PAPER

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PAPER

IPEM topical report: personal dose monitoring requirements in healthcare

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Abstract

There are two major challenges for personal dosimetry in healthcare. The implications for interventional clinicians of the reduction in eye dose limit in the European Basic Safety Standards and UK regulations, and the large dose gradients across the hands of nuclear medicine staff who manipulate radionuclides. Guidelines on personal dosimetry have been prepared to address these and other issues. Collar dosemeters are recommended for assessment of eye doses for the majority of staff working with x-rays and, for interventional operators, dosemeters under their lead aprons to monitor effective dose together with eye dosemeters. When a dedicated eye dosemeter is worn together with lead glasses a correction might be required to allow for the protection provided. A dosemeter worn on the chest should provide an indication of eye dose for nuclear medicine workers. Finger doses for interventional clinicians can be monitored with ring dosemeters, but radionuclide workers may need to wear finger stalls if doses to fingertips are likely to be over 100 mSv. If only ring dosemeters are used, ratios for doses to the tip and base of the finger should be established. Guidance is given on levels where dose monitoring would be required and methods to predict dose levels based on local practices.

1. Introduction

The requirements of the new European Basic Safety Standards (EC 2013) have been incorporated into the revised Ionising Radiations Regulations (2017) (IRR17) implemented into UK law on 1 January 2018. One of the more significant changes is a substantial lowering of the annual equivalent dose limit for the lens of the eye, which has been reduced from 150 mSv to 20 mSv. This follows a recommendation by the International Commission on Radiological Protection (ICRP) based on evidence accumulated on the radiation induction of cataract (ICRP 2012) and requires modifications to dose monitoring practices for the eyes. In addition to this, it has been acknowledged for some time that proper assessment of the equivalent dose to the skin (dose limit of 500 mSv), which is nominally the dose averaged over any area of 1 cm^2, can be difficult when applied to the fingertips. These aspects of personal monitoring have significant implications in several areas of medicine.

2. Methods

The Institute of Physics and Engineering in Medicine (IPEM) set up a working party in 2015 to prepare guidance on personal monitoring to assist healthcare staff in developing effective strategies for complying with IRR17. The Working Party compiled personal monitoring data, reviewed relevant publications, sought views from healthcare staff throughout the UK, and consulted the Health and Safety Executive (HSE) who regulate staff safety, and have produced guidance based on these investigations (Martin *et al* 2018). Some of the requirements under the new regulations and information on dosemeters that are available are described in this section of the

paper, the main recommendations relating to dose monitoring for healthcare workers are summarised in the results for applications using x-rays for diagnostic and interventional procedures, radiopharmaceuticals for diagnosis and therapy, and radiotherapy. Approaches that might be used to predict dose levels for use in initial risk assessments are outlined in section 4. One of the biggest challenges associated with personal monitoring of staff in the health care sector is ensuring that staff reliably and regularly wear their dosemeters correctly and return the dosemeters for assessment at the end of the issue period. Recent professional body advice (Rogers *et al* 2017) described the robust management systems that need to be in place. These are covered in the working party report but are not discussed further here.

2.1. Personal monitoring requirements

Healthcare employees who are likely to receive an effective dose or an equivalent dose to an organ or tissue including the skin of more than 3/10th of the relevant dose limit must be designated as 'classified' (Category A) radiation workers. A different arrangement applies to the lens of the eye where employees who are liable to receive doses of over 15 mSv, the dose limit for a member of the public, will require to be classified. The employer is required to arrange with an Approved Dosimetry Service (ADS) for systematic assessments of doses to be made and dose records maintained for classified workers. However, other workers who may be exposed to radiation, but are not designated as classified workers, may also need to be monitored to verify that results of prior risk assessments are correct, demonstrate that their doses comply with IRR17, and ensure that there are suitable records of doses should any accident occur that involves a radiation exposure. Information on the arrangements that should be in place for dose monitoring of outside workers, that is any workers who carry out services in controlled or supervised radiation areas belonging to other employers, is given in the guidance, as well as information on the requirements for approval of ADSs by the HSE.

2.2. Dosimetric quantities and practical dosemeters

Regulations define dose limits in terms of effective dose or equivalent dose, but personal monitoring is undertaken with operational quantities defined by the International Commission on Radiation Units and Measurements (ICRU 1993). These act as surrogates for the dose quantities specified in the limits. Personal dose equivalent $H_p(d)$ is used for external personal monitoring and is the dose equivalent in soft tissue below a specified point on the human body at an appropriate depth, d. $H_p(10)$ at a depth of 10 mm is employed as a surrogate for effective dose and equivalent doses to other organs deep within the body. $H_p(0.07)$ and $H_p(3)$ are used when monitoring doses to the skin and the lens of the eye respectively to represent the depths of sensitive tissues. Because dosemeters are worn on different parts of the body, their exposure to radiation scattered from adjacent tissues varies, and calibrations are carried out on phantoms made of tissue equivalent material that simulate the conditions in which they are worn in practice. For example a slab phantom (30 cm × 30 cm × 15 cm) is used for $H_p(10)$ to assess effective dose, a cylinder phantom (20 cm diameter and 20 cm height) is used for eye dosimetry in terms of $H_p(3)$, and a rod phantom (a cylinder of 19 mm diameter) is used for extremity doses in terms of $H_p(0.07)$.

2.3. Passive dosemeters

Routine personal monitoring can be carried out with active or passive systems. Passive dosemeters such as thermoluminescent dosemeters (TLDs) or optically stimulated luminescent (OSL) dosemeters are worn for extended monitoring periods (e.g. 1, 2 or 3 months). Body dosemeters can incorporate several elements behind different filters to enable estimations of doses at several depths. TLDs are usually used for extremity and eye dose assessments because of their convenient size. Extremity dosemeters often consist of a thin uniform layer of phosphor held within a sandwich that is included in a stall placed over the finger to enable monitoring of the tip or in a plastic ring worn on a finger. Extremity doses for PET and β-therapy radionuclides must be measured with dosemeters capable of recording $H_p(0.07)$, as thicker dosemeters will underestimate skin doses from radionuclides emitting positrons or β-particles (Carnicer *et al* 2011). Various designs of eye dosemeters measuring $H_p(3)$ are available and an important consideration for interventional radiology operators is whether these can be positioned so that they take account of protection offered by lead glasses.

