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Occupational Radiological Protection in
Interventional Procedures



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Aims and Scope

The International Commission on Radiological Protection (ICRP) is the primary body in protection against ionising radiation. ICRP is a registered charity and is thus an independent non-governmental organisation created at the 1928 International Congress of Radiology to advance for the public benefit the science of radiological protection. ICRP provides recommendations and guidance on protection against the risks associated with ionising radiation from artificial sources such as those widely used in medicine, general industry, and nuclear enterprises, and from naturally occurring sources. These are published approximately four times each year on behalf of ICRP as the journal *Annals of the ICRP*. Each issue provides in-depth coverage of a specific subject area.

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ICRP is composed of a Main Commission, a Scientific Secretariat, and five standing Committees on: radiation effects, doses from radiation exposure, protection in medicine, the application of ICRP recommendations, and protection of the environment. The Main Commission consists of a Chair and twelve other members. Committees typically comprise 10–15 members each.

ICRP uses Task Groups to prepare its reports. A Task Group is usually chaired by an ICRP Committee member and usually contains a number of specialists from outside ICRP. Thus, ICRP is an independent international network of specialists in various fields of radiological protection, and, at any one time, about two hundred eminent scientists and policy makers are actively involved in the work of ICRP. The Task Groups are assigned the responsibility for drafting reports on various subjects, which are reviewed and finally approved by the Main Commission. These reports are then published as the *Annals of the ICRP*.

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ICRP PUBLICATION 139

Occupational Radiological Protection in Interventional Procedures

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Editorial

HISTORY IS MORE OR LESS BUNK – OR IS IT?

When the International X-ray and Radium Protection Committee [now the International Commission on Radiological Protection (ICRP)] was established back in 1928, its main concern was the occupational exposure of medical staff and the deterministic effects that were already being seen at this time. Old photographs showing doctors with missing fingers and scarred skin are a salient reminder to modern practitioners of the effects that radiation caused because the dangers were not appreciated and appropriate protection was not used. ICRP is celebrating its 90th anniversary in 2018, so it is timely that one of its publications should still have relevance in addressing occupational radiological protection of medically exposed workers (i.e. those involved in interventional procedures).

Interventional procedures using ionising radiation have revolutionised medicine in the last few decades for diagnosis, therapy, and palliation, resulting in more patients being offered treatments that would not have been possible previously. As technology continues to advance at an astonishing rate, so the interventional procedures become more complex, and some may take several hours to complete. New technologies also present new challenges for radiological protection, such as positron emission tomography-computed tomography guided interventions and selective internal radiation therapy.

Although the photographs of missing fingers are now a thing of the past, several studies have demonstrated increased opacities in the lens of the eye and, in some cases, cataracts among interventionalists. Education and training of personnel who perform and who are associated with interventional procedures cannot be emphasised enough, as good practices will reduce doses to patients and staff. A successful radiological protection programme for such procedures requires a team effort from all individuals involved, including doctors, nurses, radiographers, physicists, regulators, and administrators. In addition, staff need to be aware of the importance of wearing personal protective equipment, including dosimeters. Too often, dosimeters and protective lead glasses are not worn, either because of lack of volition or fear of recording high doses that may threaten continuing clinical practice. Interventionalists should take some responsibility for their own personal protection, and not just assume that this is the role of radiation supervisors and medical physicists. A change in behaviour is required to improve compliance with recommended personal protection, and education is key in achieving this goal.

Having worked as an interventional radiologist for nearly 30 years, I acknowledge that it takes a degree of self-discipline to constantly remember to wear several dosimeters, protective glasses, and a thyroid collar for each case, but keeping these items together and performing the same preparatory ritual is not difficult. One would hope that, nowadays, nearly all drivers setting off on a journey remember to put on their seat belt, and the start of an interventional procedure should include a similar routine with protective equipment.

Just over 100 years ago in 1916, several years before the existence of ICRP, Henry Ford gave an interview published in the Chicago Tribune in which he said:

History is more or less bunk We want to live in the present, and the only history that is worth a tinker's damn is the history that we make today.

However, it can be argued that it is only by looking back at events of the past, and learning from them, that we can hope to adopt safer practices today and for the future. After all, this is at the core of ICRP's business – to provide recommendations and guidance related to the use of ionising radiation – and, as demonstrated in this publication, medicine is a very important part of this. Some of the interventional procedures performed at the present time are likely to be obsolete in a couple of decades as they are superseded by the development of new treatments. If history had been considered 'bunk', we would not have the system of radiological protection that has evolved to date, but we should not forget that we are undoubtedly making history today.

CLAIRE COUSINS
CHAIR, ICRP

OCCUPATIONAL RADIOLOGICAL PROTECTION IN INTERVENTIONAL PROCEDURES

ICRP PUBLICATION 139

Approved by the Commission in October 2017

Abstract—In recent publications, such as *Publications 117* and *120*, the Commission provided practical advice for physicians and other healthcare personnel on measures to protect their patients and themselves during interventional procedures. These measures can only be effective if they are encompassed by a framework of radiological protection elements, and by the availability of professionals with responsibilities in radiological protection. This framework includes a radiological protection programme with a strategy for exposure monitoring, protective garments, education and training, and quality assurance of the programme implementation. Professionals with responsibilities in occupational radiological protection for interventional procedures include: medical physicists; radiological protection specialists; personnel working in dosimetry services; clinical applications support personnel from the suppliers and maintenance companies; staff engaged in training, standardisation of equipment, and procedures; staff responsible for occupational health; hospital administrators responsible for providing financial support; and professional bodies and regulators. This publication addresses these elements and these audiences, and provides advice on specific issues, such as assessment of effective dose from dosimeter readings when an apron is worn, estimation of exposure of the lens of the eye (with and without protective eyewear), extremity monitoring, selection and testing of protective garments, and auditing the interventional procedures when occupational doses are unusually high or low (the latter meaning that the dosimeter may not have been worn).

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Keywords: Occupational radiological protection; Interventional procedures; Exposure monitoring; Exposure of the lens of the eye; Protective garments

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PREFACE

Over the years, the International Commission on Radiological Protection (ICRP), referred to below as ‘the Commission’, has issued recommendations and guidance on protection against the risks associated with ionising radiation. *Publication 103* (ICRP, 2007a) contains the most recent update of these recommendations, and *Publication 105* (ICRP, 2007b) summarises the application of the principles to medical exposures.

These publications are of a general nature, but the Commission also decided to address specific problems and difficulties that have been observed, especially in the rapidly evolving use of radiation in medicine. This has been achieved by means of concise publications focused and written in a style that is accessible to those directly involved in the procedures and who are, therefore, directly concerned in their daily work, and by making efforts to ensure wide circulation of such publications.

Examples of these concise publications are those concerned with interventional procedures, such as *Publication 85* (ICRP, 2000b) on avoiding radiation injuries, *Publication 117* (ICRP, 2010a) on radiological protection from fluoroscopically guided procedures outside the imaging department, and *Publication 120* (ICRP, 2013a) on radiological protection in cardiology. These publications provide practical advice aimed at protecting all members of staff involved in the interventions.

