at the collar may indicate to omit the measurement near the eye lens in the following occasions:

- The ratio between whole body dose and eye lens dose is constant over a prolonged measurement period. This may be the case when no protective shielding is used.
- The whole body dose is systematically higher than the eye lens dose (with no exceptions).

If one of these situations occurs, the whole body dosimeter may be used to monitor the eye lens dose. The duration of the monitoring period depends on the variability of the ratio in time.

4. Dosimeter should be placed above personal protective equipment where possible

In analogy to the policy NCS recommends for the lead apron [64], it is preferable to place the dosimeter above the personal protective equipment. Advantages of this approach are that the measured dose is more likely to exceed the background dose and that the risk that the dosimeter is only partially covered is eliminated. However, this may not be practicable in every situation. Therefore the following guidance is given:

- Radiation safety glasses: the dosimeter should be worn outside the radiation safety glasses near the most exposed eye.
- Radiation safety mask: the dosimeter may be positioned inside or outside the mask. If the mask is appointed to one specific worker and if the mask is worn consistently, it is feasible to attach the dosimeter to the outside of the mask. However, if the mask is used by multiple workers or not worn consistently, it is recommended to wear the

dosimeter separately from the mask near the most exposed eye, for example on a head band.

- Lead cabinet: the dosimeter should be worn by the worker positioned inside the lead cabinet near the most exposed eye, since it is impossible to measure the eye lens dose close to the eyes when the dosimeter is positioned on the outside. Moreover, there is a reasonable chance that the dosimeter will be left inside the room after termination of the procedure.

5. A dose reduction factor can be applied under specific conditions

When the dosimeter is placed near the eye, outside of the personal protective equipment, the measured eye lens dose may be corrected for the attenuation of the eyewear. A conservative dose reduction factor of 2 can be applied for radiation safety glasses, when the following conditions are met [18, 19, 59, 68, 79]:

- the worker is conscientious in wearing protective eyewear;
- the eyewear contains a minimum of 0.5 mm of lead equivalent [19, 59]. This applies to the lenses as well as to the frame (side shielding). Note that Koukorava et al [80] report no statistically significant difference between the use of 0.3 and 0.75 mm lead;
- the display is positioned at eye level of the operator, so that back tilting of the head is avoided and the worker looks through the radiation safety glasses to the scattering object.

The local radiation protection expert should analyse individual conditions to apply the appropriate factors if one wishes to apply a dose reduction factor higher than 2. In optimised situations where the radiation safety glasses nicely connect to the nose and cheeks and the previously mentioned conditions apply as well, a factor of 3 to 5 is achievable [19]. However, ICRP-139 [72] states that the DRF that is applied should not be greater than 4.

Additionally, when a dose reduction factor is applied for the calculation of the eye lens dose, the degree to which a protection measure is used in practice should be monitored [72].

6.2 Nuclear medicine

6.2.1 Exposure conditions in nuclear medicine

Radioisotopes used in nuclear medicine can be divided into three categories: SPECT-isotopes, PET-isotopes used for imaging purposes and isotopes used for therapy. These radiopharmaceuticals are prepared in radionuclide laboratories and subsequently administered to patients for therapy or to enable scintigraphy. In each of these steps workers are exposed to ionising radiation. SPECT-isotopes typically transmit gamma radiation with an energy of 100 – 200 keV while PET-isotopes emit positrons, which, after annihilation, transform into gamma radiation with an energy of 511 keV. Therapeutic radioisotopes can emit alpha radiation, beta radiation and gamma radiation.

In general, nuclear medicine comprises the following work procedures:

1. *Preparation of radiopharmaceuticals in radionuclide laboratories* – During the preparation of radiopharmaceuticals staff is working in close proximity to relatively large amounts of radioactivity. Preparation is typically performed in a flow cabinet. The worker is then performing his/her activities behind a shield of PMMA (acrylic glass) or lead glass, depending on the type of radiation emitted by the radionuclide. Most of the time the radiopharmaceutical is shielded in a container.
2. *Administration* - When the radiopharmaceutical is administered to the patient, it flows as a radioactive fluid out of the shielding material into the patient. The radiation attenuation provided by the patient's body is considerably lower. At this stage the occupational exposure to ionising radiation increases.
3. *Imaging* - During imaging, workers stay most of the time in the control room behind shielding. Therefore, as the worker typically spends only a few minutes close to the patient, occupational exposures to ionising radiation during imaging procedures are expected to be limited.

6.2.2 Expected eye lens dose in nuclear medicine

The largest exposures take place during preparation in the radionuclide laboratories, during nuclear therapy and PET administration. During SPECT administration, imaging and quality control the worker exposure is lower due to the type and amount of radioactivity handled.

The eye lens dose was investigated in several studies [81-83]. Measured eye lens dose varied between 0.6 to 9.3 mSv per year. No significant difference between either eye was found [81]. In two studies the ratio between the measured eye lens dose, $H_p(3)$, and whole body dose, $H_p(10)$, was investigated. The ratio $H_p(3)/H_p(10)$ varied between 0.3 to 2.3 in the

study by Dabin and between 0.7 to 1.1 in the study by Kopec [84]. This suggests that the whole body dose at the chest can be used as a first estimate for the eye lens dose, but this data should be evaluated with care. The whole body dose recorded in the Dutch national dose registry for this population confirms this dose range. Doses larger than 10 mSv per year are not expected, unless an incident occurs. A Belgian/Polish study [81] also addresses eye lens doses for certain therapeutic procedures in which beta-emitting isotopes are used. It was concluded that, per procedure, the eye lens dose did not exceed the personal dose equivalent of 100 µSv. Because of the limited occurrence of these therapeutic procedures (three procedures per month), the annual eye lens dose is expected to be limited to a few mSv.

6.2.3 Protective measures in nuclear medicine

Depending on the radiation emitted by the used radionuclides, there is a significant difference in the amount of shielding required and the type of material that is recommended. Radioisotopes used for SPECT-procedures typically have a half value layer in lead of less than 1 mm, while PET isotopes have a half value layer in lead of in the order of 6 mm [85]. Because of the penetrating nature of the radiation, protective radiation safety glasses do not play a role in nuclear medicine.

Protective measures used in nuclear medicine can be summarised as follows:

1. The (effective) use of shielding

The radionuclide laboratories have flow cabinets available with permanent shielding. The largest reduction in eye lens dose is obtained by the lead glass positioned on the worker's side of the flow cabinet. The lead glass is available in different lead equivalent thicknesses of up to 30 mm for PET-procedures. The worker is able to assess the procedure directly through the lead glass while being shielded. The radioactivity can be stored in different forms of shielding throughout the entire preparation of the radiopharmaceuticals. The generator which provides the required radioisotope is shielded with several centimetres of lead, depending on the radioisotope used. Labelling is also performed using dedicated lead shielding. The end product, the radiopharmaceutical, is stored in a shielded syringe as well as in a lead container. Protective measures during administration consist of applying the correct amount and type of shielding for the prepared radiopharmaceuticals. In case of gamma radiation exchanging lead for the same thickness of tungsten improves the shielding. The use of PMMA as a shielding material for beta radiation reduces bremsstrahlung. Where both beta and gamma radiation are concerned, syringe shieldings are in use which consist of a combination of PMMA and lead. A measure, that can be used to reduce the exposure

during extraction, is to extract the activity from the vial while it is being monitored in a shielded dose calibrator. The activity can be extracted to the shielded syringe without the need to measure the activity afterwards.

2. Limitation of the time spent in proximity to the source

Exposure time can be reduced for all mentioned procedures by optimising work routines. Especially for either new or rare routines, practising procedures in advance helps reducing exposure times. Different types of automation are in use in nuclear medicine. Automated systems are available for those procedures where exposure to ionising radiation of the workers gets too high. During preparation, either the generator or the vial is placed in such a system and the final product is retrieved automatically, resulting in less exposure time of the worker in proximity to the source. Automated systems, in which the syringe or vial can be placed, are available for administration as well.