2.4. Electronic personal dosemeters and their use in optimisation

Electronic personal dosemeters (EPDs) can provide immediate feedback to staff about cumulative doses and dose rates. Dosemeters that display values are useful in dose investigation, improving technique and optimisation of radiation protection. Some systems used for fluoroscopically guided procedures provide real-time visualisation of radiation dose rate on a display for monitoring the personal exposure of individual staff members working with fluoroscopically guided procedures (Clairand *et al* 2011, Sandblom *et al* 2013). Data can be downloaded from EPDs for later analysis and this can reveal periods when dose rate levels are high enabling those procedures that make significant contributions to staff doses to be identified (Whitby and Martin 2003a). Such analyses can raise staff awareness of tasks that make significant contributions to their dose for which differences would

be lost in results of monthly monitoring with passive dosemeters. Probes connected via a cable to a data logger are available that are small enough to attach to a finger or at the side of the eye. Several modern EPDs have been designed as a direct replacement for the more traditional passive dosemeters providing dosimetry data that are approved for entry into official records. They do not have a display so the user obtains the dose by reading the device on a computer, perhaps via WiFi or Bluetooth. Linking the readout process directly to a web based programme can allow the assessed doses to go directly into the wearer's dose records, so that the wearer does not need to return the dosemeter for processing.

3. Results and recommendations for dosimetry practices

3.1. Dosimetry for personnel working with x-ray equipment

Healthcare staff from many different groups are involved in some capacity in the use of x-rays. Apart from radiologists and radiographers, there are a number of surgical specialties, anaesthetists, nurses, dentists, and various allied health professionals. The majority are unlikely to receive occupational exposures approaching any dose limits, but hospital management must decide which staff should be monitored and what dosemeters they should wear. Hospital staff using x-rays wear protective lead/rubber aprons that protect organs within the trunk when working directly with x-rays, but these leave the head, neck, arms and lower legs unshielded (Hiles *et al* 2016). As a result the dose limit that is more likely to be approached for the majority of staff working with x-rays is that for the lens of the eye when this is unprotected.

Personal dose monitoring requirements should be determined through risk assessments based on each individual's work. The superficial dose $H_p(3)$ to a dosemeter worn at the collar above the lead apron can be used as an indicator of eye dose. It is sufficient for the majority of staff working with x-rays and can be used to demonstrate whether the wearer is likely to require a dedicated eye dosemeter. Recommendations about monitoring requirements at different dose levels are summarised in table 1.

The employer's radiation protection service can use the following relationships to obtain approximate assessments of effective dose (E) and eye lens dose (D) from monitoring results for a collar dosemeter worn by staff who always wear lead coats when exposed directly to x-radiation (Martin and Magee 2013).

$$E = 0.1 \times H_p(10) \tag{1}$$

$$D = H_p(3) \ \ (\text{or } H_p(0.07) \ \text{for x-rays.} \tag{2}$$

Staff working with x-rays who record annual $H_p(10)$ values of more than 6 mSv on their collar badge are recommended to use a double dosemeter approach, one either on the head adjacent to the eye or at the collar of the lead apron, and the second under the lead apron. If the $H_p(10)$ reading is more than 10 mSv, staff should be monitored with a dedicated eye dosemeter at least for a trial period and comparisons made with results from a collar dosemeter in order to evaluate options for future monitoring. A flow chart setting out the recommended approach is given in figure 1.

3.1.1. Dosimetry for interventional operators and users of mobile C-arm units

The staff groups more likely to be classified (Category A) radiation workers are interventional radiologists and cardiologists. Classified workers are recommended to use a double dosemeter approach (ICRP 2018), one preferably on the head adjacent to the eye or alternatively at the collar of the lead apron (depending on the type(s) of approval given by HSE for the dosimetry service being used) measuring $H_p(3)$, and the second under the lead apron recording $H_p(10)$. The under apron $H_p(10)$ measurement will be recorded as the effective dose in UK dose records and the eye dosemeter $H_p(3)$ measurement recorded as the eye dose. When two dosemeters are worn, they should always be located in the correct position. If an under-apron dosemeter is worn inadvertently outside the lead apron, it can have a significant impact on the assessment of effective dose, since the exposure received by an unshielded dosemeter may be ten times that of an under-apron one.

Staff working with mobile C-arm units may not have access to the protective devices such as overhead protective screens and lead curtains used in interventional suites and cardiac catheterisation laboratories. Such applications include orthopaedics, endoscopy, urology, pacemaker insertions, obstetrics/gynaecology and pain clinics. Although patient dose levels for these procedures should be lower, there will be less protection of operators from scattered radiation arising from the patient and operating table than in a dedicated interventional room. Therefore the ICRP recommends that 'methods which provide reliable estimates of eye dose under practical situations should be established' (ICRP 2010).

All non-classified (Category B) radiation workers using mobile C-arm units, including mini C-arms, are recommended to wear a collar dosemeter. Radiation protection services should use dose measurements to estimate approximate eye doses (equation (2)) and effective doses (equation (1)) to determine whether additional

Table 1. Proposed dose levels for radiation dose monitoring.