However, a reader audience composed of hospital administrators, staff in charge of radiological protection of the hospital, dosimetry services staff, clinical applications specialists from the suppliers and maintenance companies, and regulators need advice on occupational exposure assessment, and tools and methods for occupational protection. They also need advice on specific issues, such as extremity and eye dose assessment (with and without eye protection), selection of protective garments (e.g. aprons, thyroid shielding, protective eye glasses), estimation of effective dose when an apron is worn, and auditing the interventional procedures when occupational doses are unusually high or low (the latter meaning that the dosimeter may not have been worn). Provision of guidance on these issues is the purpose of this publication.

The membership of the Working Party was as follows:

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EXECUTIVE SUMMARY

1. Background

(a) Physicians in many medical and surgical specialties, assisted by nurses and radiographers (radiological technologists), perform interventions guided by radiological imaging as an alternative to conventional surgery. On average, these interventions are less invasive, their recovery periods are shorter, and – for many types of interventions – the complication rate is lower than for the equivalent conventional surgery. In addition, some patients who may not tolerate anaesthesia and conventional surgery, as well as lesions that were not previously accessible, can now be treated by less-invasive image-guided interventions.

(b) The number of interventions guided by imaging is increasing greatly in both developed and developing countries. New types of interventions are also of increased complexity, require extensive use of x-ray imaging, and raise new issues of occupational protection. As well as interventional radiologists and cardiologists, other specialists, usually with little or no training in radiological protection, are now users of interventional guidance.

(c) The considerable variation in occupational exposures observed for the same type of procedure suggests that radiological protection practices can be improved. Some recent ophthalmological studies described below, such as those performed under the coordination of the International Atomic Energy Agency (IAEA) programme, the Retrospective Evaluation of Lens Injuries and Dose (RELID study), have shown an increased incidence of radiation-related eye lens opacities in interventionalists when radiological protection devices were not used properly and radiological protection principles were not followed.

2. Purpose and scope of the publication

(d) In *Publications 117* (ICRP, 2010a) and *120* (ICRP, 2013a), the Commission provided practical advice on occupational radiological protection for physicians and other healthcare personnel involved in interventional procedures. This publication provides guidance on exposure monitoring strategies, methods and options, radiological protection approaches and garments, their use and testing, the development of a radiological protection programme, education and training, and quality assurance of the programme implementation. The guidance is meant for medical physicists and other healthcare professionals in charge of occupational protection, personnel working in dosimetry services, clinical applications support personnel, regulators, and all those having an influence on the overall safety culture and on quality assurance and improvement. In addition, the guidance will be useful to those engaged in training, standardisation of equipment, and procedures; those with responsibilities for occupational health; hospital managers and administrators responsible for providing financial support for protection purposes; and professional bodies (interventionalists, medical physicists, nurses, and radiographers).

3. Uses of image-guided interventions, occupational exposures, and observed effects

3.1. Uses

(e) Interventions are usually guided by fluoroscopy, and radiographic cine-like series of images are taken to document both normal and abnormal conditions and the outcome of diagnosis or treatment. Interventions can also be guided by computed tomography (CT) imaging, with images taken while the interventionalist can step behind a mobile shield or out of the room, or by CT fluoroscopy, in which the interventionalist stays in the room when exposing the patient for obtaining images during device manipulation. The principal advantage of CT fluoroscopy over ordinary CT images is the real-time monitoring to access lesions that move within the body as a result of patient breathing or other motion. Its use allows interventions to be performed more rapidly and efficiently. On the other hand, CT fluoroscopy may result in relatively high radiation exposure to both the patient, the interventionalist, and other staff involved in the intervention.

(f) X-ray image-guided therapeutic interventions such as radioembolisation with ^{90}Y -labelled microspheres [selective internal radiation therapy (SIRT)] are an alternative method to treat patients with unresectable primary or secondary liver tumours. Several hospitals are exploring the use of real-time positron emission tomography (PET)-CT guidance during interventional procedures, such as for biopsies and/or radiofrequency ablations. ^{18}F -FDG PET-CT imaging is performed within the suite to identify where an embolisation or biopsy should be performed, to check on effectiveness of interventions, and for early detection of residual disease (e.g. after radiofrequency ablation, so that ablation can be repeated, if necessary, in order to obtain the maximum therapeutic benefit).

3.2. Occupational exposures and observed effects

(g) While, with the appropriate protection, it is possible for interventionalists to keep their annual occupational effective dose below 10 mSv, and typically within a range of 2–4 mSv or less, some surveys have shown that individual occupational doses may exceed these values and have considerable variation.

(h) The equivalent dose to the lens of the eye has received increased attention as evidence has become available that cataract development may have a much lower threshold for occurrence than was historically believed. The Commission's recommendations have lowered the equivalent dose limit for the lens of the eye from $150 \text{ mSv year}^{-1}$ to 20 mSv year^{-1} , averaged over defined periods of 5 years with no single year exceeding 50 mSv. The nature of interventions guided by radiological imaging is such that, without protective measures for the eyes, personnel with a medium or high workload could receive doses to the lens of the eye that would exceed the new annual equivalent dose limit, and could result in eye lens opacities over time.

(i) Several ophthalmological studies were conducted on a sample of interventional cardiologists and nurses who were attending cardiology congresses and who participated voluntarily under the coordination of the IAEA programme, the RELID study. Approximately 40–50% of interventionists and 20–40% of technicians or nurses, were found to have posterior subcapsular opacities compatible with injuries derived from exposure to ionising radiation. The incidence rate in interventionists was four to five times higher than that in unexposed individuals in the control group (approximately 40–50% vs 10%). Lifetime lens absorbed doses were estimated to reach several Gy in some cases.

(j) Extremity equivalent dose may be of concern, as the dose to the interventionalist's hand that is nearest to the irradiated patient volume can be high and requires specific hand monitoring. Values for annual lower extremity equivalent doses up to 110 mSv have been found, despite the use of a protective curtain hanging on the side of the treatment couch. This exposure is attributed to the gap between the protective curtain and the floor, the size of which is dependent on the height of the x-ray table during exposure.

4. Occupational exposure monitoring and exposure evaluation

(k) A survey performed within the IAEA Information System on Occupational Exposure in Medicine, Industry and Research (ISEMIR) (IAEA, 2014b) showed that 76% of interventional cardiologists stated that they always used their dosimeters and 45% used two dosimeters. This survey relied on self-reporting and may overestimate true dosimeter use. In addition, in some parts of the world, there is a lack of proper monitoring of radiation doses to professionals involved in interventional procedures, and individual dosimeters are often not worn regularly.

(l) In addition to assessing effective dose, occupational exposure monitoring in interventions guided by radiological imaging should include an estimate of the equivalent dose received by the lens of the eye and, in some cases, the extremities.

