IAEA
International Atomic Energy Agency
Atoms for Peace and Development

Assessment of Occupational Exposure due to External Radiation Sources

Other types of Dosimetry

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- Eye lens dosimetry
- Double dosimetry
- Aircrew dosimetry
- Need for special dose assessment

Extremity dosimetry

Monitoring of extremity dose

- $H_p(10)$ is considered an estimate of effective dose E
- Dose limit for stochastic effects is 20 mSv/year for E
- If $H_p(10)$ is below dose limit, no risk for deterministic or tissue effects
  - Except for localised and non-homogeneous exposures, like skin on the extremities
- Extremity dosimeters sometimes needed to assess doses to skin, hands/ forearms, feet/ankles…

General guidance: ISO 15382 standard

- ISO 15382: “Procedures for monitoring the dose to the lens of the eye, the skin and the extremities”
  - How to determine the need to use dosimeters ?
  - How to ensure that individual monitoring is appropriate to the nature of the exposure ?
  - How to design a monitoring program which ensure compliance with legal individual dose limits ?
  - How to choose the type of dosimeters ?
  - How to choose positioning of the dosimeters ?
  - How to use correction factors ?

Quantities: how to measure the extremity doses?

- Skin and extremity monitoring:
  - Measurement of $H_p(0,07)$, the equivalent dose to the skin
- The ICRP recommended dose limits :
  - An equivalent dose limit to the extremities (hands and feet) or the skin of 500 mSv in a year
  - The equivalent dose limits for the skin apply to the average dose over 1 cm^2 of the most highly irradiated area of the skin

- In practice, an estimate of equivalent dose to the skin is a conservative estimate of equivalent dose to the extremities

When monitoring?

- in situations with nonhomogeneous exposure conditions for which the whole-body monitoring does not provide an adequate estimate of the dose to the skin or the extremities
  - Exposures can be significant when weakly penetrating radiation such as low energy photons or beta radiation is present
  - Workplaces where extremities are particularly close to the radiation emitter or radiation beam
    - E.g. nuclear medicine, and dismantling applications

Monitoring levels and periods

- For the extremities or the skin, monitoring should be undertaken if there is a reasonable probability to receive a dose greater than 150 mSv per year
- For dose levels expected to be lower than the recommended monitoring levels, a survey, demonstrating that the levels are not exceeded, should be sufficient
- For doses above the monitoring level, a monitoring period of one month is recommended

Characterisation of radiation fields

- Characterization of the radiation fields is important to determine the need for and the type of monitoring required.
  - Photon fields (X and gamma radiation) of any energy can contribute to the skin and extremity exposure
  - Electrons (beta radiation) with energy above 60 keV penetrate 0.07 mm of tissue
- In medical fields, the type of radiation and radionuclides are very well known
- In nuclear installations, low energy betas are to be expected in the vicinity of unsealed radioactive materials. In nuclear installations handling used fuel as well as in nuclear reactors experiencing fuel leakage high energy betas (above 700 keV) should be expected

Assessment of dose levels prior to monitoring

- Prior to routine monitoring, it is important to assess the dose levels in a workplace field situation in order to decide which method and period of routine monitoring is necessary
- The doses obtained should be extrapolated to annual doses and compared with the monitoring levels
- The assessment should be repeated when the working conditions or workload change significantly, or if the effect of such changes cannot be estimated with confidence

1. Indications of workplace monitoring

- In work situations with radiation fields that are predictable over a long period: possible to estimate the worker doses using workplace measurements at relevant locations
- For determining the directional dose-equivalent rate dH'(0,07)/dt, suitable dose-equivalent rate meters (i.e., with thin walls and small detector thickness) shall be used. If protective clothing is worn, H'(0,07) shall be measured behind the respective layer of clothing
- The measurement position shall be representative of the exposure conditions of the person surveyed
- If tools are used, measurements shall be performed at the distance appropriate for the use of such tools

2. Indications of whole body monitoring

- A dosimeter worn on the trunk is used for the estimation of effective dose
  - The results from the whole body dosimeter can give an indication of the level of exposure to the extremities or the skin, provided the exposure conditions and the radiation field characteristics (especially the spatial distribution) are taken into account
- When the whole body dosimeter is worn under the protective clothing, its reading strongly underestimates the dose to the unprotected extremities and can therefore not be used to provide an indication of the level of these doses

3. Indications of literature

- In the literature, some typical dose values are given for various workplace situations
- When using literature it should be ensured that the data are truly representative of the current workplace conditions regarding the radiation source, the geometry and types of protective measures

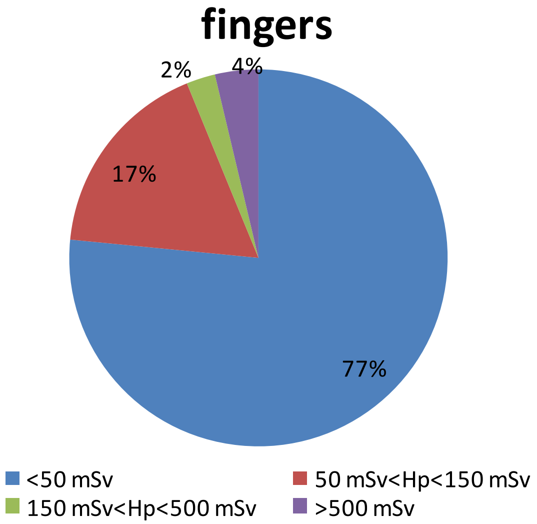
3. Indications of literature

- Martin and Whitby: with good practices it is possible to stay within the limits

Group	Range of annual doses [mSv]
Interventional radiologists (hands)	10-200
Interventional radiologists (legs)	10-200
Interventional radiologists (legs, with shield)	1-15
Cardiologists (hands)	5-100
Cardiologists (legs)	5-100
Cardiologists (legs, with shield)	0.5-10
Radiopharmacy staff	10-200
Nuclear medicine staff	5-40

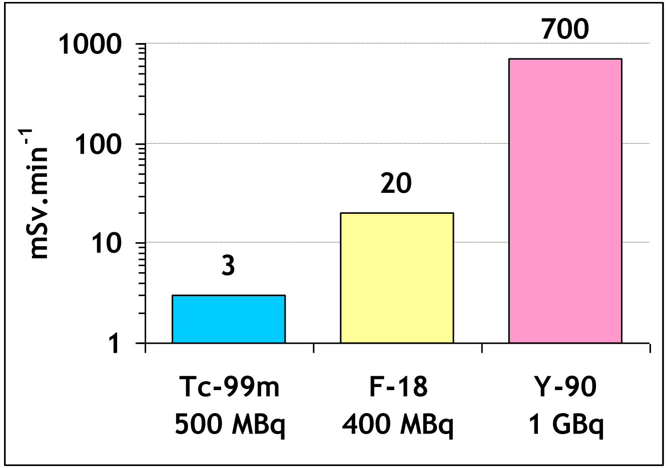
ORAMED project: Extremity doses in interventional procedures

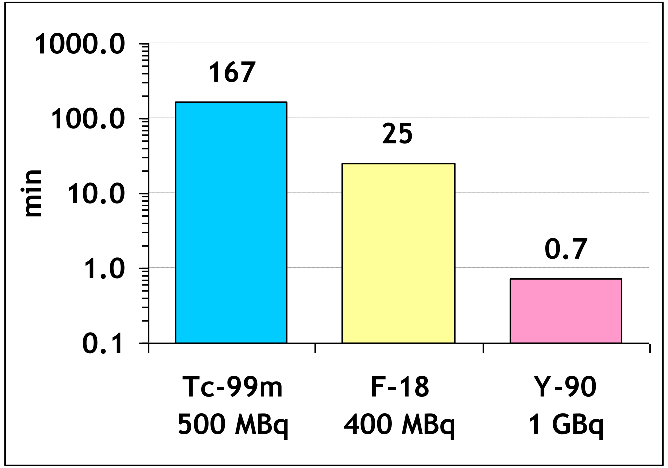
- Wide range of staff doses
  - Importance of protective measures, personal habits
- Feet and legs can also have significant doses



