Staff Exposure Monitoring in Interventional Radiology

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Background

- Interventions guided by radiological imaging have many advantages
- Considerable variation in occupational doses observed, suggesting that radiological protection practices can be improved
- Recent studies: high incidence of radiation-related eye lens opacities (pre-cataracts) in interventionalists and other professionals
- Proper monitoring of radiation doses to professionals in the interventional room is crucial for radiation protection
- In many parts of the world individual dosimeters are not worn regularly. Data on occupational doses may not always be reliable.
Learning objectives

- To know the radiation protection dose quantities
- To understand the need of the operational dose quantities
- To know the operational dose quantities used in external dosimetry and their relationship with air kerma and radiation protection quantities
- To know the operational dose quantities and the methods used in the monitoring of extremities and eye lens
- To know the type of dosimeters used in IR and their performances
- To be able to discuss pro/con of the single and double dosimetry methods for the monitoring of staff that make use of protective garments
- To understand the potentialities of the new monitoring technologies making use of active (electronic) dosimeters
Recommendations of ICRP 103 (2007) have revised the dose quantities that allow to evaluate the radiation-induced effects with regard to late stochastic and genetic effects.

**EQUIVALENT DOSE**

$$ H_T = w_R \cdot D_T $$

$J/Kg = Sv$

$w_R$ expresses the biological effectiveness of a given type of radiation.

**EFFECTIVE DOSE**

$$ E = \sum H_T \cdot w_T $$

$J/Kg = Sv$

$H_T$ is the averaged equivalent dose for reference male and female, $w_T$ represent the relative contribution of that organ or tissue to the total detriment. In brackets the weighting factors of ICRP 60 modified in ICRP 103 (2007).

<table>
<thead>
<tr>
<th>Type of radiation and energy interval</th>
<th>Weighing factor $w_r$</th>
<th>Organ or tissue</th>
<th>Weighing factor $w_t$</th>
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<tbody>
<tr>
<td>Photons (all energies)</td>
<td>1</td>
<td>Gonads</td>
<td>(0.20) 0.08</td>
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<tr>
<td>Electrons (all energies)</td>
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<td>Colon</td>
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</tr>
<tr>
<td>Neutrons (&lt; 10 KeV)</td>
<td>5</td>
<td>Red bone marrow</td>
<td>0.12</td>
</tr>
<tr>
<td>Neutrons (da 10 KeV a 100 KeV)</td>
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<td>Lungs</td>
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<tr>
<td>Neutrons (da 100 KeV a 2 MeV)</td>
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<td>Stomach</td>
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<tr>
<td>Neutrons (da 2 MeV a 20 MeV)</td>
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<td>Bladder</td>
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<tr>
<td>Neutrons (&gt; 20 MeV)</td>
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<td>Breast</td>
<td>(0.05) 0.12</td>
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<tr>
<td>Protons (&gt; 2 MeV)</td>
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<td>$\alpha$ particles</td>
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<tr>
<td></td>
<td></td>
<td>Thyroid</td>
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<tr>
<td></td>
<td></td>
<td>Bone surface</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Skin</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Remaining organs and tissues</td>
<td>0.05</td>
</tr>
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</table>
Operation dose quantities

• The body-related protection quantities (equivalent dose and effective dose) are not measurable
• **Operational quantities** are therefore used for the assessment of effective dose or equivalent doses in tissues or organs
• Operational quantities are aimed at providing an estimate or upper limit for the value of the protection quantities related to an exposure
• They are often used in practical regulations or guidance.
The concept of operational quantities

• Radiation incident on the human body can be **penetrating or low-penetrating radiation**
  – **Low-penetrating** when the dose equivalent to the skin (at depth 0.07 mm) is higher than 10 times the effective dose (α-particles, β-particles at energies <2 MeV, and photons with energies <12 keV)