4.1. Assessment of effective dose

(m) The combination of the readings of two dosimeters, one shielded by the apron and one unshielded above the apron at collar level, provides the best-available estimate of effective dose (as has been stated by the Commission in previous publications). The dosimeter under the apron also provides evidence that an apron that provided sufficient shielding was worn regularly.

4.2. Assessment of equivalent dose to the eye

(n) The dosimeter over the apron, at collar level on the side of the interventionalist closer to the irradiated volume of the patient, not only contributes to assessing

effective dose, but also provides a reasonable estimation of the equivalent dose to the lens of the eye and the head.

(o) Improved computational methodologies need to be developed to assess occupational doses, including equivalent dose to the lens of the eye, in high-dose procedures. These methods may be helpful to audit the regular and proper use of personal dosimeters and to assess the need for additional protection (e.g. protective glasses). Research programmes should pursue the development of computational technologies (not requiring dosimeters) together with personnel position sensing devices to assess personnel doses, including dose to the eye.

4.3. Equivalent dose to the extremities

(p) Assessment of equivalent dose to the hands in some specific complex interventional procedures needs more attention in the future. Finger dosimeters may be needed if the hand is very close to the direct x-ray beam. Similarly, assessment of exposure to the lower extremities, including the feet, will also require increased attention, especially when protective curtains are not available or there is a gap between the curtains and the floor. A gap may be present depending on the height of the table during the intervention.

4.4. Examples of errors with the use of dosimeters and indirect approaches to correct the situation

(q) Examples of errors include not using the assigned dosimeter, wearing a dosimeter over the apron that was intended for use under the apron, wearing a ring dosimeter on the incorrect hand, wearing a dosimeter assigned to another person, or losing a dosimeter.

(r) Indirect approaches to dose assessment may be useful in identifying a lack of compliance in wearing personal dosimeters, and also in estimating occupational doses when personal dosimeters have not been used. These approaches may be based on area dosimetry of the scatter radiation near the patient (e.g. at the C-arm), together with conversion coefficients from patient-related quantities such as kerma-area product for different types of procedures and geometries to the dose to the lens of the eye of workers.

5. Guidance on occupational radiological protection

5.1. Relationship between patient and staff exposure

(s) Occupational protection in interventions guided by radiological imaging is closely related to patient protection, and most actions to protect the patient also protect the staff. There are, however, additional measures and protective devices that

protect the staff alone. The use of these devices should not interfere with the manipulations of the procedure, nor increase patient exposure.

5.2. Protection by shielding devices

(t) Shielding aprons should be worn by all interventional staff working inside the x-ray room. Aprons usually contain the equivalent of 0.25 mm, 0.35 mm, or 0.5 mm of lead. Some designs overlap at the front to provide protection of 0.5-mm lead equivalence, with 0.25-mm lead equivalence elsewhere. Transmission is typically between 0.5% and 5% in the range 70–100 kV (i.e. attenuation factor between 200 and 20). Aprons shield the trunk against scattered radiation, but parts of the body including the head, arms, hands, and legs are not protected by the apron. These parts of the body need to be considered in the radiological protection programme.

(u) The most important factor in protection of the head is the proper use of ceiling-suspended lead acrylic shields. They should always be included in interventional installations, as they can reduce doses to the whole head and neck by a factor of 2–10, depending on how efficiently they are positioned.

(v) Staff, such as nurses and anaesthesia personnel, who need to remain near the patient may benefit from the additional protection provided by movable (rolling) shields that can be positioned between them and the source of scattered radiation.

(w) As described in Point (h), under occupational exposure, the equivalent dose to the lens of the eye can exceed the new dose limit if protective measures are lacking. Over time, this could result in lens opacities. Conversely, if the interventional fluoroscopy equipment is operating correctly, procedure protocols have been optimised, the operator has been trained, and protective tools for the eyes are being used, the dose to the lens of the eye should be lower than the dose limit.

(x) A close fit of leaded glasses to the facial contours, particularly around the sides and underside of the glasses, is important because the clinician is looking at the image monitor during the x-ray exposures. As a result, the eyes may be irradiated from the side and below.

(y) Lead drapes attached to the bottom edge of the ceiling-suspended shield, as well as shielding drapes and pads, can be effective in protecting the hands in some procedures. This type of protection should be considered for procedures where the operator needs to be close to the source of scattered radiation (i.e. the irradiated volume of the patient). When placing disposable drapes on the patient, attention is required to avoid having the drapes in the primary beam, which might increase patient and operator exposure.

(z) Staff who stand near the patient table during interventions should be aware that the radiation field is more intense in the region adjacent to the beam entrance side. This is particularly important when projections are oblique or lateral. Doses to the head, upper body, and hands of the interventionalist from fluoroscopy with the tube positioned under the table will be substantially lower than the doses received by the lower extremities.

(aa) This is particularly true when no shielding curtains for the lower extremities are available, and when the table is at a higher position, so that the feet may stay unprotected even if the curtains are in place. Rolling lead shields, when available, decrease the effective dose to staff by more than 90% if used properly.

(bb) In summary, all staff in the room should wear protective aprons. Wraparound aprons are desirable for individuals who may not be able to face towards the patient at all times when the beam is on. The interventionalist should be protected by ceiling-suspended screens, table-suspended curtains, and shielding drapes when feasible. Staff can also reduce doses received during the use of high-dose acquisition modes (e.g. image acquisition series and digital subtraction angiography) and during injection of contrast media using an automatic injector by stepping back and increasing the distance to the patient. Staff, such as nurses and anaesthesia personnel, who need to remain near the patient can benefit from protection by movable screens. Other personnel should increase protection by increasing their distance from the irradiated volume of the patient or, if possible, leaving the room during image acquisition.

5.3. Protection of the embryo and fetus

(cc) After a pregnant woman has declared her pregnancy, her working conditions should ensure that the additional dose to the conceptus does not exceed 1 mSv during the remainder of the pregnancy.

(dd) Current data do not justify precluding pregnant woman from performing interventions guided by radiological imaging completely if they follow proper procedures. Pregnancy, in any case, requires that the employer carefully reviews the exposure conditions and other aspects of occupational hazards (e.g. back pain with use of lead aprons) of the pregnant worker.

6. Quality assurance

(ee) Quality assurance with regular documented checks to confirm that professionals involved in interventions guided by radiological imaging always wear their dosimeters and protective equipment, including eyewear, is very important.

(ff) Acceptance tests for protective devices are crucial; some supplies of defective protective clothes have been documented. In addition, handling protective devices with care (e.g. avoid folding) and regular testing are required as part of the quality assurance and improvement programme, as described in Section 5.

7. Education and training

(gg) Initial and continuing education and training of professionals in occupational safety and radiological protection is required. This is especially important regarding safety culture and the proper use of imaging equipment and radiological protection tools (e.g. ceiling-suspended shields and/or leaded eyewear and shielding curtains).