Nuclear medicine: high dose rates possible

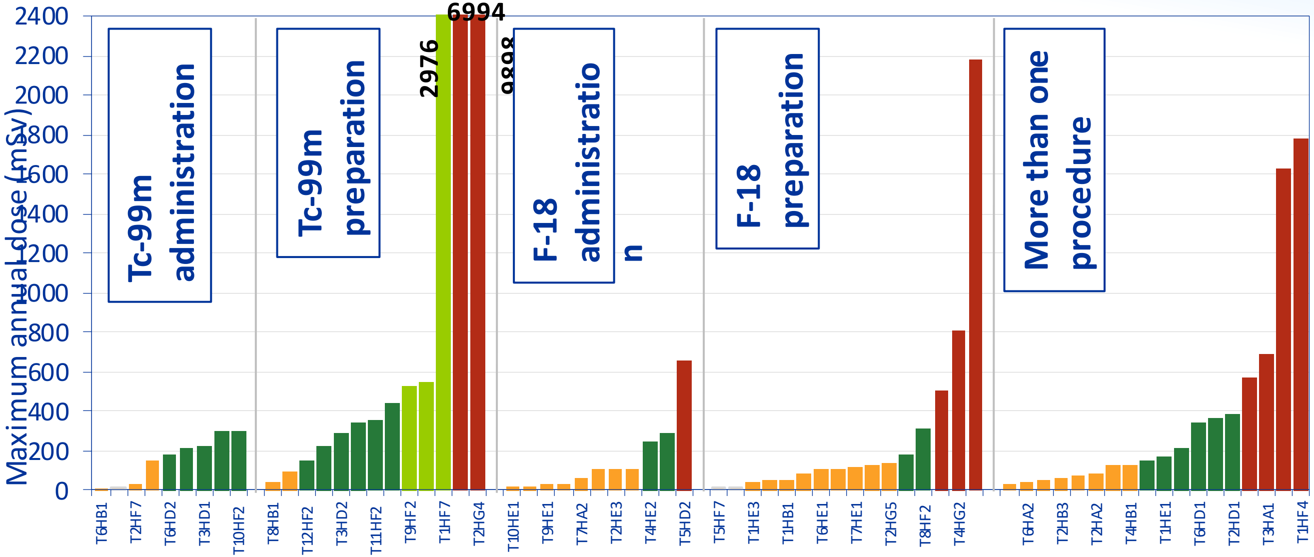
- Contact of an unshielded (5 ml) syringe
  - $H_p(0.07)$ rate (in mSv.min-1)
  - Time (in min) to reach 500 mSv





- The hands are particularly exposed in nuclear medicine

ORAMED project: Annual dose estimation for nuclear medicine workers



D < 150 mSv → 49%

150 mSv < D < 500 mSv → 31%

D > 500 mSv → 19%

- Real risk of surpassing the dose limits

4. Indications from simulations

- Numerical simulations can be very powerful and can provide important information on the parameters affecting and influencing the doses

- Simulations are often complex and time consuming

5. Indications from confirmatory measurements

- Measurements to assess the level of doses to the workers in the specific workplace field
- Confirmatory measurements can be used as guidance in determining whether the monitoring level might be reached
- Shall fulfil the following requirements:
  - the confirmatory measurements shall mimic routine measurements:
    - The working procedures shall not be changed because of the confirmatory measurements
    - The confirmatory measurements shall be performed for a minimum of 3 consecutive periods
    - The intention is to have a representative sample of the annual doses

Locations for monitoring

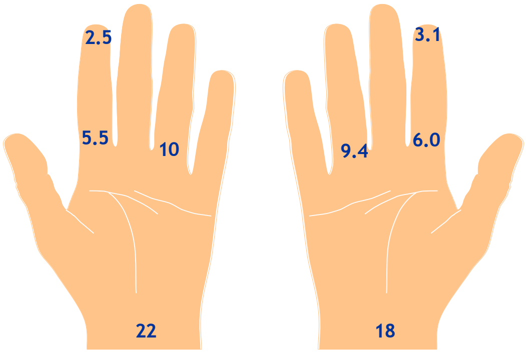
- For direct or close handling of radioactive sources, finger-stall dosimeters on the fingertip, or ring dosimeters should be used on the finger which is frequently the most exposed
- The dosimeter should be oriented towards the radiation source
- For nuclear industry fields, interventional radiology, or other similar radiation fields, either a ring dosimeter or a wrist dosimeter worn at the most exposed hand shall be used
- The dosimeter shall be worn under protective clothing, especially inside gloves, if such clothing is worn
- The dosimeter can also be worn outside the protective clothing, but under an appropriate thickness of material that approximates the type and thickness of the protective clothing

Application of correction factors

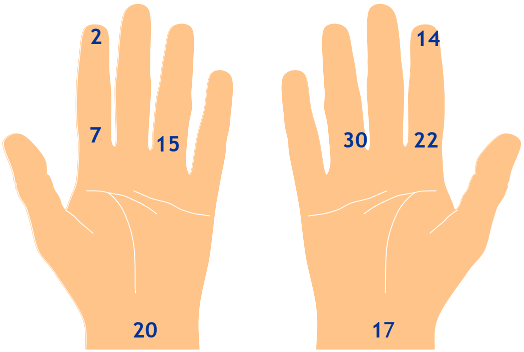
- Common extremity monitoring positions, such as the base of the fingers or the wrist, often underestimate the maximum dose
    - To estimate the maximum skin dose from a routine dosimeter, a correction factor shall be established and employed
- This value could be determined independently for each worker by individual measurements for a short trial period
- Existing correction factors can be employed considering the routine monitoring position

Recommended correction factors for nuclear medicine: ORAMED project

- A rough estimate of the maximum dose to the hand can be obtained by multiplying the reading of the dosimeter worn in the base of the index of the non dominant hand by 6



Diagnostics



Therapy

Application of correction factors for nuclear medicine

- Tip of index finger is likely to receive highest dose
  - This position recommended for monitoring
  - Base of index finger receives factor 2-4 less than of tip dose (C. Martin)
  - Higher factors when not using syringe shields
- Other studies:
  - Ranges from 1.4 to 7.0 for different manipulations and operators
- For nuclear medicine, ICRP Publication 106 recommends placing the routine dosimeter on the base of the middle finger with the detector positioned on the palm side. In this case, a correction factor of 3 (6 if the dosimeter faces the back) can be applied to get the value at the tip of the finger

Extremity dosimeters

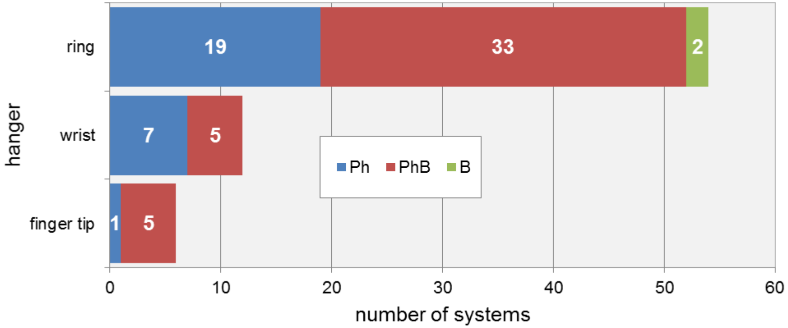
- Only one element is mostly possible in ring dosimeter
- Limited to tissue equivalent detectors, not possible to use algorithm
- A simple, one element TLD may be sufficient
- Also OSL materials possible
- The detector should be thin
- Filtered by a tissue equivalent material so that the dose at a nominal depth of 7 mg/cm^2 can be assessed
- Measurement in the range 5 to 10 mg/cm^2 would suffice