Tissue and dose quantity reported	Dosemeter position	Annual dosemeter reading (mSv)	Monthly dosemeter readings (mSv)	Dose monitoring recommendations
Body for NM staff $H_p(10)$	Body dosemeter	⩾1	⩾0.1	Regular monitoring at chest, waist or collar depending on exposure situation
Body for x-ray users $H_p(10)$	Collar above apron	⩾6	⩾1	Regular monitoring with under-apron dosemeter is recommended
Eyes for x-ray users $H_p(3)$	Collar or headband	1–5[a]	0.1–0.4	Initial monitoring with collar or head dosemeter to establish dose levels
Eyes for x-ray users $H_p(3)$	Collar or headband	6–10[a]	0.5–1	Regular monitoring with collar or head dosemeter recommended
Eyes for x-ray users $H_p(3)$	Headband	>10[a]	>1	Regular monitoring with head dosemeter recommended
Hands $H_p(0.07)$	Finger	20–50[b]	2–4	Assessment of most exposed area and initial monitoring to establish dose levels
Hands $H_p(0.07)$	Part of finger with highest dose	50–100[b]	4–10	Regular monitoring with finger dosemeters considered. Finger stalls considered for NM
Hands $H_p(0.07)$	Finger	>100[b]	>10	Regular monitoring of highest dose part recommended. Finger stalls may be required for NM

[a] The recorded dose divided by a suitable factor (e.g. 2—see section 3.1.4) may be used as the indicator if protective eyewear is worn consistently by the staff member and the dosemeter is worn outside the protection.
[b] After application of any required factor to correct for position of the dosemeter.
NM—nuclear medicine.

monitoring is required from levels given in table 1, following the approach set out in the flow chart in figure 1. Investigation levels set in terms of the annual dose received during a calendar year provide a tool through which individuals receiving higher doses can be highlighted on the dosimetry system and suggested values that might be used are given in the guidelines (Martin *et al* 2018). Risk assessment (section 4) should be performed to determine which members of the clinical team require monitoring based on their proximity to the patient. For all applications, even if the risk assessment indicates that a dosemeter is not required routinely, periodic checks should be made to confirm that dose levels remain low.

3.1.2. *Diagnostic radiography and fluoroscopy in x-ray departments*

Radiographers perform many different types of x-ray procedure. Many radiographers will assist in fluoroscopic or other examinations for which they will be present in the controlled area, where they are more likely to receive an exposure, and they will at these times wear a protective lead apron. However for much of their work they are located behind a protective screen and during these periods they will not be wearing a lead apron, but their doses are likely to be below the detection limit of any dosemeter. They will also take radiographs with mobile units when they will also wear lead aprons. In the past these staff have been monitored using a dosemeter worn under the apron that provided a record of their body dose and this was usually close to the minimum level. Because of the introduction of a 20 mSv dose limit for the eyes, which may not be protected when they are working directly with x-rays, it has become more important to record a measurement that can give an indication of the dose to the eyes than to the body. Therefore a dosemeter worn at the collar outside any body protection is recommended to record $H_p(3)$ for assessment of exposure of the eyes. Since radiographers will in general be several metres from the x-ray sources and patients, the exposure of the eye is likely to be similar to that at the neck. The $H_p(10)$ reading of the dosemeter should be used to give an indication of likely effective dose using equation (1). All radiographers and radiologists should be monitored initially and the majority are likely to require regular monitoring. Mammographic imaging is usually carried out with a single operator positioned behind a protective lead screen and the likelihood of significant occupational exposure is very low. For staff working exclusively in mammography a trial period of wearing a collar dosemeter to assess eye and effective dose is recommended, but routine monitoring is unlikely to be required.

3.1.3. *Use of a collar dosemeter*

The change to a dosimetry system based on a collar dosemeter worn outside any protection as the primary measurement for non-classified (Category B) staff working with x-rays is a major shift from current UK practice. It will involve an increase in the magnitude of doses that staff record so reasons for the change, and the consequential higher doses recorded, need to be fully explained to staff. A collar dosemeter will give a measurement of the radiation level to which a person is exposed and provide a dose related to that received by