An overview of the costs of protection measures in nuclear medicine is given in Table 6-4.

Table 6-4 Costs of protection measures (€ = € 0-100, €€ = €100-1000, €€€ = €1000-10.000, €€€€ = > €10.000)

Protective measure	Costs
Vial shielding	€€ (a piece)
Syringe shielding	€€ (a piece)
Shielded flow cabinet	€€€€
Automated system	€€€€

6.2.4 Individual monitoring of the eye lens dose

Workers in nuclear medicine departments that only perform planar imaging or SPECT imaging, prepare and inject radiopharmaceuticals, emitting photons with energies in the range between 100 and 200 keV, mostly receive a frontal exposure. In this case, dosimeters calibrated in terms of $H_p(3)$, $H_p(0.07)$ or $H_p(10)$ can be used as adequate dose quantity (Table 5-1).

Workers in nuclear medicine departments additionally involved in PET imaging are not only exposed to photon radiation (of 511 keV), but also to beta radiation when radiopharmaceuticals are being prepared. The same holds for departments performing therapy with radionuclides. For the most common PET radioisotopes (e.g. F-18, Ga-68), but also for some therapeutic isotopes (I-131, Lu-177) the maximum beta energy is below 700 keV. Therefore, no specific monitoring for the beta radiation is necessary as it does not penetrate the eye lens (Table 5-2). For some therapeutic radioisotopes, such as Y-90, the

maximum beta energy is of the order of several MeV (Y-90: 2.280 MeV) and monitoring of the beta contribution might also be needed if the shielding used is not sufficient to absorb the beta radiation completely. In this case, only eye lens dosimeters calibrated in terms of $H_p(3)$ are appropriate (Table 5-2). For PET radioisotopes such as O-15, N-13 and C-11, the maximum beta energy is larger than 700 keV and a contribution from the betas to the eye lens dose can be expected as well.

As the technologist, preparing or injecting the radiopharmaceuticals (photons or betas) is positioned very close to the source, the distance between trunk and source or eyes and source tends to be different, so that the worker is exposed to a rather inhomogeneous radiation field. Therefore, dose monitoring near the eyes is always necessary, in case the risk analysis predicts an annual eye lens dose above 15 mSv.

6.3 Veterinary medicine

6.3.1 Exposure conditions and expected dose in veterinary medicine

Veterinary X-ray imaging

The highest worker dose in veterinary medicine is found amongst those imaging horses. During these inspections it is common to acquire about twenty X-ray images of knee and hoof (podo). In addition, images of back and neck may be acquired. Examinations take place on-site at the client, or at the practice of the veterinarian. Although bucky systems are being used in some practices, in most practices mobile x-ray equipment is used in combination with DR (digital radiology) or CR (computed radiology) imaging systems. The imagers are positioned by hand or with tools such as distance holders or mobile stands. Staff holding the imagers wear a lead apron and sometimes lead gloves. The use of additional lead shielding is usually not practically feasible.

In veterinary practices for pets, the measured whole body doses outside the lead apron are below 6 mSv and staff are classified as category B workers or not classified as an exposed worker at all (dose below 1 mSv), as is confirmed in the worker population overview presented in Section 4.2. At busy horse practices, producing more than 10.000 images per year, measured whole body doses between 6 and 15 mSv can be found [86, 87], although this is not very common (the data presented in Section 4.2 suggests that only a small fraction of the workers receives a whole body dose of more than 6 mSv). However, it is possible that eye lens doses approach and even exceed the value of 15 mSv in specific situations with a high workload [88].

Veterinary nuclear medicine

In some specialized veterinary practices in the Netherlands radiopharmaceuticals are used for scintigrafic examination in horses and pets and/or radionuclide therapy in cats. Within the scope of this report only scintigraphy in horses using photon emitting radiopharmaceuticals is of interest with an ambient fluence spectrum around 100 keV in the examination room e.g. technetium-99m (^{99m}Tc) [89]. Recent data show that a dose rate of 2 µSv per hour per GBq is typical for these procedures, resulting in a whole body dose less than 6 mSv a year measured outside the lead apron [90, 91].

In a local investigation by Winderickx [90] a ratio of 0.7 between the eye lens and whole body dose was found with a measured eye lens dose of 4 µSv per procedure per GBq. On a yearly basis this results in an eye lens dose of less than 5 mSv (based on ~200 procedures per

year). Based on this data, the measured whole body dose outside the lead apron provides a safe estimate of the eye lens dose.

6.3.2 Protection measures in veterinary medicine

Radiation protection for veterinary medicine is strongly influenced by the fact that animals may move during examination and time is a limiting factor, especially when many images are acquired during inspections. When working on-site the options to bring (protective) equipment are limited as well.

Veterinary X-ray imaging

The dose reduction strategy in veterinary X-ray imaging applications consists of three parts:

1. dose reduction options on the X-ray system;
2. dose reduction measures in the setup;
3. the use of personal protective measures.

These three parts will be discussed consecutively.

1. Options to reduce the dose by choice of X-ray and imaging system

In general, aspects such as optimal beam collimation and optimisation in the choice of kV and mAs settings apply in a similar way to the medical practice. DR (digital radiology) and CR (computed radiology) imaging systems are both in use in veterinary practice. DR systems can be applied with lower dose for the imaged object. DR systems are heavier than CR systems, so it is more difficult to use a distance holder.

2. Dose reduction measures in the setup

Several tools may be used to increase the distance of the workers with respect to the radiation (scatter) source during horse inspections.

A podoblock can be used for fixing of the hoof, so that it is possible to keep the horse at a larger distance and therefore reduce the worker dose. The use of podoblocks is common practice, nowadays, in horse inspections [92].

The use of distance holders (with or without foot) allows the worker to achieve more distance from the imaged object (Figure 6-12). The use of distance holders is easier for CR systems due to their lower weight, especially when the imaged area is at height. Several international guidelines promote the use of cassette holders and recommend a minimum distance for the worker to the primary beam of 1 or 2 metres [93-96].

A third option to increase the distance to the imager is the use of a mobile stand with a cassette holder. Several types of stands are available, portable and on wheels. Drawbacks

of the use of a mobile stand are the increased time for inspections and the risk that the horse moves in the meantime.

Another choice that can be made is the choice between a mobile system (on-site) and a bucky system (at the practice of the veterinarian). When a bucky system is used, it is (often) not necessary to hold the imager by hand, allowing the worker to achieve greater distance.

Figure 6-12 Positioning of the imager when using a distance holder.

Reprinted with permission from MXR Podoblock B.V.[97], 2016.

3. The use of personal protective measures

With reference to medical applications, personal protective measures can be applied to reduce the eye lens dose. The use of radiation safety glasses is currently not very common. Table 6-5 provides insight into the costs for the different possible protection measures that can be taken to reduce the eye lens dose in veterinary medicine with horses.

Table 6-5 Overview of protection measures for the eye lens in veterinary medicine (€ = € 0-100, €€ = €100-1000, €€€ = €1000-10.000, €€€€ = > €10.000).

Protective measure	Costs
Podoblock	€€
Distance cassette holder	€€
Mobile stand with cassette holder	€€€
Radiation safety glasses	€€
Prescription radiation safety glasses	€€€
Use of bucky vs portable system	€€€€

Veterinary nuclear medicine

The following dose reduction measures can be considered for veterinary scintigraphy:

1. reducing the dose by choice of the activity of the radiopharmaceutical

For scintigraphic examination on a horse the activity of ^{99m}Tc administered is usually 4 to 8 GBq (10 to 15 MBq kg^{-1}). Dose reduction can easily be achieved by choosing the lowest activity for optimal imaging results.

2. dose reduction measures in the setup

During the examination the horse must be sedated adequately to eliminate unexpected movements and mobility. For safety reasons as well as for limiting the duration of the examination the procedure needs a minimum of two staff members, one to hold the horse in a proper position by the head and the second to acquire the images.

The most efficient way to achieve dose reduction is to keep the distance to the horse as large as possible but in most cases this is not practicable.