Different type of extremity dosimeters available

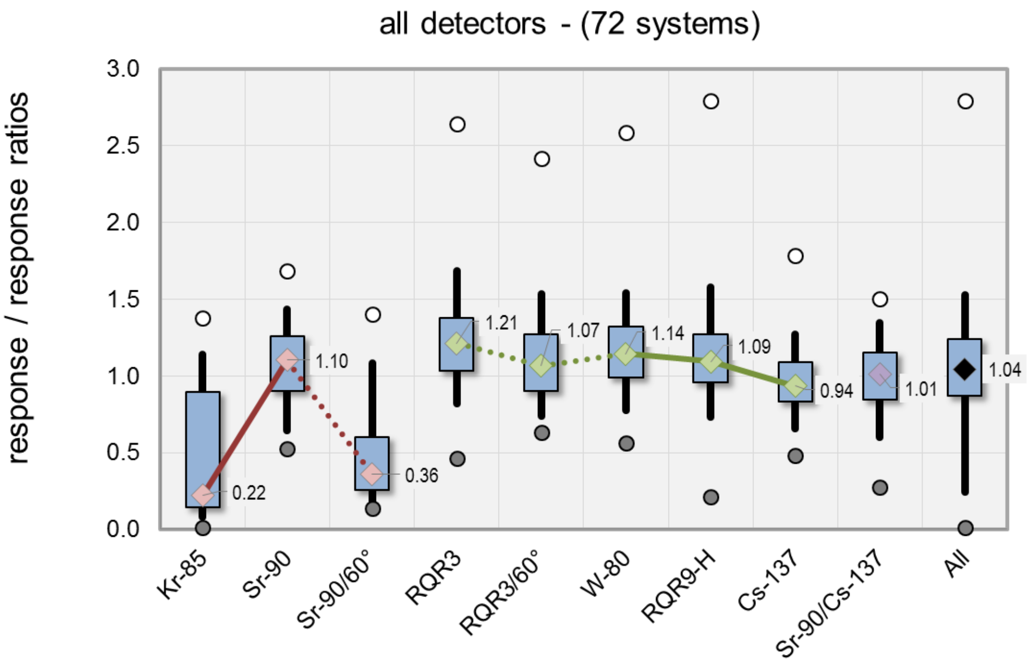
- EURADOS organizes periodic intercomparison of extremity dosimeters
- The overall objective is to verify the performance of different extremity dosimeters to measure the quantity $H_p(0.07)$ in photon and beta reference fields and in workplace fields found in interventional radiology and nuclear medicine
- Gives good overview of common practices

Dosimeter Types Participating

detector type	systems	% of all	% of type
TLD	**69**	**96%**	
LiF:Mg,Ti	36	50%	52%
LiF:Mg,Cu,P	29	40%	42%
Li2B4O7:Cu	3	4%	4%
LiF:Mg,Ti/LiF:Mg,Cu,P	1	1%	1%
Other	**3**	**4%**	
AlO	2	3%	67%
LiF T-100	1	1%	33%
All	**72**	**100%**	

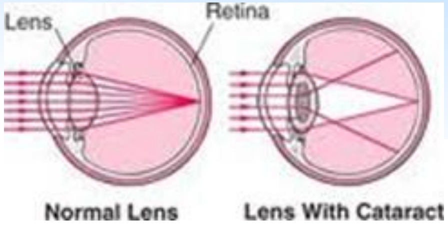


All response values



Eye lens dosimetry

What is cataract?



- Cataract: “loss of transparency of the lens of the eye”
  - Starts with lens opacities
- Cataract: most frequent cause for blindness worldwide
  - Genetic component
  - Age related effect
  - Additional risk factors include
    - Sunlight, alcohol intake, nicotine consumption, diabetes, use of corticosteroids
  - Also induced by RADIATION…

- Types of cataract: nuclear, cortical, posterior subcapsular
- Radiation: mostly posterior subcapsular (but not exclusively)

Cataract: Stochastic or deterministic effect?

- Cataracts as deterministic or stochastic effect?
  - Deterministic: threshold dose
  - Stochastic: no threshold dose…

- No answer yet….

- Latency and severity dependent on
    - Age, gender, type of irradiation, dose, dose rate, dose fractionation
    - Genetic component
    - Subsection of population genetically predisposed to cataract development

Previous ICRP position

- ICRP
  - Cataract induction = deterministic effect with definite threshold
    - Acute exposure: 0.5-2 Gy
    - Prolonged exposure: 5 Gy (detectable opacities)
    - Prolonged exposure: 8 Gy (visual impairment)

  - Latency period that can last for decades

  - Dose limits:
    - 150 mSv/year for professionally exposure

ICRP new position: based on new data

- Previous studies:
    - Not sufficient follow-up time, few subjects above Gy, not included longer latency time for lower doses,…
- Now better techniques, better dosimetry
    - Findings of radiation induced cataract at lower doses
    - No indication that fractionated is less harmful than acute exposures
- ICRP 118:
    - threshold dose around 0.5 Gy for acute exposures
    - Not certain there is a threshold
    - Idem for fractionated exposures (but for opacities instead of cataract)
- ICRP statement 2011:
    - new eye lens limit: 20 mSv per year

(averaged over 5 year, with not more than 50 mSv/year)

Guidance on eye lens dosimetry in ISO 15382

- ISO 15382: “Procedures for monitoring the dose to the lens of the eye, the skin and the extremities”
- It covers practices which involve a risk of exposure to photons in the range of 8 keV to 10 MeV and electrons and positrons in the range of 60 keV to 10 MeV
- Does not cover exposure to alphas and neutrons
- The questions on which the new standard gives guidance are:
  - How to determine the need to use dosimeters ?
  - How to ensure that individual monitoring is appropriate to the nature of the exposure ?
  - How to design a monitoring program which ensure compliance with legal individual dose limits ?
  - How to choose the type of dosimeters ?
  - How to choose positioning of the dosimeters ?
  - How to use correction factors ?

Quantities: how to measure the eye lens doses?

- Dose limit: 20 mSv/year
  - for $H_{T,\ eyelens}$: equivalent dose at the eye lens
- Not directly measurable
  - Need for operational quantity: $H_p(3)$
  - $H_p(3)$: dose equivalent at 3 mm depth
- Operational quantity > limiting quantity
- $H_p(3)$ was hardly used in the past
  - Few dosimeters are designed for $H_p(3)$, but now increasing
- $H_p(0.07)$ or even $H_p(10)$ can sometimes be used as a good operational quantity

Practical guidelines

<table>
<tr><th>Impact factor</th><th colspan="4">Comment</th></tr>
<tr><td rowspan="3">A
(Energy and angle)</td><td colspan="4">Is the mean photon energy below about 40 keV?</td></tr>
<tr><td rowspan="2">If yes
↓
$H_p(0,07)$ may be used instead of $H_p(3)$ but not $H_p(10)$</td><td colspan="3">If no
↓
Is the radiation coming mainly from the front or is the person moving in the radiation field?</td></tr>
<tr><td colspan="2">If yes
↓
$H_p(0,07)$ or $H_p(10)$ may be used instead of $H_p(3)$</td><td>If no
↓
$H_p(0,07)$ may be used instead of $H_p(3)$ but not $H_p(10)$</td></tr>
<tr><td rowspan="2">B
(Geometry)</td><td colspan="4">Are homogeneous radiation fields present?</td></tr>
<tr><td colspan="2">If yes
↓
Monitoring on the trunk may be used.</td><td colspan="2">If no
↓
Monitoring near the eyes is necessary.</td></tr>
<tr><td rowspan="2">C
(Protective equipment)</td><td colspan="4">Is protective equipment such as lead glasses, ceiling, table shields, and lateral suspended shields in use?</td></tr>
<tr><td colspan="2">If used for the eye
↓
Monitoring near the eyes and behind the protective equipment or behind an equivalent layer of material is necessary. Otherwise, appropriate correction factors to take the shielding into account should be applied.</td><td colspan="2">If used for the trunk (e.g., a lead apron)
↓
Monitoring behind the shielding underestimates the dose to the lens of the eye as the eye is not covered by the trunk shielding.
↓
Separate monitoring near the eyes is necessary.</td></tr>
</table>