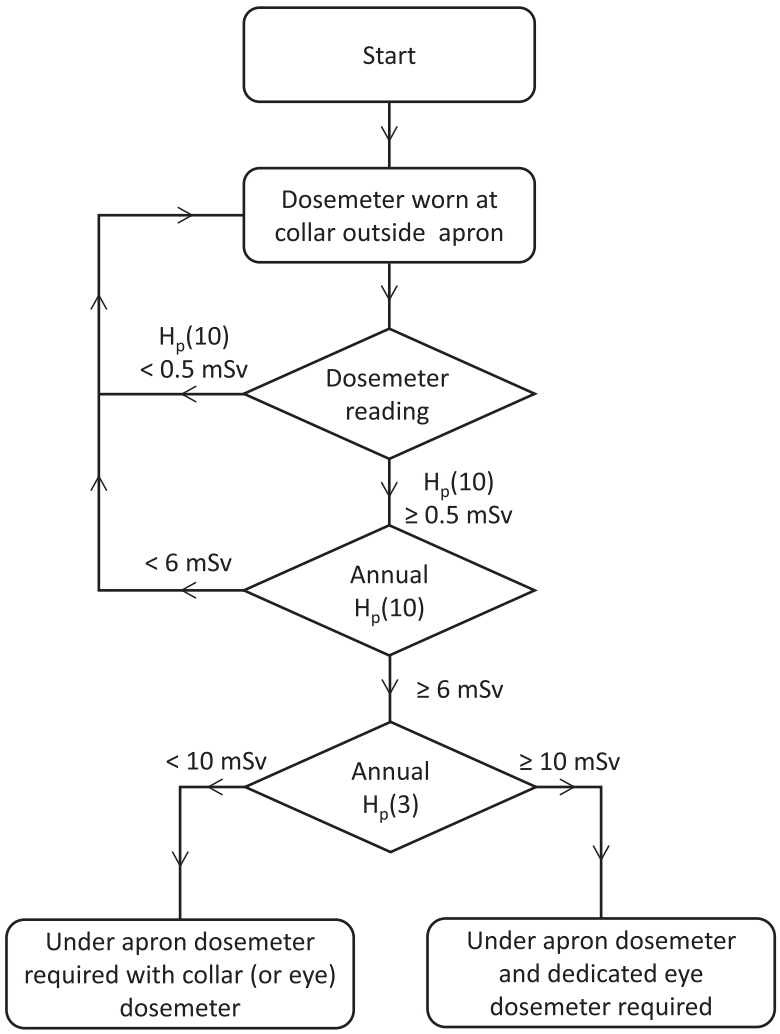

Figure 1. Flowchart to illustrate when collar, body and eye dosemeters should be worn for monitoring of staff working with x-rays, who wear lead aprons. Dose values are based on a monitoring period of one month, and should be adapted accordingly for other monitoring periods. (Reproduced from Martin *et al* (2018) with permission from IPEM.)

the lens of the eye. The dosemeter can also be used to give an indication of the effective dose by application of the adjustment factor (equation (1)), but a complicating factor in employing this method is that some staff may only wear personal protective equipment for part of the time. The doses received when radiology staff are not wearing lead aprons should be small, provided they are within a protected area and staff are trained when to use personal protective equipment, so the approximations should be reasonable. Initial checks on work patterns should be made for groups that only wear lead aprons for part of the time. An additional under apron dosemeter should be considered if the projected annual dose approaches 6 mSv (figure 1). Arrangements may be more complex for any staff who work between radiology and nuclear medicine, and they may need to wear an eye and an under apron dosemeter if their exposures are significant.

3.1.4. Eye dose monitoring

Interventional clinicians who record annual doses of 6–10 mSv on their collar dosemeter are recommended to consider wearing a dedicated dosemeter on the head near to the more exposed eye (figure 1 and table 1). Training in the effective use of ceiling suspended screens should reduce eye dose levels and eye dose monitors can assist in demonstrating good practice. Dosemeters worn at the side of the eye, on the eyebrow ridge adjacent to the x-ray tube (usually the left) or in the middle of the forehead have all been found to provide reasonable assessments of eye doses (ICRP 2018).

Interventional clinicians may wear eye protection, and this should be taken into account in assessment of the dose to the eye lens. For the majority of the time that an interventional radiologist or cardiologist is carrying out a procedure, he/she will be looking at the image on a display monitor and not towards the patient when x-rays are being emitted. Therefore the protection factor required must take account of x-ray beams incident from the side and below the level of the head. Ideally the dosemeter would be positioned behind any protective eyewear, but if this is not possible, a protection factor of 0.5 (Dose Reduction Factor = 2) could be applied to assess the

eye lens dose (Magee *et al* 2014, ISO 2015, ICRP 2018). If a protection factor is to be applied, there must also be a documented quality assurance programme in place to confirm that the staff member concerned wears both the protective eyewear and the dosemeter for all procedures. Whether or not this method can be used for the official UK dose record will depend on whether the ADS obtains approval from HSE to apply the correction factor.

3.1.5. *Extremity monitoring*

Since interventional clinicians, orthopaedic surgeons, and other healthcare staff operating mobile C-arm equipment are using x-ray imaging to aid surgical manipulations, their hands need to be close to the x-ray field. The dose rate within the primary beam transmitted through a patient is typically 2–5 μGy s^{-1}, but dose rates from primary beam x-rays scattered directly from the surface of a patient will be much higher and direct exposure to the incident primary beam in an overcouch configuration could be 50–100 times greater (Domienik *et al* 2014). The dose limit for the skin is averaged over an area of 1 cm^2, so it is important to position the dosemeter near the most exposed area. Small ring shaped dosemeters usually provide the best option for interventional radiologists and cardiologists and are recommended if the finger dose is likely to be in the range 2–4 mSv per month. In most procedures the hand is exposed to scatter from a large x-ray field, so the dose to the hand is relatively uniform and wearing a ring dosemeter on the little finger of the hand nearest to the x-ray tube generally provides a good option for monitoring (Whitby and Martin 2005a). If the dose exceeds 4 mSv per month, the dose distribution across the hand should be determined and monitoring arrangements adjusted to take this into account. For percutaneous interventional radiology procedures or manipulations in orthopaedic surgery, it may be the tip of the finger that receives the highest dose (Hafez *et al* 2005, Whitby and Martin 2005a) and in this case a finger stall dosemeter should be considered. Placing a ring dosemeter on the second phalanx is a possible alternative in this case if it is thought that the tip dosemeter might interfere with touch sensation and impede catheter manipulations. Extremity monitoring may need to be considered for mobile C-arm operators in other specialties if their hands are close to the primary beam and high doses are recorded on collar dosemeters, particularly if mobile systems are used with the x-ray tube above the couch.

In CT fluoroscopy, the operator's fingers can receive doses of hundreds of μGy in a few seconds if they enter the primary beam (Buls *et al* 2003, Saidatul *et al* 2010). However, the dose distributions are very non-uniform and the dose recorded by an extremity dosemeter is unlikely to be representative of the actual dose received. Prior risk assessment should be undertaken to determine likely dose levels if fingers were to enter the beam and training given to operators to ensure they are aware of the dose levels. Strict dose management arrangements involving review of images to ensure that the operator's hands have not entered the primary beam is recommended rather than dose monitoring.