• Monitor of areas and individuals are performed with dosemeters
  – The radiation “seen” by the dosemeter worn on a body where radiation field is strongly influenced by the backscatter and absorption in the body differs from the radiation “seen” by an area dosemeter (usually in air)
  – Different **operational quantities** are necessary to relate:
    • Field doses (air kerma, absorbed dose, fluence) → dosemeter doses
    • Dosemeter doses to equivalent dose → an organ or effective dose
Operational Quantities

• Where doses are estimated from area monitoring results, the relevant operational quantities are:
  – ambient dose equivalent $H^*(d)$
  – directional dose equivalent $H^*(d,\Omega)$

• For individual monitoring, is recommended the use of the
  – personal dose equivalent $Hp(d)$
OPERATIONAL QUANTITIES HAVE THE BODY IN MIND

- All 3 quantities are defined in specific radiation fields using tissue-like objects to simulate radiation interaction properties of tissue.

ICRU soft tissue substitute:
- 10.1% hydrogen
- 11.1% carbon
- 2.6% nitrogen
- 76.2% oxygen
• The expanded field is one in which the fluence, and its angular and energy distribution, are the same throughout the volume of interest as in the actual field at the point of reference.

*Field at point, P*

(e.g. the sphere is uniformly illuminated by the radiation in multi-directional.)
• In the expanded and aligned field, the fluence and its energy distribution are the same as in the expanded field, but the fluence is unidirectional.
The ambient dose equivalent, $H^*(d)$, at a point, is the dose equivalent that would be produced by the corresponding field, in the ICRU sphere at a depth $d$ in millimeters on the radius opposing the direction of the field.

- For measurement of strongly penetrating radiations, the reference depth is 10 mm and the quantity denoted as $H^*(10)$.
- The unit is J kg$^{-1}$. The special name for the unit of ambient dose equivalent is Sievert (Sv).
• The directional dose equivalent, $H'(d, \Omega)$, at a point, is the dose equivalent that would be produced by the corresponding expanded field in the ICRU sphere at a depth $d$ on a radius in a specified direction $\Omega$.
  
  – Directional dose equivalent is of particular use in the assessment of dose to the skin or eye lens
  
  – The unit is J kg$^{-1}$. The special name for the unit of ambient dose equivalent is Sievert (Sv)
The personal dose equivalent, $Hp(d)$, is the dose equivalent in soft tissue, at an appropriate depth $d$, below a specified point on the body,

- $Hp(d)$ can be measured with a dosimeter which is worn at the surface of the body and covered with an appropriate thickness of tissue-equivalent material
  - $Hp(10)$, measured at a depth of 10 mm in soft tissue, is the operational surrogate for the effective dose, $E$
  - The unit is J kg$^{-1}$. The special name for the unit of ambient dose equivalent is Sievert (Sv)
VERIFICATION OF COMPLIANCE WITH DOSE LIMITS

III.4. The effective dose limits specified in this schedule apply to the sum of the relevant doses from external exposure in the specified period and the relevant committed doses from intakes in the same period; the period for calculating the committed dose shall normally be 50 years for intakes by adults and shall be up to age 70 years for intakes by children.

III.5. For occupational exposure, the personal dose equivalent $H_p(10)^{69}$ may be used as an approximation of the effective dose from external exposure to penetrating radiation.

III.6. Values of the effective dose per unit air kerma free-in-air and per unit particle fluence are given in Tables III.1A–III.1D [30].
Relationship of dosimetry quantities

**Primary physical quantities**
- Fluence, $f$
- Kerma, $K_a$
- Absorbed dose, $D$

**Protection quantities**
- Organ absorbed dose, $D_T$
- Organ equivalent dose, $H_T$
- Effective dose, $E$

**Operational quantities**
- Ambient dose equivalent, $H^{*}(d)$
- Personal dose equivalent, $H_P(d)$

**Monitored quantities**: Instrument responses

*Calculated using $Q(L)$ and simple phantoms (sphere or slab) validated by measurements and calculations.*

*Compared by measurement and calculations (using $w_T$, $w_R$ and anthropomorphic phantoms).*

*Related by calibration and calculation.*
• Photon dose conversion coefficients for $E$ and $H_{\text{slab}}$ (the calibration quantity of the personal dosimeter)

• Relationship of $E$ and $H_{\text{slab}}(10)$ as a function of photon energy
  – It demonstrates that $H_p(10)$ at lower photon energies, overestimates the effective dose.
  – At diagnostic x-ray qualities the overestimation is quite important
The value of $Hp(d)$ depends on the position of measurement on the body.