3. the use of personal protective measures

When other measures don't result in enough reduction of the eye lens dose, the use of protective lead glasses can be considered. Based on the half-value layer of 0.27 mm for ^{99m}Tc, in theory a reduction of 3.7 can be achieved for 0.5 mm lead. In practice, the efficiency of radiation safety glasses will be lower.

6.3.3 Individual monitoring of the eye lens dose

Veterinaries that image horses with X-rays are exposed to (scattered) photon radiation with energies comparable to the medical fluoroscopic applications (mean energies ranging from 20-100 keV). The imaged anatomic regions produce a scattered photon field that incidences the veterinary from different angles, depending on the region of interest and the tools used for positioning of the detector. In this case dosimeters calibrated in terms of $H_p(3)$ or $H_p(0.07)$ may be used (Table 5-1). Because of the close proximity to the radiation field, the operator is not exposed to a homogeneous radiation field. This indicates, according to Table 5-1, that monitoring near the eyes is necessary, in case the risk analysis (Chapter 4) indicates a possible eye lens dose > 15 mSv.

In analogy with the measurement position while wearing a protective (lead) apron [64], the committee recommends to wear the eye lens dosimeter outside radiation safety glasses near the most exposed eye, and to apply a suitable dose reduction factor for the protective effect of the glasses. For further considerations and guidance on using a dose reduction factor for personal protective measures, the reader is referred to Section 6.1.4.

For those imaging horses using scintigraphy the considerations in Section 6.2.4 apply. As in practice the expected eye lens dose is well below 10 mSv [90], the measured whole body dose may provide a conservative estimate of the eye lens dose.

6.4 Industrial radiography

6.4.1 Exposure conditions and expected dose

Industrial radiography is a method of non-destructive testing where many types of manufactured components can be examined to verify the internal structure and integrity of the specimen. Industrial radiography is usually performed utilising either high energy X-rays (> 200 kV) or gamma rays (^{192}Ir or ^{60}Co). In general, industrial radiography procedures consist of different steps, where workers may be exposed [98]:

- transport of the source from the depot to the site (worker exposure only for sealed sources);
- on-site transit of the source from container to the object (worker exposure only for sealed sources);
- exposure of the object (worker exposure for both sealed and X-ray sources).

Although the sealed source is shielded during transport to the site, the distance to the worker may be small. This may involve in a substantial part of the worker's dose, especially when the worker is carrying the source or transporting the source by car. Although in this case the radiation field cannot be considered homogeneous, the trunk is usually closer to the radiation source than the eye lens. During transit of a sealed source to the object under investigation, the distance of the worker to the source is larger (5 metres or more). The worker can, in this case be exposed to a homogenous field of the unshielded source. During irradiation of the object, the worker is usually only exposed to leakage or scattered radiation. Again, the distance is large and the field may be considered homogeneous.

The expected dose in industrial radiography was investigated in a worldwide survey in 2009 [99]. The radiographers reported a mean dose of 2.9 mSv per year with a maximum of 30 mSv; the regulatory bodies reported a mean dose of 3.4 mSv per year with a maximum of 150 mSv. This data is consistent with the Dutch practice (usually not exceeding 5 mSv per year [100] and only a few workers with higher doses were found in the Dutch national dose registry). According to the Dutch registry, higher exposures are usually found with sealed sources. These higher exposures can usually be attributed to radiation accidents, for instance during evacuation of a trapped source [99]. Le Heron reports that approximately 20% of industrial radiographers have had an accident, near miss or deviation in the last 5 years, with an approximate incidence of 8 accidents per 1000 operators per year [99].

6.4.2 Protection measures in industrial radiography

The most important protection measures for industrial radiography are the basic principles such as limiting the exposure time, maximising the distance to the radiation source and proper orientation and collimation of the source. If possible, sealed sources can be transported using a cart. During exposure, the worker may step back behind a wall. Due to the high energy of the radiation source, the effectiveness of protective radiation safety glasses is limited (transmission of 70% or more).

6.4.3 Individual monitoring of the eye lens

Workers performing industrial radiography are exposed to high energy photon radiation. In most of the exposure situations described in Section 6.4.1, the worker is exposed to a homogeneous radiation field. During transport of the sealed source and during radiation accidents, the distance can be shorter and the field can be considered inhomogeneous (but usually the radiation source will be closer to the trunk than to the eye lens). This indicates, according to Table 5-1, that in most exposure conditions in industrial radiography the whole body dosimeter will provide an adequate estimate of the eye lens dose. For the inhomogeneous exposure conditions, the whole body dosimeter is expected to provide a conservative estimate of the eye lens dose. The worker dose due to (rare) radiation accidents is not included in the calculation for the expected dose in the prior risk assessment and is therefore not taken into account in the categorisation of the worker. When the necessary adequate dosimetry is chosen, this potential dose contribution is therefore not taken into consideration, even if it would lead to a higher eye lens dose than whole body dose.

6.5 Isotope production and nuclear industry

Moderate eye lens exposure may be seen in staff working in the nuclear industry and in isotope production. Two groups will be mentioned explicitly in this section:

- workers replacing foils at cyclotron targets;
- workers inspecting steam generators at nuclear facilities.

For other worker groups in the nuclear industry with expected high dose, who are not covered in this section, the reader is referred to the general guidelines in Chapter 5.

6.5.1 Exposure conditions and expected dose

Cyclotron operator:

For operators replacing activated target foils at cyclotrons the distance may be as small as 40 cm for the eye lens [101]. The operator may be positioned behind shielding, but visual guidance of his activities is necessary (see Figure 6-13). The spectrum of the radiation depends on the target and the accompanying foils being irradiated with protons and the energy of the cyclotron beam. Although the activated products emit a mix of beta and gamma radiation, the effect of the beta radiation is limited due to the aluminium flange holder. The typical energy of the gamma radiation is about 800 keV for the iodine targets.

Figure 6-13 Operator replacing activated target foils on a cyclotron.

Reprinted with permission from GE Healthcare [101], 2017.

The expected eye lens dose may be as large as 12 mSv per year, based on 6 foil replacements for iodine targets [101]. For fluoride targets the eye lens dose is expected to be lower.

Nuclear facility workers:

Workers at nuclear facilities may receive a moderate eye lens dose during inspection of steam generators [22, 102]. The generator is inspected during a limited period of time, with the radiation source closer to the head than to the body, resulting in a body to eye lens dose ratio close to 1.5 [22]. An example of such an inspection is illustrated in Figure 6-14. The radiation field consists of a mix of beta and gamma radiation, typically primarily based on activation products, such as ^{58}Co and ^{60}Co.

Figure 6-14 Inspection of a steam generator at the nuclear facility in Borselle, the Netherlands.
Reprinted with permission from EPZ [102], 2018.

During large maintenance operations, where workers are moving in the proximity of these generators, the estimated eye lens dose is between 5 and 10 mSv per year, based on H*(10) measurements outside the respirator mask near the eye in one of the Dutch nuclear facilities [102]. Japanese and British studies [103, 104] confirm the view that moderate eye lens exposures can be found at nuclear facilities, but eye lens doses of more than 15 mSv are very rare. Risk groups that are mentioned are workers involved in decommissioning and

maintenance or repair work, where beta radiation may significantly contribute to the eye lens dose if the eyes are not specifically protected.

6.5.2 Protection measures

Cyclotron operators:

Due to the high energy of the gamma radiation, protection measures are only effective when substantial shielding is applied. Because visual guidance is required for manipulation of the foils a logical choice for shielding would be the use of lead glass behind which the operator is exchanging the foil.

Nuclear facility workers:

For the moderate risk activities in nuclear facilities a significant portion of the eye lens dose may be delivered by beta radiation. During inspection of steam generators, a respirator mask is being used to prevent internal exposure. A side effect of these masks is that they provide protection against the beta radiation. Another measure to limit the eye lens dose for the workers inspecting steam generators is to minimise the time in proximity of the generator. The inspections are trained extensively in an environment without ionising radiation.