(hh) Use of real-time active dosimeters not only helps in optimising protection of specific high-dose procedures, but also contributes to the education of professionals on the level of doses being received.

(ii) In addition to knowledge of general radiological protection, hospital staff in charge of occupational protection, dosimetry services staff, clinical applications specialists from suppliers, and regulators need knowledge of clinical practice, the x-ray equipment used in interventions, strategies for occupational exposure assessment, the protection methods, and selection and testing of protective garments.

8. Availability of key professionals for radiological protection

(jj) The role of the medical physicists or others in charge of creating and maintaining a radiological protection and training programme is crucial. They are part of the team that ultimately designs and implements optimal radiological protection and care by the interventionalists, radiographers, and nurses.

GLOSSARY

Absorbed dose (D)

The quotient of the mean energy imparted to an element of matter by ionising radiation and the mass of the element.

$$D = \frac{d\bar{\epsilon}}{dm}$$

Absorbed dose is the basic physical dose quantity and is applicable to all types of ionising radiation and to any material. Absorbed dose is a measurable quantity for which primary standards exist. In the International System of Units (SI), the unit for absorbed dose is J kg^{-1} , and its special name is gray (Gy).

Carers and comforters

Individuals, other than staff, who care for and comfort patients. These individuals include parents and others, normally family or close friends, who hold children during diagnostic procedures or may come close to patients following the administration of radiopharmaceuticals or during brachytherapy (ICRP, 2007a).

Deterministic effect

See Tissue reaction.

Dose coefficient

Used to express dose per unit intake of a radioactive substance, but sometimes also used to describe other coefficients linking quantities or concentrations of activity to doses or dose rates, such as the external dose rate at a specified distance above a surface with a deposit of a specified activity per unit area of a specified radionuclide (ICRP, 2007a).

Dose limit

The value of the effective dose or the equivalent dose to individuals from planned exposure situations that shall not be exceeded (ICRP, 2007a).

Dosimeter over apron

Dosimeter unshielded by the protective apron.

Dosimeter under apron

Dosimeter shielded by the protective apron.

Effective dose (E)

The tissue-weighted sum of the equivalent doses in all specified tissues and organs of the body, given by the expression:

$$E = \sum_T w_T H_T = \sum_T w_T \sum_R w_R D_{T,R}$$

where w_T is the tissue weighting factor for tissue or organ T , and w_R is the radiation weighting factor. The unit for effective dose is the same as for absorbed dose, J kg^{-1} , and its special name is sievert (Sv).

The sum is performed over all organs and tissues of the human body considered to be sensitive to the induction of stochastic effects. The tissue weighting factors are age- and sex-averaged, and intended to apply as rounded values to a population of both sexes and all ages.

Employer

An organisation, corporation, partnership, firm, association, trust, estate, public or private institution, group, political or administrative entity, or other persons designated in accordance with national legislation, with recognised responsibility, commitment, and duties towards a worker in her or his employment by virtue of a mutually agreed relationship. A self-employed person is regarded as being both an employer and a worker (ICRP, 2007a).

Equivalent dose (H_T)

The dose in a tissue or organ T given by:

$$H_T = \sum_R w_R D_{T,R}$$

where $D_{T,R}$ is the mean absorbed dose from radiation R in a tissue or organ T , and w_R is the radiation weighting factor. Since w_R is dimensionless, the unit for equivalent dose is the same as for absorbed dose, J kg^{-1} , and its special name is sievert (Sv).

Fluoroscopically or computed tomography guided interventions

Procedures comprising guided therapeutic and diagnostic interventions, by percutaneous or other access, usually performed under local anaesthesia and/or sedation, with fluoroscopic or computed tomography (CT) imaging used to localise the lesion/treatment site, monitor the procedure, and control and document the therapy (ICRP, 2000b). Three-dimensional (cone beam CT) imaging using fluoroscopic equipment is also used in some interventional procedures.

Gray (Gy)

The special name for the SI unit of absorbed dose: $1 \text{ Gy} = 1 \text{ J kg}^{-1}$.

Mean absorbed dose in a tissue or organ (T) (D_T)

The absorbed dose D_T , averaged over the tissue or organ T , which is given by:

$$D_T = \frac{\varepsilon_T}{m_T}$$

where ε_T is the mean total energy imparted in a tissue or organ T , and m_T is the mass of that tissue or organ (ICRP, 2007a).

Medical exposure

Exposure incurred by patients as part of their own medical or dental diagnosis or treatment; by persons, other than those occupationally exposed, knowingly, while voluntarily helping in the support and comfort of patients; and by volunteers.

Occupational exposure

This refers to all exposures incurred by workers in the course of their work, with the exception of: (1) excluded exposures and exposures from exempt activities involving radiation or exempt sources; (2) any medical exposure; and (3) the normal local natural background radiation. However, because of the ubiquity of radiation, the Commission limits its use of ‘occupational exposures’ to radiation exposures incurred at work as a result of situations that can reasonably be regarded as being the responsibility of the operating management. Excluded exposures and exposures from exempt practices or exempt sources do not generally need to be accounted for in occupational protection (ICRP, 2007a).

Operational quantities

Quantities used in practical applications for monitoring and investigating situations involving external exposure. They are defined for measurements and assessment of doses in the body. In internal dosimetry, no operational dose quantities have been defined that directly provide an assessment of equivalent or effective dose. Different methods are applied to assess the equivalent or effective dose due to radionuclides in the human body. They are mostly based on various activity measurements and the application of biokinetic models (computational models).

Optimisation of protection (and safety)

The process of determining what level of protection and safety makes exposures, and the probability and magnitude of potential exposures, as low as reasonably achievable, economic and societal factors being taken into account (ICRP, 2007a). In medical imaging and radiotherapy procedures, optimisation of radiological protection means keeping the doses ‘as low as reasonably achievable, economic and societal factors being taken into account’, and is best described as management of the radiation dose to the patient to be commensurate with the medical purpose.

Personal dose equivalent

The operational quantity for individual monitoring is the personal dose equivalent $H_p(d)$, which is the dose equivalent in soft tissue at an appropriate depth, d (in mm), below a specific point on the human body. The unit of personal dose equivalent is J kg^{-1} , and its special name is sievert (Sv). The specified point is usually given by the position where the individual’s dosimeter is worn. For monitoring effective dose, the operational quantity $H_p(10)$ is used, and for assessment of the dose to the skin, hands, and feet, the personal dose equivalent, $H_p(0.07)$ is used. A depth $d = 3 \text{ mm}$ is adequate for monitoring the dose to the lens of the eye. In practice, however, in many countries, calibration of dosimeters in terms of $H_p(3)$ has not been implemented, but $H_p(0.07)$ can be used for the same monitoring purpose for photon radiation, which is the case in interventions guided by radiological imaging.