3.1.6. *Doses to the legs of interventional staff*

Interventional radiologists and cardiologists need to stand close to the patient in order to carry out complex procedures. Most procedures use an undercouch C-arm configuration in which radiation from the primary beam is scattered downwards directly from the surface of the patient and couch (Artschan *et al* 2014). Lead aprons do not protect the lower legs, so lead/rubber curtains suspended from the side of the patient couch are used (Whitby and Martin 2003b, Artschan *et al* 2014, ICRP 2018), but the feet may still be exposed when the operator stands close to the patient couch. If there are no additional protective devices, doses to the legs and feet can be higher than those to the hands (Whitby and Martin 2003b, Vanhavere *et al* 2012) and in these circumstances it is recommended that a risk assessment is carried out to determine skin doses to the lower extremities. If doses to the shins and feet are likely to be of the order of 10 mGy per month or greater, dosemeters should be attached to the shoe or lower leg in order to assess dose levels and protection implemented.

3.1.7. *Dental radiography*

Dental professionals taking radiographs should be able to stand at over 2 m from the patient during an exposure, and the dose received should be about 0.1 μGy per radiograph (Sutton *et al* 2012). Therefore a dentist taking 100 radiographs per week would be unlikely to exceed 0.5 mSv per year to either the body or eye. Panoramic radiology units involve exposure from different directions and the scatter level at 1 m is approximately 0.65 μGy per examination (Sutton *et al* 2012). Although, the operator can stand at some distance, he/she needs to observe the complete examination during which the tube rotates around the patient. Personal monitoring with a collar dosemeter should be considered for staff whose weekly workload exceeds 100 intra-oral or 50 panoramic images, or a pro-rata combination of each type. As staff do not normally wear lead aprons, the collar dosemeter measurements will provide direct measures of the dose to the eye $H_p(3)$ and effective dose to the body $H_p(10)$. This dosimetry data can be used in risk assessments, and based on the results and the workload it may be possible to discontinue routine monitoring in many clinics. Dental staff operating cone beam CT dental x-ray equipment are recommended to wear a collar dosemeter as a means to establish eye dose and effective dose levels and

determine whether regular monitoring is required. Dedicated eye dosimetry is unlikely to be required. Periodic monitoring is useful to check that staff adhere to recommended protection practices.

3.2. Nuclear medicine

3.2.1. Monitoring of the body and the eyes

Staff working in nuclear medicine departments are exposed to radiation emitted directly by radiopharmaceuticals contained within vials and syringes, and from patients containing radioactivity, as well as from handling radioactive sources and radioactive waste. The manipulation of small vessels containing radiopharmaceuticals can lead to significant exposure of the hands as well as the whole body. Protection is provided through shielding of vials and syringes and use of bench top shields, while protection when dealing with patients is achieved through maintaining distance and limiting the time spent in close contact. Nuclear medicine staff should be issued with passive whole body dosemeters routinely. The appropriate interval for exchange should be determined by risk assessment (and the dosimetry service's approval) and for those involved with PET imaging it is likely to be monthly. For diagnostic nuclear medicine staff, exchange intervals are typically 1–2 months. Since the radiation exposure across the body is comparatively uniform for the majority of imaging tasks, the dosemeter can be worn at waist, chest, or collar level.

Doses to the eyes of nuclear medicine staff are unlikely to approach the revised dose limit (Dabin *et al* 2016), so dedicated eye dosemeters would only be required in specific circumstances. Since personal protective equipment is not worn generally, exposure for the majority of tasks is relatively uniform, and data from dosimetry records should provide a reasonable basis for evaluating potential exposure levels provided dosemeters are worn on the chest or at the collar. ^{99m}Tc is the predominant radionuclide used in nuclear medicine and 88% of the atoms decay through emission of a 140 keV γ-ray. However, the other 12% of atoms decay through internal conversion and emit a low energy electron that is heavily absorbed in superficial tissues and this contributes to the $H_p(0.07)$ reading, but not $H_p(3)$. Therefore, existing staff dose records for $H_p(10)$ can be reviewed to obtain an indication of eye dose levels for ^{99m}Tc use. For other radionuclides emitting β-particles it is important that a dosemeter calibrated in terms of $H_p(3)$ is used, as the dosemeter response varies substantially with energy and direction (Behrens 2012, Behrens *et al* 2017). Lower energy β-particle emissions from ^{131}I and ^{177}Lu will not penetrate to the depth of the eye lens, while higher energy β-particles from ^{90}Y will.

3.2.2. Monitoring of the hands

3.2.2.1. Radionuclide imaging

Monitoring of doses to the hands is recommended for all radiopharmacy staff preparing ^{99m}Tc radiopharmaceuticals and for staff who administer imaging radiopharmaceuticals regularly. There may be high dose gradients across the hands of nuclear medicine workers (Whitby and Martin 2003a, 2005b, ICRP 2008, Vanhavere *et al* 2012) and these complicate routine monitoring since the maximum dose may be 3–6 times greater than that measured by ring dosemeters. For small sources such as syringes and vials containing radioactive liquid, the magnitude of the dose gradient is determined by the proximity of the fingertip to the unshielded source. If the finger tips are some distance from the source for most of the time, then ring dosemeters are likely to be suitable. But if fingertips are within 5 cm of the unshielded source for the majority of the time, or may come into direct contact with the source, finger stalls provide a better option. If the exposures are received from manipulations that are repeated many times, then the use of ring dosemeters with a scaling factor provides a possible option. The scaling factor could be applied by the radiation protection service in order to derive an estimate of the dose to the fingertip. (The ADS will need to be approved by HSE to apply correction factors to their dose records—see below.) If doses measured with ring dosemeters worn at the bases of the index fingers with the detector elements located on the palmar sides are less than 2 mSv per month, then ring dosemeters should be sufficient. But if the annual dose to a fingertip is likely to be over 100 mSv, then it is necessary to measure the highest doses at the tips of the fingers and thumbs using finger stall dosemeters. A flow chart to aid in the selection of the dose monitoring strategy for finger doses in nuclear medicine is given in figure 2.