From IAEA TecDoc No. 1731, Behrens

Practical guidelines

Impact factor	**Comment**	
A **(Energy and angle)**	Is the maximum beta energy above about 0.7 MeV?	
	If no ↓ No monitoring due to beta radiation is necessary as it does not penetrate to the lens of the eye.	If yes ↓ Monitoring is necessary
B **(Geometry)**	As beta radiation fields are usually rather inhomogeneous, monitoring of the dose to the lens of the eye is necessary with the dosimeter placed near the eyes.	
C **(Protective equipment)**	Is protective equipment such as shields and glasses that are thick enough to absorb the beta radiation in use?	
	If used for the eye ↓ Consider 'photon radiation' as the beta radiation is completely absorbed in the shielding; however, bremsstrahlung has to be taken into account — the contributions from both that produced outside and that produced inside the shielding.	If not used ↓ $H_p(3)$ is the only appropriate quantity.

Monitoring levels and periods

- The following monitoring levels are recommended:
  - 3/10th of the limit
- For the lens of the eye: if there is a reasonable probability to receive a dose in a single year greater than 15 mSv or in consecutive years greater than 6 mSv per year
- For dose levels expected to be lower than the recommended monitoring levels, a survey, demonstrating that the levels are not exceeded, should be sufficient
- For doses above the monitoring level, a monitoring period of one month is recommended
- For workers whose doses are probable to stay below the monitoring level, the monitoring period in the latter case can be longer, e.g., three months

Characterisation of radiation fields

- Characterization of the radiation fields is an important step to determine the need for and the type of monitoring required
  - Photon fields (X and gamma radiation) of any energy can contribute to the lens of the eye exposure
  - Electrons (beta radiation) with energy above 700 keV penetrate 3 mm of tissue and can contribute to the dose to the lens of the eye
- Monitoring of the lens of the eye particularly relevant for workers in medical sector and in nuclear facilities eg interventional radiologists and decommissioning
  - In medical fields, the type of radiation and radionuclides are very well known
  - In nuclear installations, low energy betas are to be expected in the vicinity of unsealed radioactive materials. In nuclear installations handling used fuel as well as in nuclear reactors experiencing fuel leakage high energy betas (above 700 keV) should be expected

Monitoring the lens of the eye

- For beta radiation, monitoring is necessary only if the maximum beta energy exceeds 700 keV, since beta radiation of lower energy does not penetrate to the lens of the eye
  - If eye shields (e.g. glasses) are used, which are thick enough to absorb the beta radiation, only photon radiation should be considered, but account should be taken of any bremsstrahlung contributions (both outside and behind the shielding) produced by high energy beta radiation
  - As beta radiation fields are usually rather inhomogeneous, the dosimeter should be positioned near the eyes

Assessment of dose levels prior to monitoring

- Prior to routine monitoring, it is important to assess the dose levels in a workplace field situation in order to decide which method and period of routine monitoring is necessary

- The doses obtained should be extrapolated to annual doses and compared with the monitoring levels

- The assessment should be repeated when the working conditions or workload change significantly, or if the effect of such changes cannot be estimated with confidence

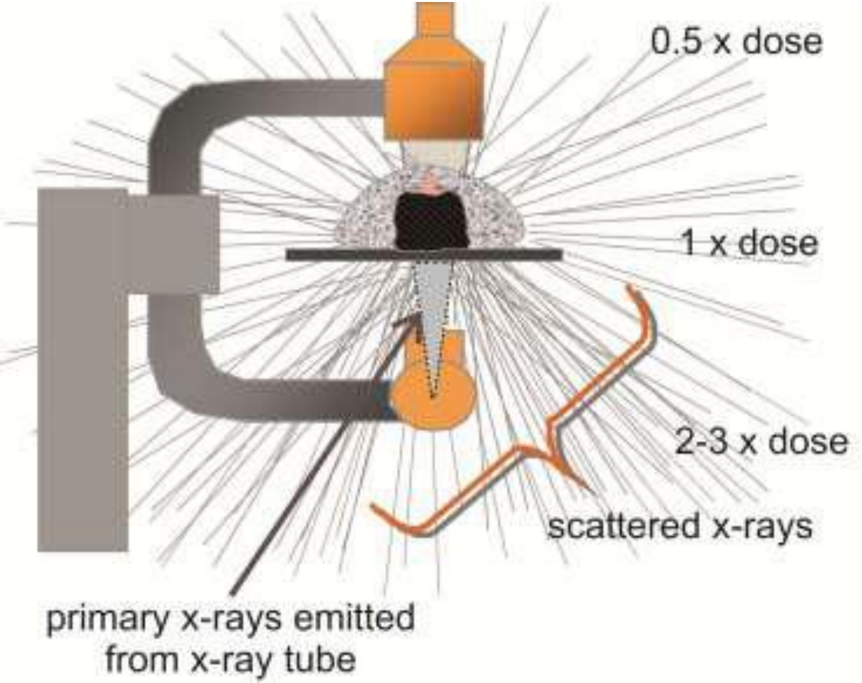
1. Indications of workplace monitoring

- In work situations with radiation fields that are predictable over a long period: possible to estimate the worker doses using workplace measurements at relevant locations
- For area dosimeters measuring the quantity H'(3), not many devices are available
  - H’(0.07) dose rate meters can be used

2. Indications of literature

- In the literature, some typical dose values are given for various workplace situations. These can in principle be used to judge if monitoring is needed
- When using literature it should be ensured that the data are truly representative of the current workplace conditions regarding the radiation source, the geometry and types of protective measures
- Most literature data are found on medical interventional procedures
- Hardly any data on NPP workers available

Medical staff involved in interventional procedures is exposed by the radiation scattered by the patient



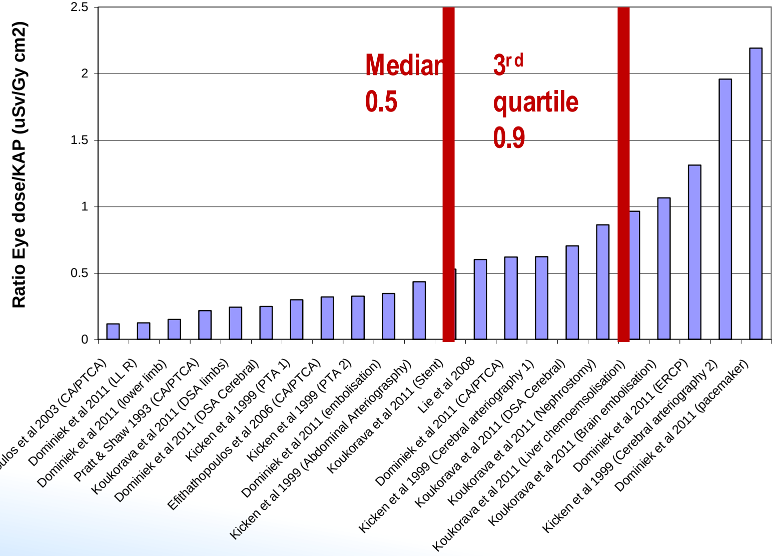
ORAMED measurements in IR/IC

- Large measurement campaign:
  - 6 different countries, 3 hospitals per country, 8 types of procedures, 10 measurements/type of procedure/hospital
  - Over 1300 measurements
  - Highest eye lens doses in embolisations (median around 60 µSv per procedure)
  - Highest eye lens doses per KAP in pacemaker implantations (PM)
  - Annual doses in ERCP relatively low: no monitoring needed
  - Annual doses in Coronary Angioplasty (CA/PTCA) can be high: monitoring needed
  - Annual doses in PM and ablations: monitoring might be needed
  - Annual doses in embolisations, vertebro and kyphoplasty can be high: monitoring needed