6.5.3 Individual monitoring of the eye lens dose

Cyclotron operators:

Workers exchanging cyclotron foils are mainly exposed to high energy photon radiation from the activated foil. The operator is usually facing the radiation source directly, where the distance to eye lens is larger than to the trunk. As the operator may also be positioned behind shielding, the radiation field geometry to which they are exposed is considered not to be homogenous. This indicates, according to Table 5-1, that monitoring near the eyes is necessary, in case the risk analysis (Chapter 4) indicates a possible eye lens dose > 15 mSv per year. Because of the high energy of emitted gamma radiation, the dosimeter may be calibrated in terms of either $H_p(3)$, $H_p(0.07)$ or $H_p(10)$.

Nuclear facility workers:

These workers are mainly exposed to a mixture of beta and high energy photon radiation. Usually the worker is facing the radiation source directly, with a smaller distance to eye lens compared to the trunk. Based on this difference in distance, the radiation field geometry to which the worker is exposed is considered not be homogenous (especially when respirator masks are used). Therefore monitoring near the eyes is necessary (Table 5-1) when the risk

analysis (Chapter 4) indicates a possible eye lens dose > 15 mSv per year. In literature, measurement of the eye lens dose outside [104] and behind the respirator mask [103] is reported. A disadvantage using a headband system behind the mask is that the hermiticity of a respirator mask needs to be maintained at all times. In analogy with the measurement position while wearing a protective (lead) apron [64], the committee recommends to wear the eye lens dosimeter outside the respirator mask, and to determine and apply an appropriate correction factor for the protective effect of the mask.

7 Recommendations for education and medical surveillance

7.1 Role of education

Education and training plays an important role in radiation protection. For medical professionals, guidance for radiation protection education and training is provided in Radiation Protection 175 [105]. One of the core radiation protection topics is “Particular staff radiation protection aspects”. This implies that occupational radiation protection should be included in the education programmes for medical professionals.

Education and training plays a role for the eye lens dose exposure in different ways. First the exposure settings as time, collimation and kV/mAs could be optimised by education and training of the activities. Practicing new skills before putting them into practice can decrease the total amount of radiation that is needed for the activity. Miller et al [106] showed that the effective dose of the worker can, indeed, be reduced by education and/or training prior to the introduction of new equipment or materials.
On the other hand, education in the use of protective measures is important. For example, the effectiveness of radiation safety glasses depends on the use of the glasses. To achieve maximum effectiveness, attention needs to be paid to issues such as the placement of the viewing monitor because this user-dependent setting will determine the angulation of the head in relation to the radiation [107]. The awareness of this fact can be created during education and increases the effectiveness of the protective measures.

7.2 Medical surveillance

The new dose limit for the eye lens asks for re-evaluation of the role of eye examinations in periodical medical examinations for category A workers with an expected eye lens dose of more than 15 mSv. The aim of this section is to provide background information on cataract and how detection of cataract could be embedded in the system for medical surveillance.

7.2.1 Background on cataract

What is cataract? What causes cataract?
The first signs of cataract manifest as small opaque spots on the lens (Figure 7-1). Specific medical circumstances, like diabetes, genetic factors and

Figure 7-1 Patient with cataract.
Reprinted with permission from Sergei Primakov/Shutterstock.com, 2018.

nutrition can add to the risk of developing these irregularities, but the main cause turns out to be ageing [108, 109]. As mentioned in Chapter 2.1, exposure to ionising radiation can also contribute to the development of cataract. Visual acuity is gradually disturbed by blurring and scattering of visual input. Early signs of cataract are double vision and diminishing of night vision [110]. The disease is progressive: small spots will develop over time into clinical manifest cataract with restrictions for work and private life.

What is the incidence of cataract?

Cataract is quite common: in the Netherlands the incidence is about 10 new cases that lead to visiting a specialist and a treatment, per 1000 inhabitants per year [111]. Population surveys indicate that there is a much larger prevalence of asymptomatic cataract of 15-30% above the age of 40 to approximately 60% above 70 years [112, 113]. This high prevalence proves that there is a significant delay between the start of the disease and the recognition of it by the patient.

How is cataract diagnosed?

Standard acuity tests (for distance- and near vision) can be used to screen for decrease of sight. This could indicate the presence of (beginning) cataract. These tests can be performed easily, for instance by the health physician at the occupational health center.

The standard technique for specific diagnosis of cataract is a slit-lamp examination. This examination should be conducted by an ophthalmologist or an optometrist with sufficient training to determine early changes in the lens. Eventual aberrations can be captured photographically, for example with Scheimpflug imaging. Together with this investigation, the ophthalmologist will examine the rest of the eye by normal fundoscopy. Occasionally, radiation can cause aberrations of the small vessels in the retina, and these can be seen in a fundoscopy. Both examinations require dilatation of the pupil with medication. This disturbs sight seriously for several hours and restricts many work tasks and for example driving a car.

How is cataract treated?

The treatment of cataract is an operative extraction of the affected lens and replacement with an artificial lens. Nowadays this is an outpatient procedure (no hospitalisation) and after a couple of days, functionality is restored.

7.2.2 System for occupational health surveillance

Periodical occupational health examinations in general

In the Netherlands, the system of occupational health is based on EU directive 89/391/EEC on measures to encourage improvements in the safety and health of workers at work. This is reflected in the “Arbeidsomstandighedenwet”. For medical surveillance with respect to occupational exposure two situations can be distinguished: voluntary and compulsory examinations.

Voluntary preventive health examinations: The employer must be in possession of an assessment of the risks to safety and health at work. The definition of groups of workers exposed to particular risks must be part of the risk assessment. The risks identified in this risk assessment determine the scope of the health surveillance offered to the worker. Employers are obliged to periodically offer workers a health surveillance, appropriate to the defined health and safety risks they incur at work[8]. This health survey is voluntary for the worker. The individual results are not reported to the employer, but relevant aggregated results will be analysed and reported with advices on prevention.

Compulsory preventive health examinations: For some high risk tasks or functions that involve particular health risks there can be legal obligations for performing medical examinations to establish the fitness of workers. Examples of these functions are fire fighters, divers, airplane pilots and truck drivers. Radiological work for workers classified as an exposed worker category A belongs to this category and thus requires yearly medical surveillance by law. For these examinations the employer will receive individual notifications, necessary for the worker to execute these tasks and functions.

Medical surveillance for classification as a category A-worker

The medical surveillance of exposed workers (with regard to their exposure to ionising radiation) is performed by occupational health services (BSS art. 80). In the Netherlands, this medical surveillance is performed by a designated occupational health physician that is also trained as radiation protection expert. The purpose of the medical surveillance is to initially determine the worker's fitness for a post as a category A worker for which the worker is being considered and to determine periodically (at least yearly) whether the worker remains fit to perform their duties (BSS art. 45.3), until the possible exposure has ended. The physician

[8] In the Netherlands, this periodic health examination is called PAGO (Periodiek ArbeidsGezondheidskundig Onderzoek).

can opt for a prolonged surveillance period if there are medical issues to be followed up. The results of these examinations are stored in (occupational) medical files under the control of the occupational health service. The occupational health physician reports the result of the medical surveillance to the employer (fit; fit subject to certain conditions; unfit).

The content of the medical surveillance of the category A worker

The medical surveillance covers possible deterministic and stochastic effects of ionising radiation. Stochastic effects that are considered in the medical surveillance comprise the excess incidence of cancer and the risk of aberrations in reproduction. As it's not useful to monitor these in (annual) physical examinations, the practice among the Dutch assigned physicians is to focus on a questionnaire on medical complaints, mental aspects and other questions about radiological safety. Based on the questionnaire's results the decision is made if further personal medical examination is necessary. The dose limits are such that deterministic effects hardly play a role in the medical surveillance for workers exclusively exposed to X-rays. If contamination is part of the radiological risk there will be a complementary periodical physical examination as well, focused on the features of the risk at stake.