A water filled slab phantom, $30\times30\times15\text{cm}^3$ is recommended for calibrating dosimeters used to measure exposure to the whole body.

Here the ISO phantoms used in the calibration of whole-body, bracelet and ring dosimeters

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**Figure 3:** Phantoms to be used for calibration of dosimeters: (a) ISO slab phantom, (b) ISO pillar phantom, and (c) ISO rod phantom.
Conversion coefficients

- Relationship of \( \text{Hp}(10) \) vs air kerma as a function of photon energy and irradiation angle on a ICRU slab (IAEA Safety Guide RS-G-1.3)

### Table V.1

<table>
<thead>
<tr>
<th>Photon energy (MeV)</th>
<th>( \text{Hp}(10,0)/K_a ) (Sv/Gy)</th>
<th>Ratio ( \text{Hp}(10,\alpha)/\text{Hp}(10,0) ) for angles ( \alpha )</th>
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<tr>
<td>0.010</td>
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<td>0.400</td>
<td>1.300</td>
<td>1.004 1.004 1.004 1.004 1.004 1.004</td>
</tr>
</tbody>
</table>

\( \text{Hp}(10,0)/K_a \) (Sv/Gy)
Exposure assessment: WHOLE-BODY

- Individual external doses should be determined by using individual monitoring devices based on radiation detectors like:
  - Thermoluminescent or optically stimulated luminescence
  - Radiographic film
  - Diodes in electronic dosimeters
- These dosimeters have usually multiple detectors measuring $Hp(10)$ and $Hp(0.07)$
- They are worn at breast level or waist level, between the shoulders and the waist
- The monitoring period should be one month, and shall not exceed three months.
- The exchange of dosimeters and report receipt should not exceed three months
• The monitoring of hand exposure is made with a ring dosimeter worn on the most exposed hand with the detector/s toward the radiation source

• Ring dosimeters are using TL or OSL detectors

• These dosimeters are calibrated in term of low penetrating radiation Hp(0.07)
The monitoring of eye lens exposure is a complex and not yet well defined methodology. It can be performed with:

- A specifically designed dosimeter worn at the level of the most exposed eye (usually on the left side) and calibrated in terms of Hp(3).
- Or, from the Hp(0.07) reading of a whole-body dosimeter worn at the collar level over protective garments.

These methodologies, with relative uncertainties, have been discussed in the workshop.
Detectors and dosimeters

- Film
- Thermoluminescence (TLD) and optically stimulated luminescence (OSL) dosimeters
- ”Electronic” dosimeters
TLD

Hp(0.07) whole body

Hp(10) extremity
Individual monitoring in interventional radiology

- In typical interventional radiology environment the assessment of the effective dose $E$ from the dosimeter/s readings is a complex dosimetry problem

  \[ \text{Dosimeter/s reading} \rightarrow \text{HP(10)} \rightarrow E \]

- function of several factors, procedure and operator dependent:
  - Type of procedure
  - Position of the operator
  - X-ray projection and kV
  - Position of dosimeter/s, outside or under protective apron
  - Apron thickness/protective collar/other protective devises

- Which is the conversion factor to use?
Effective dose assessment in interventional radiology

- ICRP Report 85 (2001)
  - Paragraph 66: The high occupational exposures in interventional radiology require the use of robust and adequate monitoring arrangements for staff.
  - A single dosimeter worn under the lead apron will yield a reasonable estimate of effective dose for most instances.
New ICRP recommendations (2018?)*

• Two dosimeters, one shielded by the apron (under apron) and one unshielded (over apron) at collar level, provide the best estimate of effective dose.