- Many other literature data to be found: can give a good idea on need for eye lens monitoring

Literature data: link with patient dose

Relationship between eye dose (μSv) and KAP (Gy cm^2)



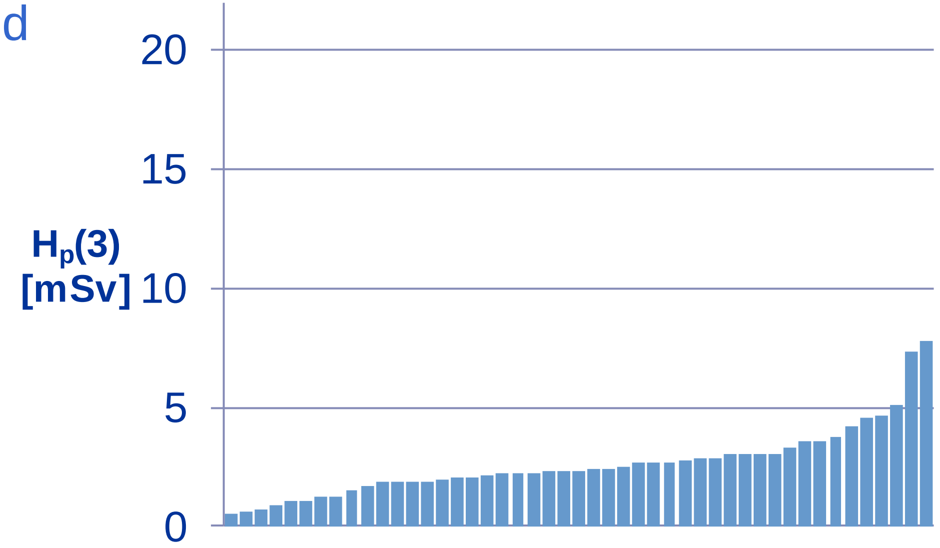
- An assumption of KAP vs Eye dose: 1 Gy cm$^2 \approx 1\ \mu$Sv

is reasonable for risk assessment

- Not recommended for monitoring purposes

Eye lens doses in nuclear medicine

- Few literature data available
- Large individual variability
- Largely dependent on workload and procedural technique
- In general monitoring is not needed



In Belgium and Poland: 47 operators: extrapolated annual doses

3. Indications of whole body monitoring

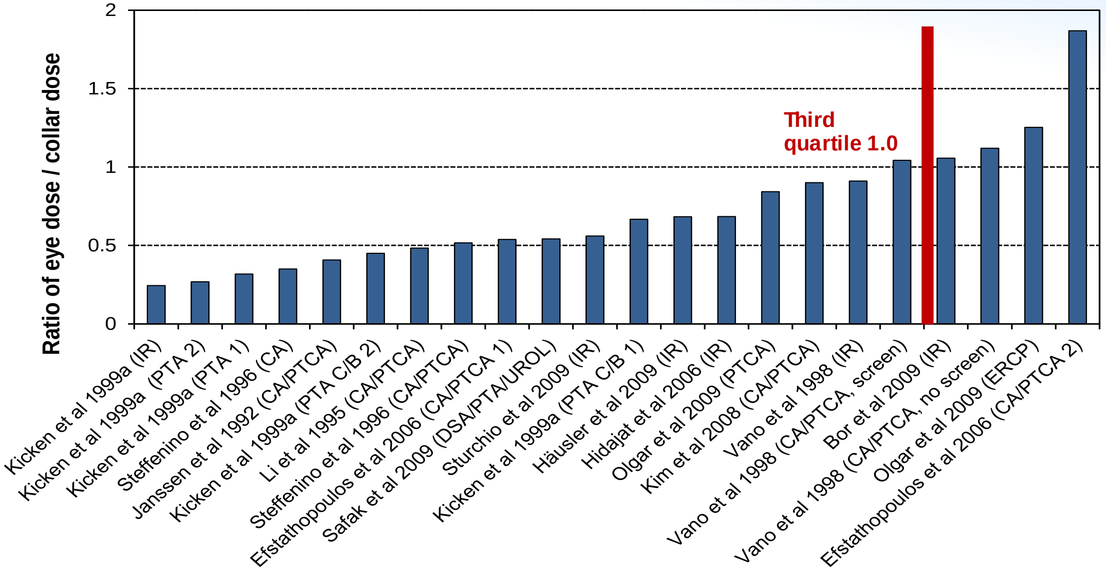
- The results from the whole body dosimeter can give an indication (not measurement) of the level of exposure to the lens of the eye, provided the exposure conditions and the radiation field characteristics (especially the spatial distribution) are taken into account

- When the whole body dosimeter is worn under the protective clothing: can therefore not be used to provide an indication of the level of the eye lens doses.

Whole body monitoring: collar dosimeter

- Some studies suggest estimating the dose to the lens of the eye from a well-placed dosimeter at collar level
- Generally: this might be acceptable in homogenous fields with higher energy radiation, but not recommended in other fields
- For interventional radiology different correction factors have been published to convert collar doses (above the lead apron) to doses to the lens of the eye for interventional procedures
    - Such correction factors are very dependent on the type of procedure, personal habits, the exact place of the above apron dosimeters and the protection measures taken, so they cannot be applied to all routine cases
    - Can lead to large uncertainties (factor of 10)
- Such a system can however provide good indications of when dedicated eye dosimetry is required

Review of studies reported in literature



- Monte Carlo simulations suggest:
  - Eye dose = 0.75 × collar dose
- Conservative assumption:
  - Eye dose = collar dose

4. Indications from simulations

- Numerical simulations can be very powerful and can provide important information on the parameters affecting and influencing the doses

- In clinical practice it is impossible to study each parameter separately, as many of them change simultaneously

- Simulations are often complex and time consuming

- When using simulations, it is necessary to validate the results with measurements

5. Indications from confirmatory measurements

- Measurements to assess the level of doses to the workers in the specific workplace field
- Confirmatory measurements can be used as guidance in determining whether the monitoring level might be reached
- Shall fulfil the following requirements:
  - The confirmatory measurements shall mimic routine measurements:
    - The working procedures shall not be changed because of the confirmatory measurements
    - The confirmatory measurements shall be performed for a minimum of 3 consecutive periods. The intention is to have a representative sample of the annual doses

Monitoring the lens of the eye

- Locations to monitor
  - The dosimeter:
    - As close as possible to the eye
    - If possible in contact with the skin
    - Faced to the radiation source
      - Interventional radiology: the side closest to the X-ray tube
  - When using protective lead glasses or face masks
    - dosimeter shall be worn preferably behind them
    - This is often not very practical
      - A dosimeter above on the outside or next to the lead glasses can be chosen
      - It can be an option to cover the front of the dosimeter with a filter that mimics the attenuation by the lead glasses
- In practical situations, dosimeters are often placed in various positions: above the eyes, at the forehead, at the side of the head, between the eyes

Application of correction factors

- If the dosimeter for the lens of the eye is not worn optimally (not close to the lens of the eye or behind shielding like e.g., lead glasses), then appropriate correction factors (DRF: dose reduction factors) shall be applied
- These factors shall normally be determined by means of measurements, possibly accompanied by numerical simulations