Medical surveillance of the eyes

Decrease of sight (and even cataract) is a common and frequently occurring medical situation. The additional effect of radiation on the incidence of cataract is very low. Therefore we propose to consider the examinations of the eye only as a voluntary aspect of the medical surveillance, which is therefore not part of the obligatory category A examination. From a legal point of view, these examinations are considered part of the health examination which must be offered to the worker, but without the obligation for the worker to undergo this examination and without notification of the employer about the result ("PAGO", see before).

7.2.3 Proposal for implementation of medical surveillance of the eye lens

The purpose of the medical surveillance is to:

- detect unnoticed decrease of visual acuity and limit the consequences for the quality of the execution of the work. Literature shows that early detection of (beginning) cataract gives no advantages in treatment and follow-up of the disease;
- evaluate the use of and coping with the necessary personal protective equipment;
- determine the onset of cataract as a base for consultation on the necessity of treatment and/or reduction of exposure of the worker.

Proposal for medical examinations:

The department “occupational health” of the Dutch Society for Radiation Protection (NVS) proposes this consent for medical surveillance of the eyes of workers at risk (with a calculated eye lens dose of more than 15 mSv):

- Yearly questionnaires should be extended with questions on visual acuity, other eye-related complaints and questions on problems in the use of and coping with personal protection of the eyes like radiation safety glasses and resulting potential neck- and shoulder complaints.
- Standard acuity tests (for distance and near vision) should be offered at least once every two years by the occupational health centre (as part of PAGO).
- If the exposed worker has visual complaints and decrease of vision at the biannual visual acuity measurement an upgrade to a slit-lamp examination should be considered.
- A slit-lamp examination should be offered periodically (as part of PAGO). The relevant frequency of periodical surveillance depends on the outcome of the (occupational) risk assessment and is, in theory, based on a combination of dose and time. For practical purposes we recommend offering it time-contingent every 5 or 10 years.
- When eye lens examinations show a significant decrease in the sight, the potential fitness or unfitness for the job must be discussed with the exposed worker.

In literature the relative risk on cataract varies between <1 and >5 for category A workers [6, 114]. In the largest study it is 1.2 [5]. For the time being, we advise considering the combination of (extended) exposure as category A worker and cataract as an occupational disease[9]. In the Dutch system, occupational diseases are reported to a national body. By gathering statistics on this worker group, the relation between radiation exposure and the disease can be further understood.

[9] A disease is considered an occupational disease when there is a plausibility of more than 50% that it is caused by work conditions.

8 Summary of the recommendations

When the calculated eye lens dose in the prospective risk assessment is higher than 15 mSv per year, a worker must be classified as a category A worker (Chapter 3). According to the EU BSS, for all category A workers with a significant exposure of the eye lens an adequate system for individual monitoring is required. The committee proposes to regard an eye lens dose of more than 15 mSv per year as a “significant” exposure (Section 3.4).

The “adequate system for individual monitoring” of the eye lens dose depends on the exposure conditions of the worker and can be determined using the tables provided in Chapter 5. The exposure conditions, expected dose and adequate dose quantity are presented in Chapter 6 for the most relevant worker groups. Workers receiving a high dose are often working in close proximity of the radiation (scatter) source. Because of this, the distance and angle under which the eye lens is exposed may differ from the trunk and a measurement near the eye lens can be considered the only accurate way to determine the eye lens dose. For this reason, eye lens dosimetry should be used for fluoroscopic procedures (6.1), nuclear medicine (6.2), veterinary medicine (6.3), nuclear industry (6.5) and cyclotron maintenance (6.5) for workers with an expected dose of more than 15 mSv per year[10]. A whole body dosimeter at the chest is considered adequate for estimation of the eye lens dose in industrial radiography[11] (6.4). For workers with an expected dose below or equal to 15 mSv per year, this overview provides a recommendation for an adequate system for monitoring, but the monitoring itself is not mandatory. Under specific circumstances where the ratio between eye lens dose and whole body dose is constant or the whole body dose is consistently higher than the eye lens dose, monitoring near the collar or on the chest may prove to be adequate (Section 6.1.4).

The committee recommends that the radiation protection expert verifies the assumptions underlying the prior risk assessment with the results of whole body and/or eye lens dosimetry. Where the calculated eye lens dose for workers lies between 10 and 15 mSv per year and no adequate monitoring data is available to validate the risk assessment, the

[10] It should be noted that part of the workers in these groups (such as nuclear industry) may be subject to different exposure conditions and the recommended wearing position is different.

[11] For accident scenarios the whole body dosimeter may not adequately estimate the eye lens dose.

committee recommends performing a survey demonstrating that the 15 mSv dose level is not exceeded (Section 3.4).

With respect to the protection measures the committee recommends the following:

- While choosing protection measures, the preferred approach would be to shield the source itself, to apply dose reduction on the system, to decrease the exposure time, to increase the distance to the source (with or without tools) and to use room protective measures. The use of personal protective measures (such as radiation safety glasses) should be considered a last step in this process (Chapter 6).
- Radiation safety glasses should contain a minimum of at least 0.5 mm lead equivalent and only be applied with careful consideration to proper fitting to the face, front and side shielding and orientation of the head with respect to the radiation source. When taking these conditions into account properly, a dose reduction factor of 2 is considered a conservative approach for medical and veterinary X-ray procedures (Sections 6.1.4 and 6.3.3).
- The eye lens dose should preferably be measured on the outside of personal protective equipment near the most exposed eye. This does require the use of a suitable dose reduction factor to estimate the actual eye lens dose. In specific situations it may be more practicable to measure under the personal protective equipment (for instance in a lead cabinet).

The following recommendations are provided for the medical surveillance of category A workers with an expected eye lens dose of more than 15 mSv per year (Section 7.2):

- Yearly questionnaires should be extended with questions on visual acuity, other eye-related complaints and questions on problems in the use of and coping with personal protection of the eyes.
- A visual acuity examination should be offered at least biannually.
- A slit-lamp examination should be offered to workers, periodically, every 5 or 10 years.

9 Literature

1. International Commission on Radiological Protection, *The 2007 Recommendations of the International Commission on Radiological Protection. ICRP publication 103.* Ann ICRP, 2007. **37**(2-4): p. 1-332.
2. International Commission on Radiological Protection, *1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60*. Ann ICRP. 1991;**21**(1-3):1-201.
3. International Atomic Energy Agency (IAEA), *International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, IAEA Safety Series No. 115*. 1996.
4. International Commission on Radiological Protection (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, ICRP Publication 118*. 2012.
5. Chodick, G., 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 Epidemiol, 2008. **168**(6): p. 620-31.
6. Vano, E., et al., *Radiation cataract risk in interventional cardiology personnel.* Radiat Res, 2010. **174**(4): p. 490-5.
7. Worgul, B.V., et al., *Cataracts among Chernobyl clean-up workers: implications regarding permissible eye exposures.* Radiat Res, 2007. **167**(2): p. 233-43.
8. Hourihan, F., P. Mitchell, and R.G. Cumming, *Possible associations between computed tomography scan and cataract: the Blue Mountains Eye Study.* Am J Public Health, 1999. **89**(12): p. 1864-6.
9. Chmelevsky, D., et al., *An epidemiological assessment of lens opacifications that impaired vision in patients injected with radium-224.* Radiat Res, 1988. **115**(2): p. 238-57.
10. Guskova, A.K., *Fifty years of the nuclear industry in Russia – through the eyes of a physician.* Atom. Energy, 1999. **87**: p. 903-908.
11. Nakashima, E., K. Neriishi, and A. Minamoto, *A reanalysis of atomic-bomb cataract data, 2000-2002: a threshold analysis.* Health Phys, 2006. **90**(2): p. 154-60.
12. Neriishi, K., et al., *Postoperative cataract cases among atomic bomb survivors: radiation dose response and threshold.* Radiat Res, 2007. **168**(4): p. 404-8.
13. European Union, *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*. 2014: Publication European Union d.d. 17 January 2014.
14. International Organization of Standardization (ISO), *ISO 4037-3:1999, 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, ISO TC 85/SC 2/WG 2*1999.
15. Daures, J., J. Gouriou, and J.M. Bordy, *Monte Carlo determination of the conversion coefficients Hp(3)/Ka in a right cylinder phantom with 'PENELOPE' code. Comparison with 'MCNP' simulations.* Radiat Prot Dosimetry, 2011. **144**(1-4): p. 37-42.
16. Gauldrini, G., Mariotti, F., Wach, S.,, *A new cylindrical phantom for eye lens Dosimetry development.* Radiat. Meas., 2011. **46**: p. 1231–1234.
17. van Elsäcker-Degenaar, H., *Ioniserende straling (AI-27), Veilig werken met radioactiviteit en ioniserende straling*. 2016.