Principles of protection

A set of principles that apply to radiation sources and to the individual in controllable exposure situations. The principle of justification and the principle of optimisation of protection are source related and apply in all exposure situations. The principle of application of dose limits is individual related and only applies in planned exposure situations (ICRP, 2007a).

Radiation weighting factor (w_R)

A dimensionless factor by which the organ or tissue absorbed dose is multiplied to reflect the higher biological effectiveness of high-linear energy transfer (LET) radiations compared with low-LET radiations. It is used to derive the equivalent dose from the absorbed dose averaged over a tissue or organ (ICRP, 2007a).

Sievert (Sv)

The special name for the SI unit of equivalent dose, effective dose, and operational dose quantities. The unit is J kg^{-1} .

Staff

In the context of this publication, staff are healthcare workers (see Worker) who participate in the care of a patient during a radiological procedure (e.g. physicians, nurses, radiographers) or who may be exposed to radiation from medical imaging equipment during the course of their work (e.g. equipment service personnel, janitorial staff).

Stochastic effects of radiation

Malignant disease and heritable effects for which the probability of an effect occurring, but not its severity, is regarded as a function of dose without threshold.

Threshold dose for tissue reactions

Dose estimated to result in 1% incidence of tissue reactions (ICRP, 2007a).

Tissue reaction

Injury in populations of cells, characterised by a threshold dose and an increase in the severity of the reaction as the dose is increased further. Tissue reactions are also termed ‘deterministic effects’. In some cases, tissue reactions are modifiable by postirradiation procedures including biological response modifiers (ICRP, 2007a).

Tissue weighting factor (w_T)

A factor by which the equivalent dose in a tissue or organ T is weighted to represent the relative contribution of that tissue or organ to the total health

detriment resulting from uniform irradiation of the body (ICRP, 1991). It is weighted (ICRP, 2007a) such that:

$$\sum_T w_T = 1$$

Worker

Any person who is employed, whether full time, part time, or temporarily, by an employer, and who has recognised rights and duties in relation to occupational radiological protection. Workers in medical professions involving radiation are occupationally exposed (ICRP, 2007).

1. INTRODUCTION

- Minimally invasive interventions guided by radiological imaging have many advantages over conventional surgery for a number of medical conditions.
- There is considerable variation in occupational exposure observed for the same type of procedure, suggesting that radiological protection practices can be improved.
- Recent studies have shown that there is a high incidence of radiation-related eye lens opacities (pre-cataracts) in interventionalists and other professionals involved in interventional procedures.
- Proper monitoring of radiation doses to professionals in the intervention room is crucial for radiological protection, but in many parts of the world, individual dosimeters are not available or not worn regularly. For these reasons, data on occupational doses may not always be reliable.
- There is a need for guidance for all those involved in occupational radiological protection and safety culture in the hospital.

1.1. Background

(1) Physicians in many medical and surgical specialties, usually assisted by nurses and radiographers, perform interventions guided by radiological imaging (NCRP, 2010) as an alternative to more complex and higher risk conventional surgery. This approach has many advantages: the interventions are less invasive than conventional surgery, recovery periods are shorter, and, for some procedures, the complication rate is lower (NCRP, 2010).

(2) Some physicians perform interventions involving multiple organ systems (e.g. radiologists), and others perform procedures within one or two organ systems alone (e.g. cardiologists, gastroenterologists, and urologists). Some interventions once performed primarily by radiologists, such as endovascular procedures to treat lower extremity arterial disease, are now performed increasingly by vascular surgeons and cardiologists (Goodney et al., 2009; Harris et al., 2011). In the USA, radiologists now perform less than 20% of these procedures (Goodney et al., 2009), and less than 35% of all fluoroscopically guided interventional procedures (NCRP, 2009).

(3) The increasing number, diversity, and complexity of new types of interventions guided by radiological imaging means that the benefits from these interventions continue to expand. However, they lead to an increase in exposure that appears to offset dose reductions obtained from improvements in technology (Kim et al., 2008). Moreover, occupational doses to interventionalists are among the highest observed in personnel working in medicine (Padovani et al., 2011). In a number of healthcare settings, there is a lack of proper monitoring of occupational radiation doses to professionals, and as a consequence, there is a lack of reliable data on occupational doses (Padovani et al., 2011; IAEA, 2014b). Too often, personal monitoring badges are worn intermittently, or are worn improperly (Padovani et al., 2011) or not provided. In some developing countries, no dose monitoring system is in place

(Tsapaki et al., 2009). In addition, there is difficulty in comparing reported dosimetry results because of significant differences in dosimetric methods used in each study (Kim et al., 2008), as well as lack of consensus on the number of dosimeters that may be used, and where the dosimeters should be worn on the body. The fact that none of the algorithms estimate effective dose adequately for all types of procedures poses difficulties in reaching a worldwide consensus regarding which of them should be used.

(4) The Commission reviewed recent epidemiological evidence suggesting that there are some tissue reaction effects, particularly those with very late manifestation, where threshold doses are or might be lower than previously considered. This is the case for the lens of the eye (ICRP, 2011). Recent studies have shown that there is an increased incidence of radiation-related eye lens opacities in interventional cardiologists when radiological protection devices are not used properly and radiological protection principles are not followed (Vaño et al., 1998, 2010, 2013a; Ciraj-Bjelac et al., 2010; Rehani et al., 2011; Jacob et al., 2012). Fairly high radiation doses to the hands and legs of interventionalists, and hair loss in the portions of the legs not shielded by a protective device (Balter, 2001) have been observed. The considerable variation in operator doses observed for the same type of procedure indicates that radiological protection practices can be improved (Kim and Miller, 2009).

(5) Physicians involved in interventional procedures vary in their level of training in radiological protection. For example, in many countries, all radiologists receive training in radiation physics, radiation biology, and radiological protection and safety as part of their radiology education, but physicians in other medical disciplines receive variable amounts of education in radiation-related topics, and may or may not be examined in these areas as part of the certification process. *Publication 113* (ICRP, 2009b) provides advice and recommendations on education and training, the professionals to be trained, objectives, contents, management approaches, approximate time needed to educate and train a wide variety of health professionals, accreditation, and certification.

(6) Several national and international medical societies have adopted guidelines to improve occupational protection and to avoid occupational radiation injuries, such as eye lens opacities (Miller et al., 2010; Durán et al., 2013).

(7) The Commission has provided practical advice regarding occupational radiological protection for interventionalists and other healthcare workers involved in x-ray-guided interventions in *Publications 85* (ICRP, 2000b), *117* (ICRP, 2010a), and *120* (ICRP, 2013a).

1.2. Purpose of the publication

(8) The purpose of this publication is to provide guidance on occupational protection to personnel involved in the interventions, but also to hospital administrators, medical physicists and those in charge of occupational protection, clinical applications support personnel from supplier companies, staff from dosimetry services,

regulators, and all those having an influence on the overall safety culture of the hospital.

(9) This guidance includes tools and methods for occupational protection and exposure monitoring strategies, selection, use and testing of protective garments, development of a radiological protection programme, education and training, and quality assurance for the programme implementation.