- Correction factors to be used should be conservative and are likely to be in the range of 5 to 3. If no facility or expertise is available to assess protection, then a correction factor of 2 may be applied
    - Many study results available in literature

Lead glasses

- The radiation attenuation factor of the eyeglass lenses is not an adequate descriptor
- Maybe a factor of 100
- The area covered by the lenses should also be considered
- Glasses should be fitted with side shields and should fit properly
- There is always backscatter in the head
- Directional influence important: radiation comes from patient, downward direction

Side view fully protected

No side protection

Application of correction factor for lead glasses

- A DRF of 2 could be applied to dosimeter results for any lead glasses
- A DRF of 3 could be applied for better designs
- Before any DRF is applied to dosimeter results there must be an arrangement to check and document compliance in wearing of both protective eyewear and dosimeters
- Closeness of fit to the facial contours is important to minimise gaps between the glasses and skin surface

Types of dosimeters

- dosimeters designed to measure $H_p(3)$ were very rare in the past, but recently specifically designed $H_p(3)$ dosimeters became available
- In principle a tissue equivalent detector with appropriate shielding is sufficient
  - Attention for angular response at high angles
  - Attention for methods for wearing it close to the eye
- If the radiation field is well known in advance, $H_p(3)$ monitoring can be performed by the use of dosimeters type tested and calibrated in terms of other quantities, i.e., $H_p(0,07)$ and $H_p(10)$

Examples of avalable dosimeters

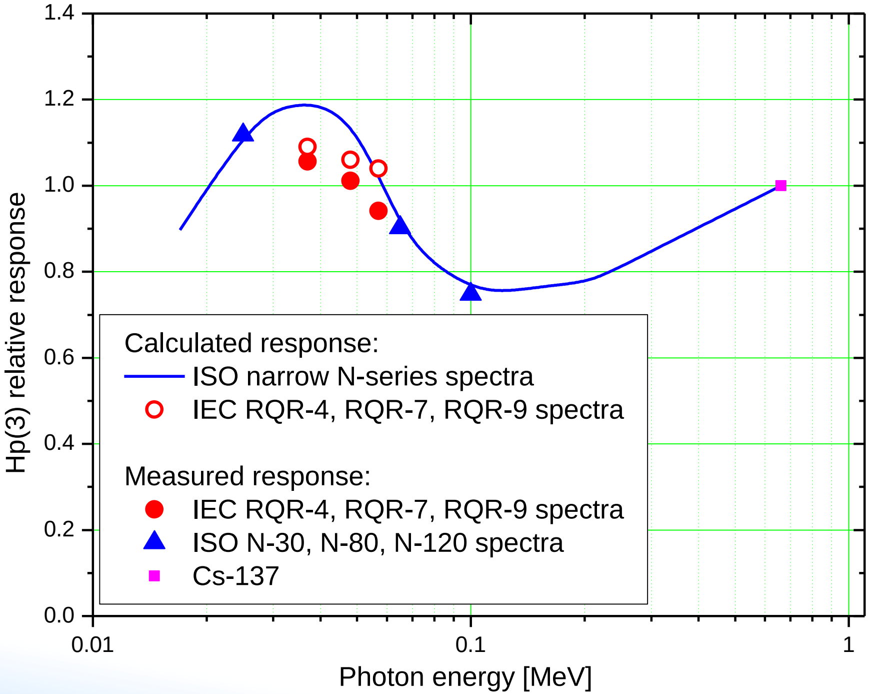
AV-Controlatom Belgium

IRSN France

EYE-D™ (Radcard)

DOZIMED S.R.L. Roumania

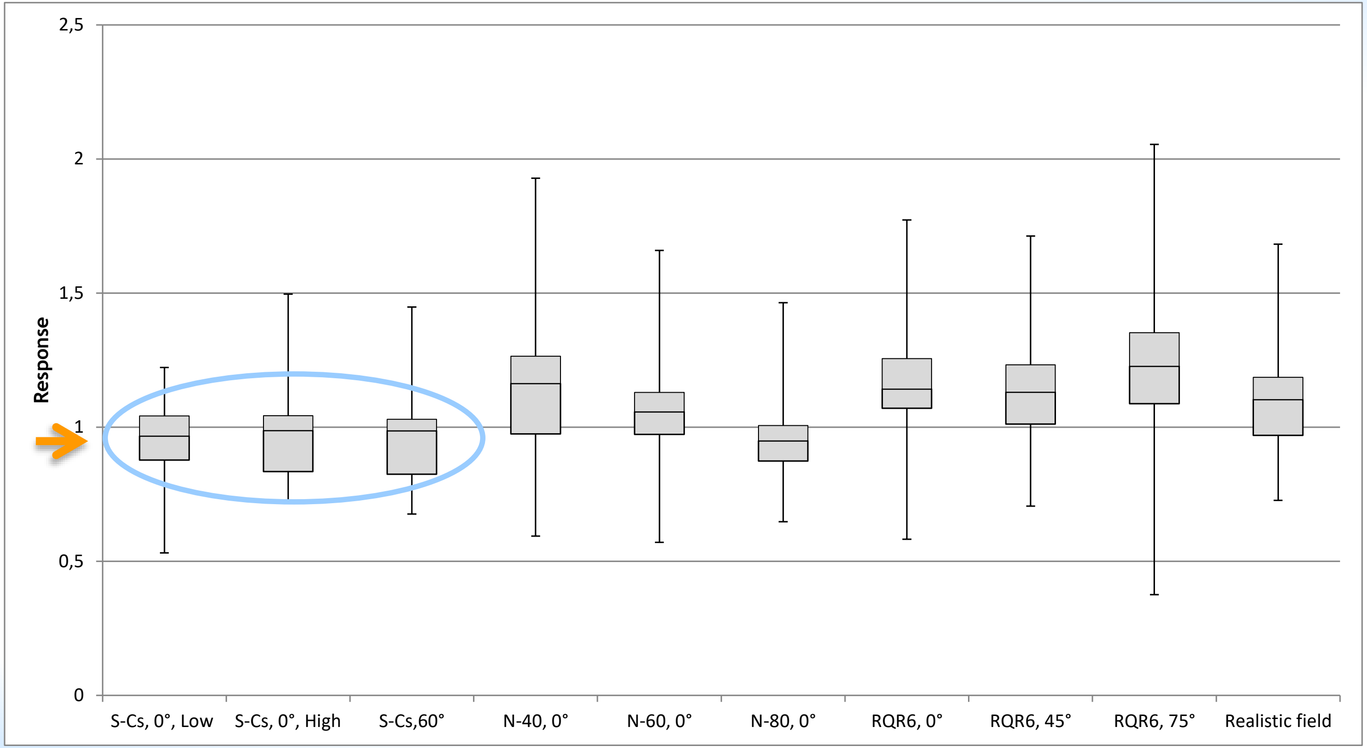
Example: energy dependence of Eye-D dosimeter



Example: EURADOS intercomparison of eye lens dosimeters

- Main objective: check the performance of eye lens dosimeters used in routine in the medical field
- Held in 2015: more dosimeters became available later
- Other intercomparisons planned in later years
- 20 participants – 15 countries

Good results in intercomparison



Monitoring the lens of the eye: conclusions

- The need for a separate eye lens dosimeter and its positioning on the body depend on the type, energy, direction and homogeneity of the radiation field, as well as on the use of shielding
- Correlation with whole body dosimeter can give indication but is not good measurement nor best solution
- Lead glasses reduce with factor 2 to 8: not zero
- One example of advice can be:

Annual dose (mSv)	Monthly dose (mSv)	Dose monitoring recommendations
1 - 6	0.1 – 0.5	Collar dosimeter to establish dose levels
6 - 10	0.5 – 1.0	Consider monitoring with head dosimeter
>10	>1	Regular monitoring with head dosimeter recommended

Double dosimetry

Double dosimetry

- In situations where workers need to be close to beam and can have high exposure: wearing of protective clothing such as lead or lead equivalent aprons
  - E.g. interventional procedures in hospitals
- Parts of the body are more protected than others
- Non-homogeneous exposure
- One dosimeter on torso does not give good estimation of effective dose
  - One dosimeter above lead apron: large overestimation of E
  - One dosimeter below lead apron: underestimation of E

- Double dosimetry is recommended: use of algorithm with 2 dosimeters

Double dosimetry

- One - under the protective apron (on the chest or waist)
- Second - on unshielded parts of the body (e.g. neck level).