18. International Atomic Energy Agency (IAEA), *Implications for Occupational Radiation Protection of the New Dose Limit for the Lens of the Eye. IAEA-TECDOC no 1731*. 2013: Vienna.
19. International Organization of Standardization (ISO), *ISO 15382: Radiological protection – Procedures for monitoring the dose to the lens of the eye, the skin and the extremities*. 2015.
20. International Radiation Protection Association, *IRPA guidance on implementation of eye dose monitoring and eye protection of workers*. 2017.
21. UNSCEAR, *Sources and effects of ionising radiation*. 2008.
22. French Radiological Protection Society, *Eye Lens: Regulatory limits. Measurement, dosimetry and medical surveillance. Technical information sheets produced by the Technical Protection Section of the French Radiological Protection Society*. 2016.
23. Cantone, M.C., et al., *Report of IRPA task group on the impact of the eye lens dose limits.* J Radiol Prot, 2017. **37**(2): p. 527-550.
24. Devin P., e.a. *9ème Congrès National de Radioprotection, Bordeaux, La dosimètre du cristallin*. 2013.
25. Behrens, R. and G. Dietze, *Monitoring the eye lens: which dose quantity is adequate?* Phys Med Biol, 2010. **55**(14): p. 4047-62.
26. Behrens, R. *Monitoring the Eye Lens*. in *IRPA*. 2013.
27. Behrens, R., *On the operational quantity Hp(3) for eye lens dosimetry.* J. Rad. Prot. , 2012. **32 (2012) 455-464**.
28. Behrens, R., et al., *Intercomparison of Eye Lens Dosemeters.* Radiat Prot Dosimetry, 2017. **174**(1): p. 6-12.
29. Clairand, I., et al., *First Eurados Intercomparison Exercise of Eye Lens Dosemeters for Medical Applications.* Radiat Prot Dosimetry, 2016. **170**(1-4): p. 21-6.
30. Gualdrini, G., P. Ferrari, and R. Tanner, *Fluence to Hp(3) conversion coefficients for neutrons from thermal to 15 MeV.* Radiat Prot Dosimetry, 2013. **157**(2): p. 278-90.
31. Domienik, J., A. Bissinger, and M. Zmyslony, *The impact of x-ray tube configuration on the eye lens and extremity doses received by cardiologists in electrophysiology room.* J Radiol Prot, 2014. **34**(4): p. N73-9.
32. Schueler, B.A., *Operator shielding: how and why.* Tech Vasc Interv Radiol, 2010. **13**(3): p. 167-71.
33. Marshall, N.W., J. Noble, and K. Faulkner, *Patient and staff dosimetry in neuroradiological procedures.* Br J Radiol, 1995. **68**(809): p. 495-501.
34. Karppinen, J.T.e.a., *Radiation risk and exposure of radiologists and patients during coronary angiography and percutaneous transluminal coronary angioplasty (PTCA).* Radiation Protection Dosimetry, 1995. **57**(1): p. 481-485.
35. Pratt, T.A. and A.J. Shaw, *Factors affecting the radiation dose to the lens of the eye during cardiac catheterization procedures.* Br J Radiol, 1993. **66**(784): p. 346-50.
36. Vano, E., et al., *Lens injuries induced by occupational exposure in non-optimized interventional radiology laboratories.* Br J Radiol, 1998. **71**(847): p. 728-33.
37. Williams, J.R., *The interdependence of staff and patient doses in interventional radiology.* Br J Radiol, 1997. **70**(833): p. 498-503.
38. Zorzetto, M., et al., *Radiation exposure to patients and operators during diagnostic catheterization and coronary angioplasty.* Cathet Cardiovasc Diagn, 1997. **40**(4): p. 348-51.
39. Carinou, E., et al., *Eye lens monitoring for interventional radiology personnel: dosemeters, calibration and practical aspects of H p (3) monitoring. A 2015 review.* Journal of Radiological Protection, 2015.
40. Vano, E., et al., *Eye lens exposure to radiation in interventional suites: caution is warranted.* Radiology, 2008. **248**(3): p. 945-53.

41. Antic, V., et al., *Eye lens dosimetry in interventional cardiology: results of staff dose measurements and link to patient dose levels.* Radiat Prot Dosimetry, 2013. **154**(3): p. 276-84.
42. Sandblom, V., et al., *Evaluation of the impact of a system for real-time visualisation of occupational radiation dose rate during fluoroscopically guided procedures.* J Radiol Prot, 2013. **33**(3): p. 693-702.
43. Lie, O.O., G.U. Paulsen, and T. Wohni, *Assessment of effective dose and dose to the lens of the eye for the interventional cardiologist.* Radiat Prot Dosimetry, 2008. **132**(3): p. 313-8.
44. Jacob, S., et al., *Eye lens radiation exposure to interventional cardiologists: a retrospective assessment of cumulative doses.* Radiat Prot Dosimetry, 2013. **153**(3): p. 282-93.
45. Ciraj-Bjelac, O. and M.M. Rehani, *Eye dosimetry in interventional radiology and cardiology: current challenges and practical considerations.* Radiat Prot Dosimetry, 2014. **162**(3): p. 329-37.
46. Principi, S., et al., *Eye lens dose in interventional cardiology.* Radiat Prot Dosimetry, 2015. **165**(1-4): p. 289-93.
47. Al-Haj, A.N., A.M. Lobriguito, and I. Al-Gain, *Staff eye doses in a large medical centre in Saudi Arabia: are they meeting the new ICRP recommendations?* Radiat Prot Dosimetry, 2015. **165**(1-4): p. 294-8.
48. Kaljevic, J., et al., *Occupational Dose Assessment in Interventional Cardiology in Serbia.* Radiat Prot Dosimetry, 2016. **170**(1-4): p. 279-83.
49. Heusch, P., et al., *Radiation exposure of the radiologist's eye lens during CT-guided interventions.* Acta Radiol, 2014. **55**(1): p. 86-90.
50. Buls, N., et al., *Evaluation of patient and staff doses during various CT fluoroscopy guided interventions.* Health Phys, 2003. **85**(2): p. 165-73.
51. Zagorska, A., et al., *Eye lens exposure to medical staff during endoscopic retrograde cholangiopancreatography.* Phys Med, 2015. **31**(7): p. 781-4.
52. Heye, S., et al., *Occupational radiation dose: percutaneous interventional procedures on hemodialysis arteriovenous fistulas and grafts.* Radiology, 2012. **264**(1): p. 278-84.
53. Anastasian, Z.H., et al., *Radiation exposure of the anesthesiologist in the neurointerventional suite.* Anesthesiology, 2011. **114**(3): p. 512-20.
54. Seals, K.F., et al., *Radiation-Induced Cataractogenesis: A Critical Literature Review for the Interventional Radiologist.* Cardiovasc Intervent Radiol, 2016. **39**(2): p. 151-60.
55. Galster, M., et al., *[Exposition of the operator's eye lens and efficacy of radiation shielding in fluoroscopically guided interventions].* Rofo, 2013. **185**(5): p. 474-81.
56. Tavares, J.B., et al., *The importance of protection glasses during neuroangiographies: A study on radiation exposure at the lens of the primary operator.* Interv Neuroradiol, 2016. **22**(3): p. 368-71.
57. Struelens, L., et al., *Extremity and eye lens dosimetry for medical staff performing vertebroplasty and kyphoplasty procedures.* J Radiol Prot, 2013. **33**(3): p. 635-45.
58. Domienik, J., et al., *Extremity and eye lens doses in interventional radiology and cardiology procedures: first results of the ORAMED project.* Radiat Prot Dosimetry, 2011. **144**(1-4): p. 442-7.
59. Koukorava, C., et al., *Doses to operators during interventional radiology procedures: focus on eye lens and extremity dosimetry.* Radiat Prot Dosimetry, 2011. **144**(1-4): p. 482-6.
60. Khoury, H.J., et al., *Radiation exposure to patients and medical staff in hepatic chemoembolisation interventional procedures in Recife, Brazil.* Radiat Prot Dosimetry, 2015. **165**(1-4): p. 263-7.
61. Urboniene, A., E. Sadzeviciene, and J. Ziliukas, *Assessment of eye lens doses for workers during interventional radiology procedures.* Radiat Prot Dosimetry, 2015. **165**(1-4): p. 299-303.