If ring dosemeters are worn, measurements at the fingertip should be carried out if the measured dose exceeds 2 mSv in order to establish a ratio between doses to the tip and the position where the dosemeter is worn and this might be used as a scaling factor. Where a reliable scaling factor has not been established from local measurements, application of a scaling factor of 6 is recommended for measurements from dosemeters worn at the base of the finger to provide a conservative estimate of the maximum dose (Vanhavere *et al* 2012, Martin *et al* 2018). Alternatively a ring dosemeter may be worn on the second phalanx, closer to the tip, and a factor of 2 applied (Martin 2016). Application of correction factors would not be appropriate where staff members undertake several different roles within a department in imaging, therapy, and a radiopharmacy. Fingertip doses derived by application of a scaling factor to a ring dosemeter measurement could not be entered into the official dose record in the UK, unless this was included in the ADS statement of service approved by the HSE. Therefore, the use of finger stalls is recommended wherever there is a risk of the annual fingertip dose being over 100 mSv.

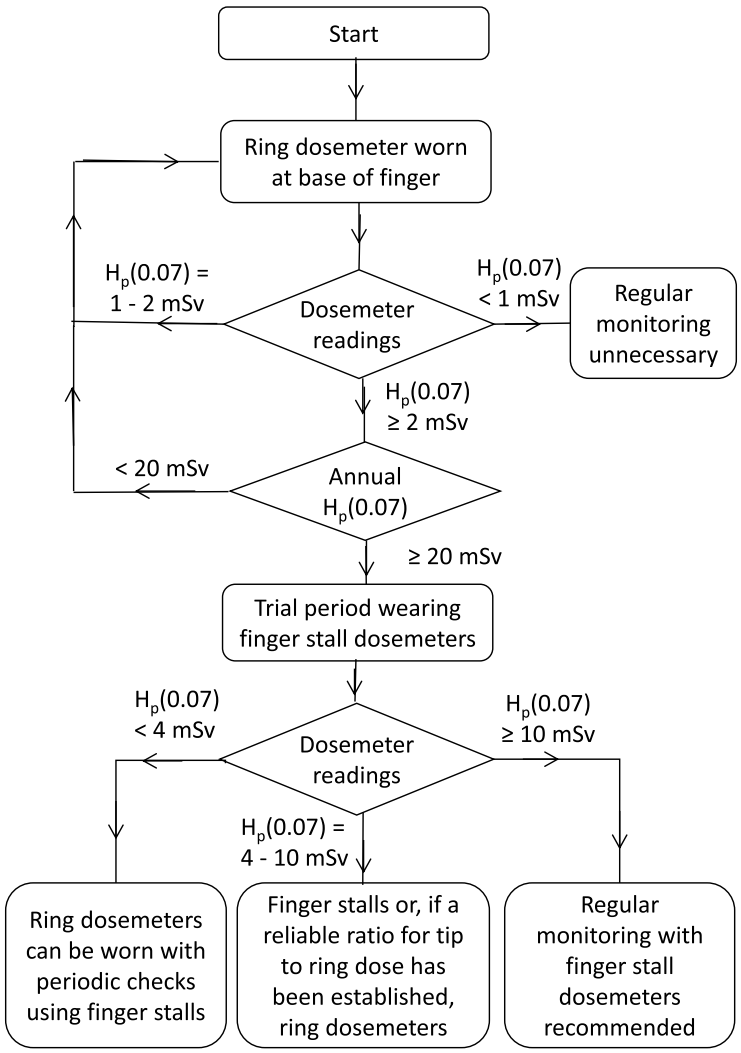

Figure 2. Flowchart based on average monthly monitoring to aid in selection of option for measuring doses to the fingers of staff working with diagnostic radionuclides in nuclear medicine.

Monitoring with a finger stall is recommended for staff working with PET imaging, if the work involves frequent manipulation of small sources such as vials and syringes. Ring dosemeters worn at the bases of the index fingers on both hands may be used, where the dose distribution across the hand is more uniform, but scaling factors should be evaluated to provide estimates of doses to the fingertips. The choice of dosemeter for radiation workers handling PET radionuclides should be agreed between the user and the ADS.

3.2.2.2. Radionuclide therapy

Radionuclides used for therapy emit particle radiations which are capable of delivering significant doses to the fingers. A dosemeter recording $H_p(0.07)$ is required to avoid underestimating the skin dose (Brasik *et al* 2007). The risks and the requirements for extremity monitoring depend on the radionuclide in question, and recommended practices are summarised in table 2. Finger doses from the use of ^{90}Y for therapeutic procedures such as RIT ^{90}Y-Zevalin® and ^{90}Y-DOTATOC of 2–50 mSv GBq^{-1} have been recorded (Vanhavere *et al* 2012), so there is the potential for the dose from a single procedure to exceed the dose limit if protection measures are not adhered to. There are also significant variations in dose distributions and there may be large differences between doses to finger tips and the bases of the fingers, so finger stalls should be used rather than ring dosemeters (Brasik *et al* 2007). The dose distribution across the hands from the lower energy β-particles used in ^{177}Lu therapy is less variable than for ^{90}Y, so ring dosemeters might be used with a scaling factor to assess dose to the fingertip. Routine finger monitoring is unlikely to be required for most other radionuclide therapies currently practised.

3.3. Radiotherapy

Radiotherapy equipment will generally be operated in dedicated facilities and systems will be in place to ensure that staff do not enter controlled areas when radiation is being emitted and so will not receive measureable doses during routine work. However, there may be risks of exposure in the event of an incident and personal

Table 2. Recommended finger dose monitoring for radionuclides therapies.