- Calculation of effective dose: $E = \boldsymbol{a}H_u + \boldsymbol{b}H_o$

- The coefficients a and b depends on application of protective devices (apron, thyroid collar, glasses, gloves and other devices)

No consensus about which algorithm to use

- No harmonized regulations
- Many different algorithms in literature
- No consensus about best algorithm
- Most algorithms overestimate E by factor 2-4 and even more than 10 for some cases
- Single dosimeter algorithms are prone to underestimation of E
- Probably not possible to have algorithm working for all relevant clinical scenarios

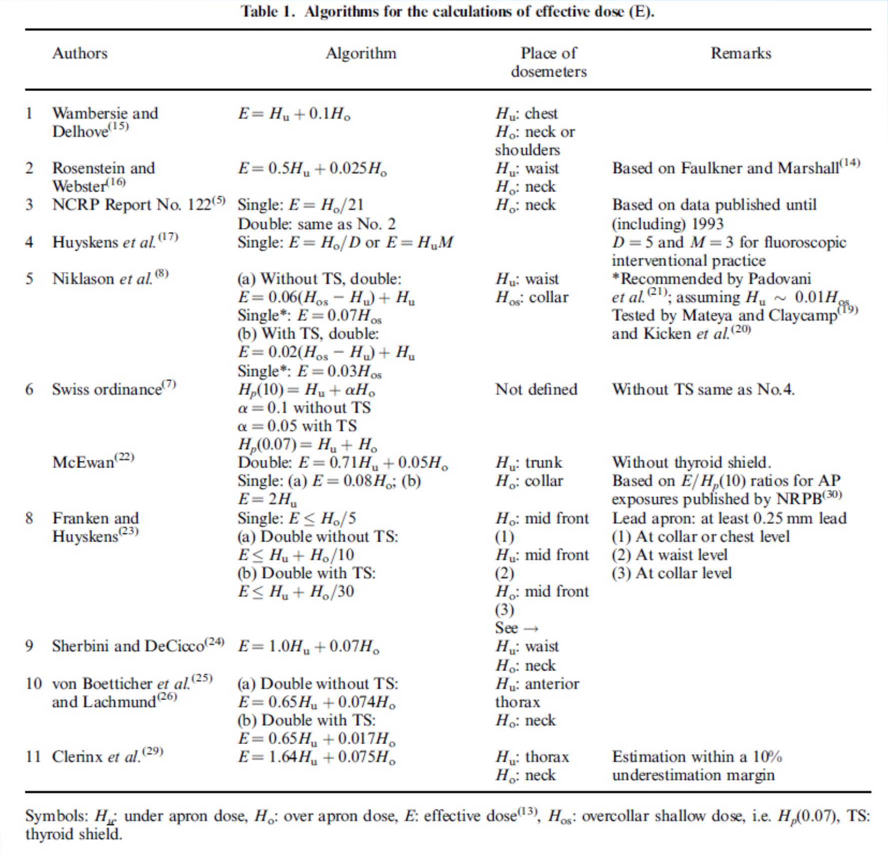


Table 1. Algorithms for the calculations of effective dose (E).

	Authors	Algorithm	Place of dosemeters	Remarks
1	Wambersie and Delhove(15)	$E = H_u + 0.1H_o$	H_u: chest H_o: neck or shoulders	
2	Rosenstein and Webster(16)	$E = 0.5H_u + 0.025H_o$	H_u: waist H_o: neck	Based on Faulkner and Marshall(14)
3	NCRP Report No. 122(5)	Single: $E = H_o/21$ Double: same as No. 2	H_o: neck	Based on data published until (including) 1993
4	Huyskens *et al.*(17)	Single: $E = H_o/D$ or $E = H_uM$		$D = 5$ and $M = 3$ for fluoroscopic interventional practice
5	Niklason *et al.*(8)	(a) Without TS, double: $E = 0.06(H_{os} - H_u) + H_u$ Single*: $E = 0.07H_{os}$ (b) With TS, double: $E = 0.02(H_{os} - H_u) + H_u$ Single*: $E = 0.03H_{os}$	H_u: waist H_{os}: collar	*Recommended by Padovani *et al.*(21); assuming $H_u \sim 0.01H_{os}$ Tested by Mateya and Claycamp(19) and Kicken *et al.*(20)
6	Swiss ordinance(7)	$H_p(10) = H_u + \alpha H_o$ $\alpha = 0.1$ without TS $\alpha = 0.05$ with TS $H_p(0.07) = H_u + H_o$	Not defined	Without TS same as No.4.
	McEwan(22)	Double: $E = 0.71H_u + 0.05H_o$ Single: (a) $E = 0.08H_o$; (b) $E = 2H_u$	H_u: trunk H_o: collar	Without thyroid shield. Based on $E/H_p(10)$ ratios for AP exposures published by NRPB(30)
8	Franken and Huyskens(23)	Single: $E \leq H_o/5$ (a) Double without TS: $E \leq H_u + H_o/10$ (b) Double with TS: $E \leq H_u + H_o/30$	H_o: mid front (1) H_u: mid front (2) H_o: mid front (3) See →	Lead apron: at least 0.25 mm lead (1) At collar or chest level (2) At waist level (3) At collar level
9	Sherbini and DeCicco(24)	$E = 1.0H_u + 0.07H_o$	H_u: waist H_o: neck	
10	von Boetticher *et al.*(25) and Lachmund(26)	(a) Double without TS: $E = 0.65H_u + 0.074H_o$ (b) Double with TS: $E = 0.65H_u + 0.017H_o$	H_u: anterior thorax H_o: neck	
11	Clerinx *et al.*(29)	$E = 1.64H_u + 0.075H_o$	H_u: thorax H_o: neck	Estimation within a 10% underestimation margin

Symbols: H_u: under apron dose, H_o: over apron dose, E: effective dose(13), H_{os}: overcollar shallow dose, i.e. $H_p(0.07)$, TS: thyroid shield.

No consensus about which algorithm to use

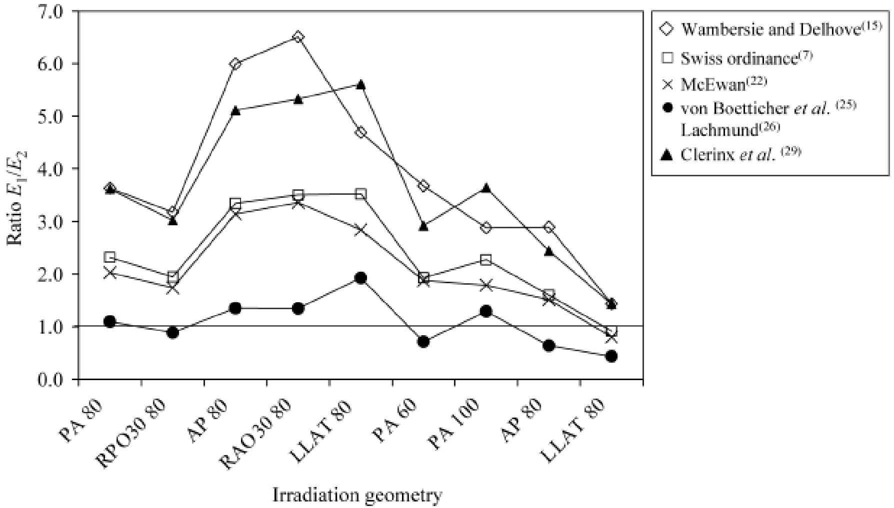


Figure 1. Ratio E_1/E_2, i.e. the effective dose calculated by the algorithm divided by the effective dose obtained from the MC calculation, for the various *double* dosimetry algorithms in the clinical cases considered and calculated by Siiskonen *et al.*(28).