• The under-apron dosimeter also provides confirmation that the apron has actually been worn and that its shielding is sufficient to keep the dose under the apron low.

• The over-apron dosimeter also provides an estimation of the doses to the eye lenses.

*Occupational Radiological Protection in Interventional Procedures
Draft approved by the ICRP Main Commission
Several personal dosimeters are recommended

From: Avoidance of radiation injuries from interventional procedures. ICRP 85
Double dosimeters algorithms

• Literature search: 140 publications, 14 different algorithms

• Early algorithms without consideration of the thyroid shield
  - Gill et al. (1980), Webster (1989) and Balter et al. (1993) based on effective dose equivalent (EDE; ICRP 26)
Double dosimetry algorithms

\[ E = \alpha H_u + \beta H_o \]

<table>
<thead>
<tr>
<th>DD algorithm</th>
<th>Without TS</th>
<th></th>
<th>With TS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rosenstein and Webster (1994), NCRP Report 122 (1995)</td>
<td>0.5</td>
<td>0.025</td>
<td></td>
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<tr>
<td>Niklason et al. (1994)</td>
<td>1</td>
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<td>Swiss ordinance (2008)</td>
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<tr>
<td>McEwan (2000)</td>
<td>0.71</td>
<td>0.05</td>
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<tr>
<td>Sherbini and DeCicco (2002)</td>
<td>1</td>
<td>0.07</td>
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<tr>
<td>Von Boetticher et al. (2003), Lachmund (2005)</td>
<td>0.84</td>
<td>0.10</td>
<td>0.79</td>
</tr>
<tr>
<td>Clerinx et al. (2007)</td>
<td>1.64</td>
<td>0.075</td>
<td></td>
</tr>
</tbody>
</table>

TS: Thyroid shielding
DD algorithms – Some studies

• MC simulations
  – Schultz and Zoetelief (2006): Comparisons of algorithms for cardiac catheterization procedures
  – Siiskonen et al. (2007): Study on the effect of apron in cardiac and cerebral IR procedures

• MC simulations and TLD measurements
  – Clerinx et al. (2007): MC calculations and TLD measurements in Rando-Alderson phantom for typical scatter field geometries in IR --> algorithm Clerinx et al. (2007)
Schultz and Zoetelief MC simulation

• Monte Carlo technique

• Basic requirements:
  – Modeling the exposure set-up
  – Tracking particles through matter
  – Interaction of particles with matter
  – Modeling the detector response

• Yields:
  – Organ doses
  – (Effective dose)
  – Dosemeter reading
Anthropomorphic phantom

- Mathematical phantom, ADAM (adult male)
  - 70 kg
  - L=170 cm (76 + 70 + 24)
  - W=40 cm
  - T=20 cm
Patient and Operator relative positions

- In Air
- couch level 80 cm
- couch width 43 cm
Schultz and Zoetelief MC simulation

Protective clothing and dosemeters
X-ray Beam

- peak tube voltage, 80 kV
- HVL, 6.5 mm Al
- IPEM-78 spectrum generator
  - filtration, 3.5 mm Al + 0.3 mm Cu
- Field size, 24 cm x 24 cm at skin entrance
- Distance, FSD = 60 cm
Irradiation of the patient

in AIR

**LLAT** (arms removed)
focus: -77.31 -3.0 51.0

**P_{AK}** at 20 cm from focus,
area = 8 x 8 cm²

**PA**
focus: -1.0 69.99 51.0
Shultz and Zoetelief conclusions

• Relationship (reading $\rightarrow E$) established

• Best dosemeter position: outside apron; central, high
  – less uncertainty
  – also information on dose to unshielded body parts
  – least sensitive to beam direction