Radionuclide	Dose range	Recommended dose monitoring strategy
^{90}Y	2–50 mSv GBq^{-1}	Monitoring with finger stalls on tips of the thumb and first three fingers of each hand. The number of fingers monitored may be reduced once a pattern of exposure has been determined
^{177}Lu	50–60 μSv GBq^{-1}	If ^{177}Lu is the main therapy administered, ring dosemeters worn at the bases of the index fingers on both hands are likely to be sufficient for routine monitoring, but initial measurements with finger stall dosemeters is recommended
^{131}I	0.02–5 mSv GBq^{-1}	Routine monitoring of finger dose for staff dispensing ^{131}I capsules is unlikely to be required. Initial assessment using ring (or stall) dosemeters is recommended
^{223}Ra	2–4 μSv MBq^{-1}	Routine dose monitoring is unlikely to be required

monitoring arrangements will need to be in place to cover such eventualities. Staff operating, maintaining, and testing external beam therapy equipment should be monitored with a body dosemeter to detect any inadvertent exposure.

Modern brachytherapy treatments are delivered by remote High Dose Rate or Pulsed Dose Rate afterloading systems and staff should not be present in the treatment room when sources are unshielded, but may be exposed if they need to intervene where a source does not return to the shielded position during treatment of a patient, as well as during quality control procedures or a source exchange. An instant read-out EPD is recommended in addition to a passive whole body dosemeter for recording whole body dose during such incidents. Manually afterloaded brachytherapy may still be in use in some centres in which pre-defined lengths of ^{192}Ir wire are cut from a coil and inserted into plastic tubing for protection and support. Staff who prepare the sources are recommended to wear a dosemeter on the chest or collar and be monitored for finger doses. Nursing staff attending the patients during treatment should also wear a chest/collar dosemeter.

Permanent implantation of ^{125}I seeds is widely used for treatment of prostate cancer and these are inserted using an applicator under fluoroscopic and transrectal ultrasound guidance to visualise the prostate (Yoshioka 2009). The surgeon carrying out the implant should wear a body dosemeter and finger stall dosemeters on either hand when first carrying out this procedure and a regime for routine monitoring should be determined based on the results. Theatre staff assisting with ^{125}I seed implants do not require dose monitoring, but finger doses of staff preparing the seeds for implantation should be monitored. Uveal melanoma and retinoblastoma are treated using ^{106}Ru or ^{90}Sr eye plaques placed on the eye. The fingertips of staff handling and inserting eye plaques should be monitored initially using finger stalls to establish whether regular monitoring is required.

Intraoperative radiotherapy or electronic brachytherapy, involving direct irradiation of the tumour bed during surgery, is delivered in a single fraction using mobile kilovoltage x-ray machines (Eaton *et al* 2013) that emit x-rays with a mean energy of ~30 keV. Provided that staff remain behind the protective screen, whole body monitoring should only be required initially to confirm that systems of work are being followed and either an EPD or a passive badge worn at the collar could be used.

3.4. Monitoring pregnant staff

Additional controls on dose levels are necessary for any woman who is, or may be pregnant in order to restrict the dose to the unborn child. A 1 mSv dose constraint is generally applied to the foetus, and although not strictly a dose limit, once the employee has notified the employer that she is pregnant the employer must ensure that the equivalent dose to the foetus is as low as reasonably practicable and unlikely to exceed 1 mSv during the remainder of the pregnancy. The most appropriate method of monitoring for external exposure is using a dosemeter worn at the waist. The employer must carry out risk assessments that consider the potential exposure of the foetus and highlight any specific restrictions in working practice that are required. The risk assessment may highlight a need for personal monitoring if this is not already being carried out or an adaptation of current practice. Additional active EPDs might be appropriate both to provide a more regular update and reassurance for the staff involved. For exposure to external radiation, a restriction of 1 mSv in dose to the foetus is broadly equivalent to a dose to the surface of the abdomen of a pregnant woman of about 2 mSv for exposure to diagnostic x-rays (HSE 2018) and 1.3 mSv for work with ^{99m}Tc or ^{131}I (Mountford 1997).

4. Discussion of dose evaluation for risk assessments

Dose monitoring practices should be based on recommendations by the radiation protection adviser, and the level of dose monitoring be evaluated through risk assessment. The main recommendations about monitoring different parts of the body are summarised in table 1. The only reliable source of personnel dose data is from personal monitoring, but information on dose levels is required initially when any practice is started. In order to

Table 3. Indicators for deriving dose estimates for use in initial risk assessments for cardiology/radiology procedures (based on data reported in Whitby and Martin (2003b), (2005a), Vanhavere *et al* (2012), Martin and Magee (2013), Martin and Sutton (2015), Martin (2009)).

Tissue	Type of procedure or arterial access routes	Dose per procedure (μGy)	Doses/KAP (μGy (Gy cm^2)$^{-1}$)	KAP per month for monitoring[a] (Gy cm^2)
Eye	Cardiology: majority of procedures	40–60	1	500
Eye	Valvular and structural heart disease	100	1	500
Eye	Embolisations	180	3	200
Eye	Angiography of lower limb	60	5	100
Eye	Pacemaker insertions	60	6	100
Eye	ERCP	40	2	300
Eye	Other mobile C-arm applications	40–400	6	100
Hand	Percutaneous procedures		50	100
Hand	Radial access		10	500
Hand	Femoral access		5	1000
Hand	Angiography lower limb		40	100
Leg	Procedures without protective drape		10	500

[a] Workload above which dose monitoring should be considered.

address this problem some indicative values of potential doses based on measurements around radiation sources and personal monitoring studies reported in the literature are provided for radiology and nuclear medicine. A few rules of thumb and calculation methods are also provided to help users estimate dose levels to which staff might be exposed.

4.1. Eye doses from x-ray procedures

Since staff performing interventional and fluoroscopy procedures wear lead aprons to protect their body, the dose to the eye is the main concern. Cardiologists and radiologists performing interventional procedures are the ones expected to receive the highest doses to the lens of the eye. Review of collated data from the literature suggests that a simple assumption of an average eye dose of 60 μSv per interventional cardiology procedure could be used in prior risk assessments for more common procedures, including coronary angiography. However, a more conservative assumption should be used for procedures such as embolisations, angioplasties of the lower leg, and pacemaker insertions where the operator is closer to the x-ray tube or the level of protection is lower (Vanhavere *et al* 2012) and some suggested values are given in table 3.