1.3. Scope of the publication

(10) The guidance provided in this publication applies to interventions guided by radiological imaging, including computed tomography (CT), cone beam CT, and positron emission tomography (PET-CT), as well as selective internal radiation therapy (SIRT). However, as the vast majority of interventional procedures relate to interventions guided by x-ray fluoroscopy and image acquisition series, the text of this publication refers to x-ray imaging, unless otherwise stated. Sections related to PET-CT and SIRT are included because they are often performed in interventional suites, and in conjunction with interventional radiology. Quantities and units relevant to interventional procedures are summarised in Annex B.

(11) For the purpose of this publication, interventional procedures are guided diagnostic and therapeutic interventions performed via percutaneous or other access routes, usually with local anaesthesia and/or intravenous sedation, which use ionising radiation in the form of fluoroscopy, CT, or PET to localise or characterise a lesion or diagnostic and/or treatment site; monitor the procedure; and/or control and document therapy.

2. ISSUES

- The number of interventions guided by radiological imaging is increasing greatly in both developed and developing countries. New types of interventions are also of increased complexity, thus requiring extensive use of x-ray imaging and raising new issues of occupational protection. As well as interventional radiologists and cardiologists, other specialists, usually with little or no training in radiological protection, are now users of interventional guidance.
- Without protection for the eyes, the equivalent dose to the lens of the eye may become the operationally restrictive dose, given the Commission's recommended new limit for the lens of the eye.
- Recent studies have shown a substantial increase in the incidence of posterior sub-capsular lens changes. With proper protection, however, the risk of radiation cataract can be decreased substantially.
- A reliable exposure monitoring is essential for radiation safety professionals to have the information needed to offer improvements to reduce doses and optimise radiological protection.
- Interventions involving PET and SIRT pose new and different radiological protection challenges. However, operators' effective dose can be kept within appropriate ranges with careful optimisation and attention to radiation fields.

2.1. Interventional procedures

2.1.1. Interventional fluoroscopy procedures

(12) There has been a large increase in the number of interventional procedures performed annually throughout the world. In the USA, interventional fluoroscopy procedures were the third largest source of medical exposure of patients in 2006, accounting for 14% ($0.43 \text{ mSv year}^{-1}$) of medical radiation exposure (NCRP, 2009) in terms of collective effective dose. Cardiac fluoroscopy procedures, including diagnostic cardiac catheterisation, represented 28% of all interventional fluoroscopy procedures, but accounted for 53% of the interventional fluoroscopy exposure. In 36 European countries, the frequency of all medical interventions guided by fluoroscopy ranges from 0.03% to 2.74%, with an average of 0.6% of all x-ray procedures. In terms of collective doses, medical radiation exposure in interventional procedures contributes from 0.001 to $0.34 \text{ mSv year}^{-1}$, corresponding to 0.4–28.7% of total radiation collective doses (EC, 2015). Seven of 11 developing countries surveyed as part of an IAEA project demonstrated a 50% or greater increase in the number of interventional procedures performed between 2004 and 2007 (Tsapaki et al., 2009).

2.1.2. Interventional computed-tomography-guided procedures

(13) Interventions can also be performed with CT guidance. Although relatively few data are available on the number of CT-guided interventions that are performed or on temporal trends, it is clear that the numbers and types of procedures are increasing. For example, the percentage of image-guided percutaneous lung biopsies performed with CT guidance at the Mayo Clinic in the USA increased from 66% in 1996–1998 to 98% in 2003–2005 (Minot et al., 2012). The remainder were performed with fluoroscopic guidance. CT is used primarily to guide biopsy of small or deep lesions in the chest, abdomen, and pelvis that are not seen well with ultrasound or fluoroscopy, as well as to guide needle placement for other procedures.

(14) CT-guided interventions can be performed by using intermittent CT scans while the physician steps behind a mobile shield or out of the scanner room, or by using CT fluoroscopy, with physician-controlled intermittent or continuous CT exposure during needle or device manipulation. CT fluoroscopy facilitates CT-guided biopsy procedures by allowing visualisation of the needle trajectory from skin entry to the target point. CT fluoroscopy is applicable to a wide variety of non-vascular interventions (Daly and Templeton, 1999). It is used for needle guidance during drainage of fluid collections and abscesses; spinal pain management; tumour ablation; and percutaneous needle biopsy in the neck, chest, spine, abdomen, and pelvis (Buls et al., 2003; Joemai et al., 2009; Hoang et al., 2011; Trumm et al., 2012). The principal advantage of CT fluoroscopy over standard CT is the ability to use real-time monitoring to access lesions that move within the body as a result of patient breathing or other motion. Its use allows interventions to be performed more rapidly and efficiently (Gianfelice et al., 2000b), and it is therefore popular. On the other hand, CT fluoroscopy also results in higher radiation doses to both the patient and the physician operator (Gianfelice et al., 2000a; Saidatul et al., 2010; Kim et al., 2011). As CT fluoroscopy images are noisier than conventional CT, this technique is predominantly used in cases of moving objects of high contrast, such as in lung biopsies.

2.1.3. Interventions for selective internal radiation therapy

(15) Less than 20% of patients with primary or metastatic liver cancers are curable at presentation. Therefore, palliative therapies such as interventional procedures for radioembolisation with the pure beta-emitter ^{90}Y -labelled microspheres (SIRT) and other loco-regional therapies have become alternative methods to treat patients with unresectable liver tumours (Camacho et al., 2015).

(16) After catheterisation of the hepatic arteries, ^{90}Y microspheres (maximal beta-energy 2.27 MeV, half-life 64.1 h) are delivered under fluoroscopic control. Two types of ^{90}Y microspheres are used: resin microspheres (SIR-Spheres, SIRTEX, Lane Cove, Australia; diameter 20–60 μm) and glass microspheres (TheraSphere, Nordion, Ottawa, Ontario, Canada; diameter 22 μm). The rationale for SIRT is

the dominant hepatic arterial supply of malignant lesions. SIRT has demonstrated a significant increase in patient survival time (Bester et al., 2012).

(17) SIRT is usually performed in two steps: in the first step, diagnostic angiography is combined with protective occlusion of non-target arteries. Then, shunting into the lung is estimated by means of a Single Photon Emission Computed Tomography (SPECT) scan of the lung and upper abdomen with ^{99m}Tc -MAA particles injected into the hepatic artery. If lung shunting is $<10\%$, SIRT with full ^{90}Y activity delivery is acceptable. A reduced amount of ^{90}Y activity (20–40% less) is recommended when shunting is 10–20% (SIRTEX). When shunting is $>20\%$, SIRT is contraindicated. The second step, usually performed 1 or more days later, is catheterisation of the hepatic artery or other arteries supplying the hepatic tumours, and administration of the microspheres. Temporary balloon occlusion of non-target arteries and antireflux catheterisation during this second step are alternatives to protective occlusion prior to microsphere delivery (Hagspiel et al., 2013; Fischman et al., 2014).