• Conversion factor: divide over-apron dosimeter reading by a factor of 20
Siiskonen et al. (2007)

• Occupational radiation doses in interventional radiology: simulations

**Lead apron protection factor**

– Average 15 (apron) or 27 (apron and thyroid shield); wide range: from 6 to 41

– Good protection in anterior projections or with low (60 kV) tube voltages: soft spectrum of scattered radiation

– Poor protection in LLAT projection or with high (100 kV) tube voltages
Siiskonen et al. (2007)

Sources of uncertainty

• Experiments in a laboratory (Monte Carlo):
  – Irradiation conditions are perfectly under control
  – Statistical uncertainty is reasonably under control (~ 5%)

• In the real world:
  – Dosimeter position, movements of the radiologist etc.: estimated variation 50% or more
  – In practice, movements of the radiologist destroy the accuracy of the conversion from the dosimeter reading to $E$ even if the projection, the tube voltage etc. are known.
Siiskonen conclusions

• Results show that dividing the over-apron dosimeter reading by a factor ≈ 60 gives a reasonable estimate for the effective dose.

• However, variations as large as a factor of 3 - 4 may be present in unfavourable situations.
Summary on DD methods

• No harmonized regulations and practices for monitoring workers in IR (see IAEA-ISEMIR Report)
• No firm consensus of the best DD algorithm
• Most algorithms overestimate E, at max over a factor of 10
• New ICRP recommendation: When the estimated effective dose is close to the annual dose limit (e.g. > 15 mSv), a more accurate estimation should be made, taking into account the specific geometry and irradiation parameters
New ICRP recommendations (2018)*

- Both high dose readings and very low dose readings may indicate misuse or failure to wear dosimeters.
- Ambient monitors (such as on the C-arm) are useful to continually assess scatter radiation fields and provide backup to personal dosimetry, to discover non-compliance in wearing individual dosimeters and to help estimate occupational doses when personal dosimeters have not been worn.

*Occupational Radiological Protection in Interventional Procedures
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IAEA-ISEMIR: personal monitoring practice in interventional cardiology

• Responses from 45 IC facilities (Chiefs)
  – From 24 countries

• Individual interventional cardiologists:
  – 201 responses from 32 countries
Personal monitoring habits

- Interventional cardiologists:
  - 76% claimed that they always used their dosimeter
  - 45% stated they always used 2 dosimeters
    - 50% in Healthcare Level I countries
    - 24% in other countries

Results from the survey probably give an over-optimistic picture
Knowledge of doses

• Interventional cardiologists:
  – 64% said they knew their own personal doses
  – 38% knew both their own and patients’ doses

Results from the survey probably give an over-optimistic picture
Radiation protection training

• Interventional cardiologists
  – 83% claimed to have had RP training
  – 52% said they had certification in RP

Results from the survey probably give an over-optimistic picture
Regulatory Bodies

• Questions addressed
  – Numbers of persons in IC being monitored
  – Dose data for IC personnel
  – Requirements for monitoring
    • Number of dosimeters
    • Position
  – Requirements for radiation protection training

• 136 answers: 24% world population
Regulatory requirements for monitoring in IC

• ~ 60% of RBs stated that they specify the number and position of dosimeters (national protocol)

• Of these:
  – 20% specify 2 dosimeters
    • 1 above and 1 below the apron
  – 40% specify 1 dosimeter
    • Most (~80%) above the apron
  – 40% did not provide information

No consistent approach to the number of or position of dosimeters
Two or just a dosimeter?

- The two-dosimeter approach provides better accuracy
- But, some authors argue that
  - The lack of international consensus on an algorithm renders comparison of effective doses difficult
  - The reliability of clinicians wearing two dosimeters correctly and consistently is questionable
  - The cost of two dosimeters is higher
  - Clinicians sometimes accidentally reverse the dosimeter positions
  - Clinicians often forget to wear the second and even the first dosimeter
Two or just a dosimeter? (cont.)