62. Cheriachan, D., et al., *Ionizing Radiation Doses Detected at the Eye Level of the Primary Surgeon During Orthopaedic Procedures.* J Orthop Trauma, 2016. **30**(7): p. e230-5.
63. Romanova, K., J. Vassileva, and M. Alyakov, *Radiation exposure to the eye lens of orthopaedic surgeons during various orthopaedic procedures.* Radiat Prot Dosimetry, 2015. **165**(1-4): p. 310-3.
64. Netherlands Commission on Radiation Dosimetry (NCS), *Code of practice for personal dosimetry of professionals wearing protective clothing during radiological procedures, Report 19 of the Netherlands Commission on Radiation Dosimetry, 2008.*
65. Struelens, L., et al., *Radiation-Induced Lens Opacities among Interventional Cardiologists: Retrospective Assessment of Cumulative Eye Lens Doses.* Radiat Res, 2018. **189**(4): p. 399-408.
66. Schächinger, V., Nef, H., Achenbach, S., et al., *Leitlinie zum Einrichten und Betreiben von Herzkatheterlaboren und Hybridoperationssälen/Hybridlaboren.* Der Kardiologe, 2015. **9**(1): p. 89-123.
67. van Rooijen, B.D., et al., *Efficacy of radiation safety glasses in interventional radiology.* Cardiovasc Intervent Radiol, 2014. **37**(5): p. 1149-55.
68. Martin, C.J., *Eye Lens Dosimetry for Fluoroscopically Guided Clinical Procedures: Practical Approaches to Protection and Dose Monitoring.* Radiat Prot Dosimetry, 2016. **169**(1-4): p. 286-91.
69. Sharma, D., et al., *Efficacy of RADPAD(R) protection drape in reducing radiation exposure to the primary operator during Transcatheter Aortic Valve Implantation (TAVI).* Minerva Cardioangiol, 2016. **64**(1): p. 41-6.
70. Safety First Sales. 2017; Available from: http://safetyfirstsales.com/glasses-2/.
71. Rivett, C., et al., *An Assessment of the Dose Reduction of Commercially Available Lead Protective Glasses for Interventional Radiology Staff.* Radiat Prot Dosimetry, 2016. **172**(4): p. 443-452.
72. International Commission on Radiological Protection, *ICRP Publication 139: Occupational Radiological Protection in Interventional Procedures.* Ann ICRP, 2018. **47**(2): p. 1-118.
73. Magee, J.S., et al., *Derivation and application of dose reduction factors for protective eyewear worn in interventional radiology and cardiology.* J Radiol Prot, 2014. **34**(4): p. 811-23.
74. Dragusin, O., et al., *Evaluation of a radiation protection cabin for invasive electrophysiological procedures.* Eur Heart J, 2007. **28**(2): p. 183-9.
75. Ploux, S., et al., *Performance of a radiation protection cabin during extraction of cardiac devices.* Can J Cardiol, 2014. **30**(12): p. 1602-6.
76. Ploux, S., et al., *Performance of a radiation protection cabin during implantation of pacemakers or cardioverter defibrillators.* J Cardiovasc Electrophysiol, 2010. **21**(4): p. 428-30.
77. Maleux, G., et al., *Radiation Protection Cabin for Catheter-Directed Liver Interventions: Operator Dose Assessment.* Radiat Prot Dosimetry, 2016. **170**(1-4): p. 274-8.
78. Poot, L., *Local measurement setup, Isala Hospital, The Netherlands.* 2009.
79. Clairand, I., *Use of personal dosemeters in interventional radiology and cardiology. Test in laboratory condition and recommendations - ORAMED project.* Radiat. Meas., 2011. **46** p. 1252-1257.
80. Koukorava, C., 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**(3): p. 509-28.
81. Dabin, J., et al., *Eye Lens Doses in Nuclear Medicine: A Multicentric Study in Belgium and Poland.* Radiat Prot Dosimetry, 2016. **170**(1-4): p. 297-301.

82. Leide-Svegborn, S., *External radiation exposure of personnel in nuclear medicine from 18F, 99mTC and 131I with special reference to fingers, eyes and thyroid.* Radiat Prot Dosimetry, 2012. **149**(2): p. 196-206.
83. Summers, E.C., et al., *Eye doses to staff in a nuclear medicine department.* Nucl Med Commun, 2012. **33**(5): p. 476-80.
84. Kopec, R., Budzanowski, M., Budzyn´ska, A., Czepczynski, R., Dziuk, M., Sowinski, J. and Wyszomirska, A., *On the relationship between whole body, extremity and eye lens doses for medical staff in the preparation and application of radiopharmaceuticals in nuclear medicine.* Radiat. Meas., 2011. **46**: p. 1295–1298.
85. Delacroix, D. e.a., *Radionuclide and radiation protection data handbook, 2002.*
86. Beukers, M., *Faculty of Veterinary Medicine, Utrecht University, The Netherlands, private communication*. 2017.
87. Leenders, W. *eDigit Equine Digital Imaging and Vetting, The Netherlands, private communication*. 2017.
88. Jonkergouw, P.A.J., *JAS Stralingszorg, The Netherlands, private communication*. 2018.
89. Clairand I., Bottollier-Depois J.F. and Trompier F., *Equine scintigraphy: assessment of the dose received by the personnel* Radioprotection, 2003. **38**(1): p. 61-73.
90. Winderickx, K. Lingehoeve Diergeneeskunde, The Netherlands, *private communication.* 2018.
91. Sommerfeld, T.C., *Strahlenexposition des Personals bei der Skelettszintigrafie mit Technetium-99m-Diphosphonat beim Pferd. Giessen (Germany*. 2016, VVB Laufersweiler Verlag, Giessen (Germany).
92. Sloet van Oldruitenborgh-Oosterbaan M., Barneveld A., Van Den Belt J., *De veterinaire keuring van het paard*. 2007.
93. *Radiological Protection Institute of Ireland. Code of practice for radiation protection in veterinary medicine*. 2002.
94. *Environmental Health Directorate (Canada). Radiation Protection in Veterinary Medicine - Recommended Safety Procedures for Installation and Use of Veterinary X-Ray Equipment, Safety Code 28.* 1991.
95. *Australian Radiation Protection and Nuclear Safety Agency. Radiation Protection in Veterinary Medicine, Radiation Protection Series 17.* 2009.
96. *U.S. Environmental Protection Agency. Federal guidance report no. 14. Radiation Protection Guidance for Diagnostic and Interventional X-Ray Procedures.* 2014.
97. *MXR Podoblock B.V.* 2016; Available from: https://view.publitas.com/db/mxr-podoblock-catalogus-2016-11/page/1.
98. v Leeuwen, D., *ANVS, The Netherlands, private communication. 2018*.
99. Le Heron, J., et al. *Current Practice of Occupational Protection in Industrial Radiography*. in *IRPA13 conference*. 2012. Glasgow.
100. Bloot, A., Luijkx, E. , *Applus RTD., The Netherlands*, *private communication.* 2018.
101. van Mierlo, M., *GE Healthcare, The Netherlands*, *private communication.* 2018.
102. Lous, C., *EPZ,* The Netherlands, *private communication*. 2017.
103. McWhan, A.F. and W. Dobrzynska, *Eye lens dose monitoring in the UK nuclear industry using active personal dosemeters.* J Radiol Prot, 2017.
104. Yokoyama, S., et al., *Current situations and discussions in Japan in relation to the new occupational equivalent dose limit for the lens of the eye.* J Radiol Prot, 2017. **37**(3): p. 659-683.
105. European Union, *Radiation Protection 175, Guidelines on radiation protection education and training of medical professionals in the European Union*. 2014.
106. Miller, D.L., et al., *Occupational radiation protection in interventional radiology: a joint guideline of the Cardiovascular and Interventional Radiology Society of Europe and the Society of Interventional Radiology.* Cardiovasc Intervent Radiol, 2010. **33**(2): p. 230-9.