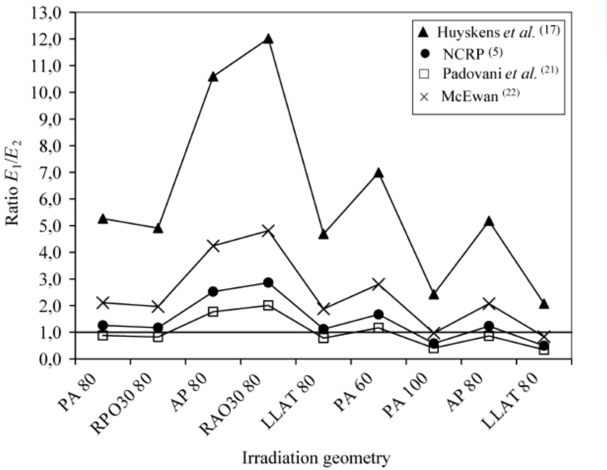
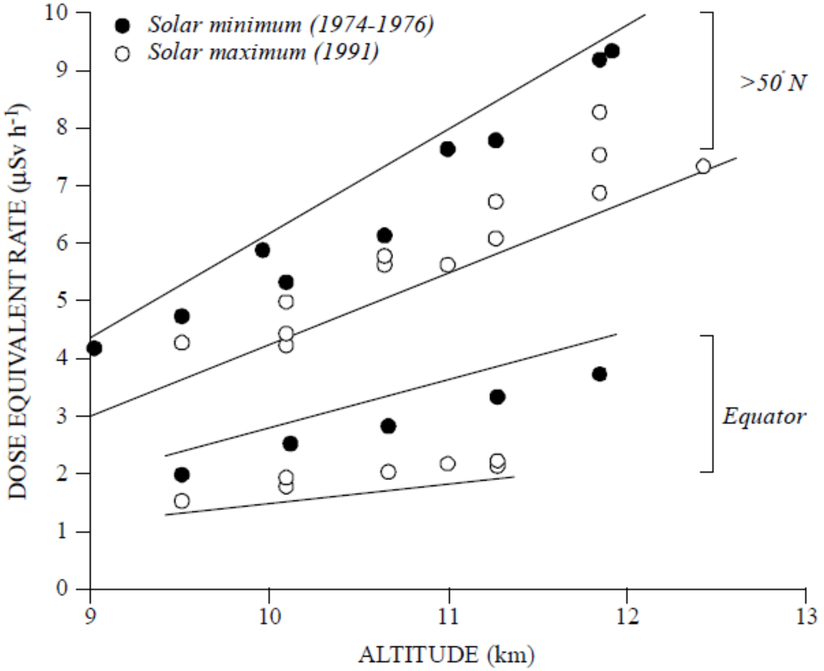


Figure 2. Ratio E_1/E_2, i.e. the effective dose calculated by the algorithm divided by the effective dose obtained from the MC calculation, for the various *single* dosimetry algorithms in the clinical cases considered and calculated by Siiskonen *et al.*(28).

Aircrew dosimetry

Elevated cosmic dose rate at flight altitudes



Aircrew considered as radiation workers

- Aircrew are exposed to elevated dose rates of cosmic radiation due to less protection by the earth’s atmosphere
- Aircrew on long-distance flight has an average yearly effective dose of the order of 2 mSv with doses above 6 mSv possible
- Aircrew are considered as radiation workers

Aircrew dosimetry

- Cosmic radiation field is very complex
  - Protons, electrons, muons, neutrons, …
  - Energies up to 10^{12} MeV
- No compact, easy to read dosimeter available for such fields
- Cosmic radiation field is relatively constant, except for limited solar modulation and exceptional solar storms
- Flight doses can be predicted well with computational methods
  - Date
  - Geographic information on latitudes and longitudes
  - Barometric altitudes

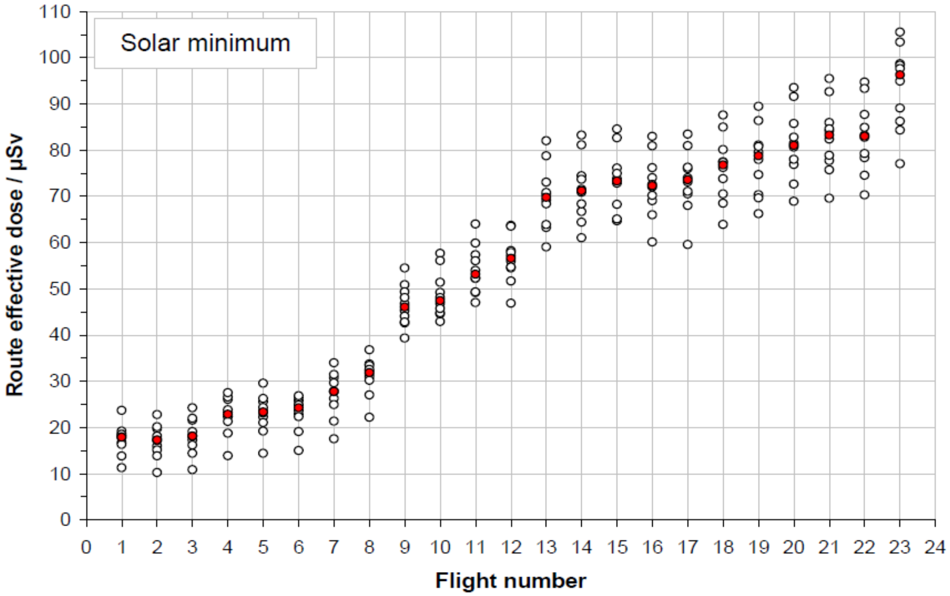
Aircrew dosimetry

- Doses calculated with dedicated software (e.g. CARI, AVIDOS, EPCARD.Net, SIEVERT, IASON-FREE, …)
  - Based on Monte Carlo radiation transport simulations
  - Based on analytical solutions
  - Based on fits of experimental data
- Dose calculations are regularly validated by measurements with dedicated complex ambient monitors (e.g. TEPC)
- Dose calculated for each flight and added up per aircrew member

EURADOS aircrew dosimetry code intercomparison

IAEA

Typical agreement within +/- 20% from median



Need for Special Dose Assessment

Interpretation of dosimeter results

- Personal whole body dosimeter should be positioned on the torso, towards main radiation source, and should be designed to measure $H_p(10)$
- In such case, the dosimeter measurement will be a good approximation of the effective dose E
- For low doses: $H_p(10)$ good approximation, no further analyses needed
- For doses near or above the dose limit: further analyses to have a better estimation of E
    - Also when individual doses summed over several monitoring periods exceed the corresponding annual dose limit
    - Also organ/tissue doses may need better estimation

Interpretation of dosimeter results

- Realistic assumptions have to be made with respect to
  - Type and uniformity of the radiation field (energy distribution)
  - Angular characteristics of the radiation field
  - Wearing position of dosimeter and the orientation of the worker
- Interpretation can include:
  - Survey of the radiation field with portable instruments.
  - More detailed characterisation of workplace (spectrometry)
  - Further analyses of dosimeter results
  - Energy estimation in case of algorithm based dosimeters
  - Special workplace field calibrations of dosimeter
  - Simulations
  - Use of more detailed conversion coefficients