(18) The second step includes dose calculation, preparation of the ^{90}Y spheres, and delivery via a catheter into the hepatic artery. Typical activities are 2–3 GBq for resin spheres (Jakobs et al., 2007) and 3–7 GBq for glass spheres (Andrews et al., 1994). Target dose is typically 120 Gy (range 80–150 Gy). Nuclide distribution may be examined either by planar or SPECT Bremsstrahlung imaging or PET-CT. PET-CT has higher spatial resolution, and quantification of delivered activity may be more accurate (Camacho et al., 2015).

2.1.4. Use of positron emission tomography in interventional procedures

(19) PET is increasingly playing a role in image-guided interventions as it provides an image guidance technique for metabolically active targets that are inconspicuous, difficult to visualise, or not detected by CT or magnetic resonance imaging (Ryan et al., 2013a). Several hospitals are exploring, as part of their research programme, the use of real-time PET-CT guidance during interventional procedures, such as for biopsies and/or radiofrequency ablations (Purandare et al., 2011; Venkatesan et al., 2011; Ryan et al., 2013a; Aparici et al., 2014; McLoney et al., 2014), and there is current development of real-time fusion imaging using x-ray CT and PET imaging (Purandare et al., 2011; Beijst et al., 2016). The use of PET and multi-modality fusion imaging within the interventional suite can also assist in identifying the location for effective embolisation or biopsies, as well as providing immediate assessment of treatment effectiveness.

2.2. Type and energy of radiation in interventional procedures

(20) Most interventional procedures are performed with a combination of fluoroscopy and image acquisition series. Beam spectra vary with tube voltage and filtration,

ranging from 50 to 125 kVp and added filtration of up to 1 mm copper (NCRP, 2010). The beam quality and operating parameters, such as tube voltage and current, pulse duration, and often beam filtration, are driven by the system's automatic exposure control (NCRP, 2010). Higher beam penetration (i.e. higher kVp and filtration) is used for fluoroscopy in low-dose-rate modes (e.g. 88–114 kVp and a half-value layer of 8–10 mm Al), while lower tube voltage is used for image acquisition mode (e.g. 68–84 kVp and a half-value layer of 3.5–4.0 mm Al) (Principi et al., 2014). In some equipment, spectral shaping for image acquisition is achieved by combining low tube voltage (for better visualisation of iodine-containing contrast media) with increased filtration (for limiting the higher patient dose associated with the lower tube voltage) (NCRP, 2010). The distribution of scattered radiation around the patient, which is most relevant to occupational exposure, is discussed in Section 5.

(21) In CT fluoroscopy, the tube voltage ranges from 80 to 140 kVp. In PET-CT examinations using ^{18}F -FDG, the photon energy of 511 keV is much higher than the energy of scattered photons in conventional interventional procedures (NCRP, 2010). The maximal beta energy from ^{90}Y used in SIRT procedures is 2.27 MeV. As the vast majority of interventional procedures relate to those guided by x-ray imaging, the text of this publication refers to them unless otherwise stated.

2.3. Occupational exposure

2.3.1. Effective doses

(22) Summaries and compilations of data on occupational exposure are available (Kim et al., 2008, 2012; ICRP, 2010a; NCRP, 2010). While it is certainly possible for active interventionalists to keep their annual occupational effective dose below 10 mSv, and typically within an effective dose range of 2–4 mSv or less (Miller et al., 2010), surveys have shown that individual occupational doses may exceed these values (Padovani et al., 2011).

(23) Annual effective doses incurred by staff depend on their function and role in the team (primary interventionalist, radiographer, nurse, anaesthesia provider), the number of interventions, the medical specifics and complexity of the cases, the patient population (e.g. paediatric patients, obese patients), and other factors such as the skill of the interventionalist and equipment as well as the use of fluoroscopic and cine times. In a review of the literature, Martin (2009) estimated that a case load of 500 cardiology procedures per year would result in an annual effective dose of approximately 2 mSv for the primary interventionalist. A maximum annual dose of 1.2 mSv [$H_p(10)$ measured under apron] was observed for cardiologists at a Glasgow hospital (Martin, 2009). Other types of procedures that result in an effective dose per procedure greater than 10 μSv for the interventionalist might lead to annual effective doses as high as 10 mSv depending on whether thyroid shields are used. Lie et al. (2008) reported a maximum annual effective dose derived from combining the readings of two dosimeters, one under and one over the apron, of 11 mSv with a mean of

5 mSv. The outcome of a review of monthly effective doses (E), obtained during 2011 and 2012, performed by a dosimetry service provider in the USA is shown in Fig. 2.1. In total, 102,199 observations refer to workers monitored with two dosimeters (one over and one under the apron) and 196,526 observations refer to workers monitored with a single dosimeter located over the apron at the collar. The outcome revealed mean values of estimated effective dose of 0.12 and 0.27 mSv, with median values of 0.03 and 0.1 mSv, respectively (Yoder and Salasky, 2016).

(24) Sánchez et al. (2012) found monthly median under-apron doses of 0.11 mSv for cardiologists and <0.01 mSv for nurses in a study of 43 workers who conducted 1467 procedures. The over-apron doses were 0.4 mSv month⁻¹ for both cardiologists and nurses. The authors noted that perhaps as many as 50% of the cardiologists did not use their dosimeters correctly, often failing to wear the over-apron dosimeter (Sánchez et al., 2012). A multi-centre study on 39 physicians and nine assistants performing nine different types of procedures in 14 hospitals in Germany showed that the median body dose per procedure was 16 µSv for an unshielded person; the partial-body equivalent dose per procedure was 2.8 µSv to the lens of the eye, 4.1 µSv to the thyroid, 44 µSv to one of the feet, and 75 µSv to one of the hands. High exposures were measured to the hands, in some cases above the limit of 500 mSv (Häusler et al., 2009).

(25) As well as the primary interventionalist, other staff may also be subject to significant exposure, such as anaesthesia providers. Kong et al. (2015) showed that radiation exposure of anaesthesia providers not only depends on their workload, but largely varies with their positions and beam projections during interventional procedures. Beam projection accounts for a factor of 10 in effective dose and 200 in dose to the lens of the eye. A position close to the patient combined with left lateral projection causes higher exposure. Optimal arrangement of the anaesthesia device was found to be useful to reduce exposure.

(26) Data on occupational exposure from CT fluoroscopy guided interventions are limited. The highest doses are received by the physician's hands, eyes, and thyroid (Saidatul et al., 2010). Use of thyroid shields provides substantial protection for the thyroid (Saidatul et al., 2010), which is especially important for younger professionals. Since average patient dose varies according to the type of procedure (Leng et al., 2011), average physician effective dose per case also varies according to the type of procedure, as would be expected; reported values measured over apron ranged from 2 to 25 µSv for $H_p(10)$, with maximum values as high as 0.4 mSv per procedure (Paulson et al., 2001; Teeuwisse et al., 2001; Joemai et al., 2009). A variety of technical approaches and protection methods have been developed that can reduce occupational dose (Daly and Templeton, 1999; Paulson et al., 2001; Carlson et al., 2005; Hoang et al., 2011).