107. Le Heron, J., Padovani, R., Smith, I., Czarwinski, R, *Radiation protection of medical staff.* European journal of radiology, 2010. **76**: p. 20-23.
108. Hoppenreijs, Staar (cataract), www.oogartsen.nl/oogartsen/ooglens_staar/staaroperatie_cataract, 4 October 2017.
109. Wu, X., et al., *Association of OGG1 and MTHFR polymorphisms with age-related cataract: A systematic review and meta-analysis.* PLoS One, 2017. **12**(3): p. e0172092.
110. Tan, H., *Leerboek oogheelkunde*. 2013: Houten, Nederland: BSL.
111. *Aantal mensen met staar (gezichtstoornissen ICPC F92)*. Available from: https://www.volksgezondheidenzorg.info/onderwerp/gezichtsstoornissen/cijfers-context/prevalentie-incidentie#node-aantal-mensen-met-staar.
112. Acosta, R., et al., *[Systematic review of population-based studies of the prevalence of cataracts].* Arch Soc Esp Oftalmol, 2006. **81**(9): p. 509-16.
113. Prokofyeva, E., A. Wegener, and E. Zrenner, *Cataract prevalence and prevention in Europe: a literature review.* Acta Ophthalmol, 2013. **91**(5): p. 395-405.
114. Ciraj-Bjelac, O., et al., *Risk for radiation-induced cataract for staff in interventional cardiology: is there reason for concern?* Catheter Cardiovasc Interv, 2010. **76**(6): p. 826-34.

Acknowledgements

The subcommittee would like to thank the NCS for the opportunity to write this report.
We would also like to thank the representatives of the consulted Dutch and Belgian scientific and professional societies t for their input and suggestions for improvement of the report.
We are thankful to the external reviewers Peter de Jong and Paul Jonkergouw for their text proposals and critical review of the report.
We are grateful to Mark van Mierlo, Kees Lous, Wouter Leenders, Martijn Beukers, Damie van Leeuwen and Andre Bloot for their input and for providing figures to illustrate the report.
Many thanks to NDRIS and the NRG dosimetry service for providing the anonymised data used in our analysis of the Dutch worker population.
Last but not least, a significant part of this work was financed by the Dutch Ministry of Economic Affairs through the subsidy provided to NRG for the research in radiation protection.

Appendix 1: Practical guidance for fluoroscopically-guided procedures

1. **Perform prior risk assessment**

The RIE-RAD (http://radiationdosimetry.org) can be used as a basis for the prior risk assessment. Specific calculations for the eye lens dose have not been implemented yet, but the system can be applied to the calculation of the eye lens dose. Remarks are the following:
Regular and potential exposure situations that are relevant specifically regarding the eye lens dose need to be added.
The distance from the radiation source to the eye lens may differ from the source-trunk distance, implying that the exposure configuration for the eye lens is different than that for the effective dose. When the worker is standing up straight, the distance from source to eyes is larger than the distance to the trunk, but when the worker is bending over the patient, the opposite is true. Additionally, the angle between the scattered radiation and the eye may differ from the angle between the radiation and the trunk.
According to Dutch legislation, the protective effect of personal protective equipment should not be taken into account in categorisation of workers. Personal protective equipment for the eyes typically includes radiation safety glasses, radiation safety masks, and lead cabinets.

2. **The calculated eye lens dose from the risk assessment is**

a. **≤15 mSv**

The worker is **not classified as exposed worker** based on the calculated eye lens dose. Individual monitoring of the eye lens dose is therefore not mandatory. However, optimisation of the exposure should still be applied and appropriate protection measures are recommended. Recommended protection measures include:

- General dose reduction measures when the calculated dose (effective and/or eye lens) is significant;
- Specific dose reduction measures for the eye lens, in case the eye lens is expected to be higher than the whole body dose. Examples include situations in which the eyes are closer to the source than the rest of the body and situations where the eyes are not protected by structural protection measures that do protect the rest of the body.

b. **>15 mSv**

The **worker is classified as A-worker** based on the eye lens dose. Adequate monitoring and health surveillance are mandatory and protection measures should be optimised.

Adequate monitoring

In fluoroscopically guided procedures:

- Monitoring near the eyes is necessary, since the radiation field cannot be considered homogeneous due to the proximity to the radiation source.
- Dosimeters calibrated for $H_p(3)$ or $H_p(0.07)$ may be used for monitoring, since the mean photon energy is usually above 40 keV and the radiation is not (only) coming from the front (Table 5-1).
- Monitoring near the collar or on the chest may prove to be adequate for assessment of the eye lens dose after a period of monitoring, if:
    - the measured eye lens dose proves to be consistently lower than the whole body dose;
    - the ratio between the eye lens dose and the whole body dose is constant.
- The eye lens dose should preferably be measured above personal protective equipment, if feasible. Exceptions are the lead cabinet and radiation safety masks that are not used continuously or used by multiple workers. For the radiation safety glasses, a conservative dose reduction factor of 2 can be applied, provided that the following conditions are met:
    - the worker is conscientious in wearing protective eyewear;
    - the eyewear (frame and lenses) contains a minimum of 0.5 mm of lead equivalent;
    - the display is positioned at eye level of the operator, so that back tilting of the head is avoided and the worker looks through the radiation safety glasses to the scattering object.
- The local radiation protection expert should analyse individual conditions to apply the appropriate factors if one wishes to apply a higher dose reduction factor than 2. In an optimised situation where the radiation safety glasses nicely connect to the nose and cheeks and the previously mentioned conditions apply as well, a factor of 3 to 5 is achievable, although ICRP-139 states that the DRF that is applied should not be greater than 4. When a dose reduction factor is applied for the use of personal protective equipment, the use of the protection measures should be monitored.

Protection measures

Optimisation of the protection measures should be applied in this order of preference:

1. dose reduction options on x-ray system (dose reduction software and hardware, protocol optimization, minimising the gap between patient and detector, minimise field size/diaphragm, optimize/reduce the frame rate);
2. measures in the field of the table and the patient (positioning of the display such that back tilting of the head is avoided, application of ceiling-suspended and/or table mounted shields, application of flexible drapes);
3. use of personal protective equipment (radiation safety glasses, radiation safety mask, lead cabinet) – In case of radiation safety glasses, best protection is obtained when the glasses fits the face of the worker, e.g. the glasses connect to the nose and cheeks and contain side shielding.

Health surveillance

- Yearly questionnaires for A-workers should be extended with questions on visual acuity, other eye-related complaints and questions on problems in the use of and coping with personal protection of the eyes.
- Additional examinations of the eyes should be offered to category A-workers with an expected eye lens dose of more than 15 mSv per year, meaning:
    - A visual acuity examination should be offered at least biannually;
    - A slit-lamp examination should be offered to workers, periodically, every 5 or 10 years.

  Both examinations are not obligatory and may be carried out on a voluntary basis.