The assumption of a dose per interventional procedure is a crude approach, as dose levels are variable, so it is helpful also to consider assessments of eye doses based on kerma-area product (KAP) workload data where these are available, and factors linking operator eye doses from scattered radiation to KAP workload are also included in table 3 (Martin and Magee 2013) and basic equations for calculating scatter levels from KAP given in the next section. These data cannot replace personal dosimetry results, as the uncertainty in the relationships is substantial, but they can provide a starting point.

4.2. Prediction of dose levels from x-ray workload

Dose levels to which staff working with x-rays may be exposed can be estimated from their workload and their position with respect to the x-ray source. Scattered air kerma levels (K_S) at 1 m from the x-ray tube and patient can be calculated from the KAP (P_{KA}) using the equation:

$$K_s = S \times P_{KA}. \tag{3}$$

Where S is a scatter factor linked to tube potential, used by Sutton *et al* (2012) to describe scatter to the side of a couch from undercouch exposures. The scatter is variable, depending on the projection, being greater for oblique projections with the tube adjacent to the operator. However, an approximate value that could be applied to body and eye exposures from a range of projections is given by:

$$S_{body} = [(0.031 \times kV) + 2.5] \quad \mu Gy\left(Gy\,cm^2\right)^{-1}. \tag{4}$$

The scatter from the base of the couch towards the feet, which is substantially greater could be estimated from the equation:

$$S_{feet} = [(0.05 \times kV) + 4] \quad \mu Gy\left(Gy\,cm^2\right)^{-1}. \tag{5}$$

Table 4. Dose rates per unit activity from a point source and from activity administered to adult nuclear medicine patients, at different distances from the anterior mid-trunk. (Based on data reported in Greaves and Tindale (1999), Mountford and O'Doherty (1999), Benetar *et al* (2000), Smith and Stabin (2012) and Greaves and Dunn (2014)).

	Dose rates (μSv h^{-1} MBq^{-1})		
Radionuclide and scan phase[a]	1 m from point source	0.5 m from patient	1.0 m from patient
^{18}F after injection	0.138	0.3	0.11
^{18}F uptake phase		0.25	0.09
^{18}F during scan		0.2	0.06
^{67}Ga	0.019	0.03	0.01
^{99m}Tc	0.019	0.05	0.02
^{111}In	0.081	0.2	0.06
^{201}Tl	0.011	0.07	0.02
^{123}I	0.042	0.1	0.03
^{131}I	0.052	0.2	0.06

[a] The values apply to the amount of activity at the time of injection, except for those for ^{18}F which relate to the average values during different phases of the examination process.

These factors all give the scatter dose at a distance of 1 m from the patient, so values of the air kerma level (K) for unprotected parts of a member of staff at distance d from the patient can then be derived by substituting values of K_s obtained using equations (3)–(5) into the equation:

$$K = K_s/d^2. \tag{6}$$

A similar approach can be used for calculating scatter air kerma levels for CT fluoroscopy from the dose length product (DLP) in regions outside the protection afforded by the scanner gantry (Wallace *et al* 2012). Here the scatter at 1 m from the iso-centre is given by:

$$K_s = S_{CT} \times \text{DLP}. \tag{7}$$

Where S_{CT} is equal to 0.36 μGy (mGy cm)$^{-1}$ for body scans and 0.14 μGy (mGy cm)$^{-1}$ for head scans. The scatter air kerma at any position can then be calculated using equation (7).

4.3. Nuclear medicine

Risk assessments for radionuclide users depend on the amount of activity that is handled and the level of protection that is in place. The times that staff members spend in close proximity to patients are significant for body exposure, and factors giving dose rates at different distances from patients taken from various studies are given in table 4. Dose rates will be lower when staff are further away and, although patients are not point sources, indicative dose rates at greater distances can be derived by application of an inverse square law to the values at 1 m. Point source dose rates are also given to enable calculations of exposure from partially shielded sources such as syringes and open vials. Approximate values for doses that might be received can be derived by multiplying dose rates (D_R) by estimations of the times (t_i) spent with corrections for distance (d_i) through the inverse square law. The results for a series of exposures received (1 to i) can then be summed to calculate the body or eye dose received D_E over a period of time from an equation of the form:

$$D_E = \sum_i \frac{D_{Ri}}{d_i^2} \times t_i. \tag{8}$$

The calculated doses can be used to provide a starting point for risk assessments of eye or body dose, but monitoring is essential in order to assess doses for radionuclide users, based on their actual practices.

5. Conclusions

The latest European and International Basic Safety Standards published in 2014 contained a substantial reduction in the dose limit for the lens of the eye and this has particular implications for practices in healthcare. Staff operating x-ray equipment need to use personal protective equipment and other protective devices, and as a result their exposure to radiation is generally not uniform. This presents particular issues for personal dosimetry. In addition, doses to the fingers of nuclear medicine workers can be high, but because of the dose gradient across the hands, assessment can be problematic. Therefore new approaches involving more personal dosimetry are required, and guidelines have been prepared for IPEM setting out recommendations to help radiation protection practitioners determine monitoring requirements (Martin *et al* 2018). The full recommendations together with discussion of specific situations are included in the report, and the principle recommendations and methodologies

are summarised in this paper. Dose levels at which monitoring should be considered are listed in a table and flow charts are included to aid decisions about the best monitoring options. Methods are described to predict dose levels to which staff might be exposed, so that risk assessments can be prepared to determine initial levels of dose monitoring for individual staff members. The implementation of robust systems for dose monitoring and arrangements for investigation when dose levels exceed pre-set levels, based on recommendations given, should facilitate an improvement in optimisation of staff radiation protection.

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