- A single dosimeter worn under the apron provides an indication of the dose received by the radiosensitive organs in the trunk, shielded by the apron.
- However, monthly readings of under-apron dosimeters are often below detection level, so the accuracy of the technique is poor and the value in providing information is limited.
Two or just a dosimeter? (cont.)

• Martin (2012) suggested a pragmatic approach of using a single dosimeter placed at the collar over the apron.

• Only when readings of the collar dosimeter exceed an established dose level in a single year a second dosimeter is provided.

• The reading of the collar dosimeter, corrected by a factor to take account of the organs that are protected (e.g. 0.1), could provide an indication of effective dose (and also of the eye lens dose).
New ICRP recommendations (2018)*

- The ICRP maintains the principal recommendation to use the two-dosimeter approach with a simple algorithm

*Occupational Radiological Protection in Interventional Procedures Draft approved by the ICRP Main Commission
New ICRP recommendations (2018)*

- Active, electronic personal dosimeters have proven useful for optimisation monitoring, for educational purposes, for special studies of dose by procedure and for specific aspects of a procedure.

*Occupational Radiological Protection in Interventional Procedures
Draft approved by the ICRP Main Commission
Active dosimeters

- Disadvantages of TLD badges:
  - Dose accumulated over a period of time
  - No real time information

New technology $\rightarrow$ Active dosimeters with automatic transfer of data
Active dosimeters

- Real-time $H_p(10)$

(Active dosimeter system (DoseAware, Philips))
Active dosimeters

- New electronic systems allow health professionals to visualize doses in real time during the procedures
- A wireless connection sends the dose readings to a database and/or display monitor
- Today active dosimeters have not minimum performance requirements to be used as legal dosimeter
• Staff dose audit in real time during interventional procedures allows correcting situations of high radiation risk for staff.
• It is also possible to do retrospective analysis of the scatter dose rates and cumulative occupational doses during the interventional procedures to audit the staff risk during the procedures.
• Correlations of occupational doses against patient doses for the different kind of procedures and the roles of the professionals involved, can also be established.
Active dosimeters

- Main characteristics of DoseAware (Philips) active dosimeter
  - Lowest sensitivity → 40μSv
  - Range → up to 10Sv
  - Updates every second and accumulated up to 5 years

Example of exposure rates and cumulative dose
Equivalent dose to the hands

• The dose limit for the skin is applied as an average over 1 cm$^2$ in the most exposed area and therefore applies to the most exposed part of the hand
• The hands of interventionalists can be close to the x-ray beam
• The ulnar aspect of the hand, which is side-on to the x-ray beam and closer to the irradiated volume of the patient, receives a higher dose, so dosimeters should be worn either on the little finger
Equivalent dose to the hands

- Wrist dosimeter: due to the inhomogeneity of the radiation field near the patient and the potential of introducing part of the hands into the direct beam, doses measured by wrist dosimeters could be much lower than actual finger doses.
- In CT: if an operator’s hand is placed in the direct beam, the annual dose limit of 500 mSv could be reached in a few minutes and dosimeter cannot measure this exposure, providing false reassurance.
Equivalent dose to the legs and feet

• Where no table shield is used, doses to the legs can be greater than those to the hands
• Consideration should be given to assess the doses to the parts of the leg that are not shielded either by the protective apron or lead/rubber drapes.
Take home messages

- Occupational exposure monitoring in interventional procedures has two major objectives: to verify compliance with dose limits and to optimise occupational protection.
- The use of two dosimeters is recommended.
- Compliance monitoring should not include also the assessment doses that could be received by non apron-protected organs.
- Wrist dosimeters may not be able to reflect actual finger doses.
- Improved technology and methodology is needed to assess lens of the eye doses when lead glasses are worn.

- The radiological protection programme should include audits of occupational doses, investigation of abnormal exposure as well as corrective actions if appropriate.