(27) The occupational radiation exposure from transcatheter aortic valve replacement or transcatheter aortic valve implantation depends on the approach (transfemoral or transapical). Values of $H_p(10)$ up to 0.23 mSv in a single procedure were obtained by Shatila (2015) from the over-apron dosimeter of the primary operator (median value 0.11 mSv), as well as significant exposures to eight of 10 other workers.

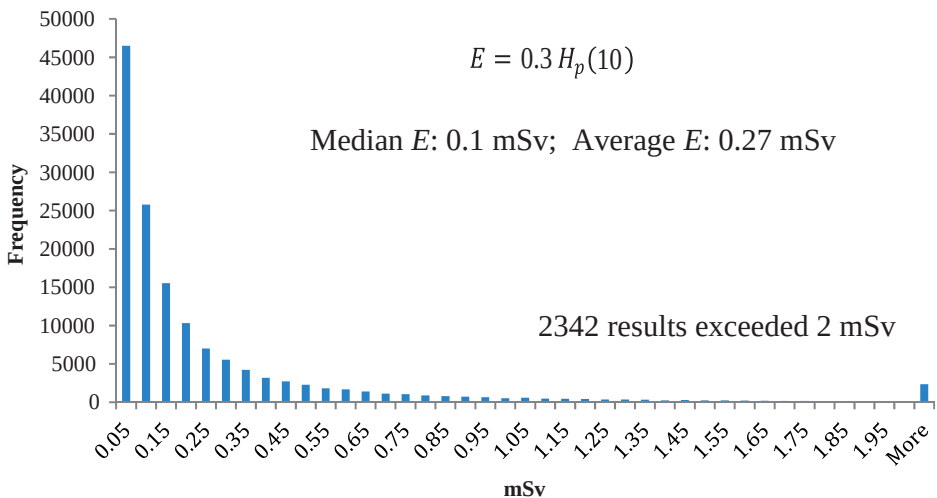
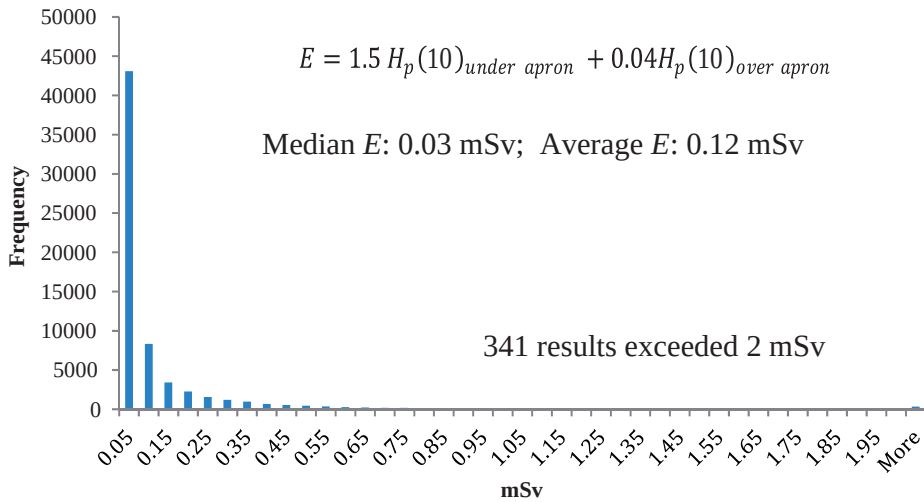


Fig. 2.1. Distribution of effective dose (E) assessed by two dosimeters (one over and one under the apron) (top) and one dosimeter (over the apron) (bottom) (Yoder and Salasky, 2016).

2.3.2. Equivalent dose to the lens of the eye

(28) The Commission issued a statement in 2011 published as part of *Publication 118* (ICRP, 2012) after reviewing epidemiological evidence suggesting that there are some tissue reactions, particularly those with very late manifestation, where threshold doses are or might be lower than considered previously. For the lens of the eye, the threshold in absorbed dose is now considered to be 0.5 Gy. For occupational exposure in planned exposure situations, the Commission now recommends an equivalent dose limit for the lens of the eye of 20 mSv year^{-1} , averaged over defined periods of 5 years, with no single year exceeding 50 mSv. Without protective eyewear, the dose to the lens of the eye may become the operationally restrictive dose (Lie et al., 2008; Korir et al., 2012), and the revised dose limit may be exceeded.

(29) Most data on eye exposures are derived either from static experiments with phantoms or from individual monitors placed on the neck. A few studies have placed dosimeters closer to the eye on the forehead. Lie et al. (2008) compared thermoluminescence dosimeters (TLDs) placed near the left eye and between the eyes for 144 procedures, mainly cardiac. The median equivalent dose to the lens of the eye was observed to be $23 \mu\text{Sv}$ per procedure, and the kerma-area product of the primary beam towards the patient was $0.4 \mu\text{Sv Gy}^{-1} \text{cm}^{-2}$. The left eye dose tended to be higher than that between the eyes due to the left eye being closer to the x-ray generator. Kicken et al. (1999) assessed the absorbed dose at the forehead for under-couch and over-couch x-ray systems. They found an average absorbed dose for the operator and assistant of 8 and $6 \mu\text{Gy}$ per procedure, respectively, at one hospital; 16 and $14 \mu\text{Gy}$, respectively, at a second hospital; and 43 and $28 \mu\text{Gy}$, respectively, at a third hospital. The first two hospitals used an under-couch system and the third hospital used an over-couch x-ray tube that puts the head closer to the beam entrance to the patient-irradiated volume. Vaño et al. (2016) derived dose to the lens of the eye from dose measured over the apron, and compared dose to the lens of the eye in urologists per nephrolithotomy procedure with dose received by interventional cardiologists and radiologists. The report concluded that, due to the lack of protective shields in urology, the dose to urologists per procedure was 18.7 times higher than the dose received by interventional cardiologists who used ceiling-suspended shields.

(30) Within the European study on optimisation of radiological protection of medical personnel, TLD measurements and Monte Carlo simulation campaigns were performed for three cardiac and five interventional radiology procedures (Vanhavere et al., 2012). The selection was based on their potential impact on annual worker exposure (i.e. procedures with high frequency or high values of kerma-area product, or both). Operators were exposed substantially from embolisation procedures as well as from percutaneous transluminal angioplasty (PTA) of the lower limbs and renal arteries. During cerebral and carotid procedures, the doses to the operators were relatively low since femoral access is usually chosen and, therefore, the operator stands further away from the irradiated part of the patient compared with other procedures performed in the thoracic or abdominal region. Equivalent dose to the lens of the eye from digital subtraction angiography (DSA)