Occupational exposure of the eye lens in interventional procedures: how to assess and manage radiation dose

Olivera Ciraj Bjelac, Eleftheria Carinou, Paolo Ferrari, Merce Ginjaume, Marta Sans Merce, Una O’Connor

13th EURADOS Winter School, Florence, 30 January 2020
Introduction

• Radiation-induced eye injuries are matter of current research interest
• Evidence on eye injuries associated with exposure to ionizing radiation*
• The duration of the latency period is inversely dependent on dose
• ICRP
  – Decrease the threshold for the eye lens from 5 Gy to 0.5 Gy (0->0.8 Gy)
  – Decreased the dose limit form workers 150 mSv ->20 mSv
• ICRP Publication 113 and 120 (interventional procedures)

*(IAEA RELID; Vano, 2013; Vano 2010; Kleiman, 2011... )
Eye dosimetry: Why is it important?

• Important for correlation of observed radiation effects with dose
• Contribute to better radiation protection
• Verification of compliance with regulatory dose limits
Eye dosimetry in medical field

- **Eye dose in fluoroscopy guided procedures** in radiology, cardiology and other areas (orthopedics, urology, anesthesiology, vascular surgery, CT fluoroscopy, gastroenterology...)

- **Eye dose in nuclear medicine**

- Photon and beta radiation
Motivation for this review

• Eye lens dosimetry is currently not well established
  – $Hp(3)$ hardly used in practice
  – Accuracy and practicality in medical field

ICRU 47, search “eye”, only 4 times in general phrases, as “… for one of the organs, lens of the eye, or skin”, or…” 0.07 mm for the skin and 3 mm for the eye are employed with analogous notation”
Objective

• To review:
  – Eye lens dose levels in clinical practice that may occur from the use of ionizing radiation in fluoroscopy-guided interventional procedures
  – Eye lens dose monitoring arrangements and dose assessment methods
  – Impact of potential dose reduction factors
A problem: Eye lens dose assessment

- Active research area
- Clinical studies
  - to review the methodology for assessing eye lens dose levels
  - to investigate monitoring arrangements using different types of dosimeter
  - to study correlation of eye lens dose with patient dose indices
  - to perform retrospective eye lens dose assessment
Matter of increasing research interest

No of published papers

Year


13th EURADOS Winter School, Florence, 30 January 2020

Vinca Institute of Nuclear Sciences
Radiation and Environmental Protection Laboratory
www.vinca.rs
Approaches to eye dosimetry

- Passive dosimetry
- Active dosimetry
- Retrospective dosimetry
  - Scatter dose levels
  - Correlation between patient dose indices and eye dose
Dosimetric quantities

- **Hp(3)** *(ICRU 39, 1985)*
- **Hp(0.07)** can be used for eye dose assessment *(Vanhavere, 2011; Lie, 2009; Martin, 2011; Domeinik, 2011, IAEA, 2013)*
  - Adequate for photons, not OK for beta radiation *(Behrens, 2012)*
- **Hp(10)** sometimes is the only available option
  - **Hp(3)/Hp(10)** in **NM 0.7-1.1** *(Kopec, 2011)*
  - **Hp(10)** badge on the left side of the body at collar level *(Farah, 2013)*

<table>
<thead>
<tr>
<th>Type of radiation</th>
<th>Area monitors</th>
<th>Individual dosimeters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>active</td>
<td>passive</td>
</tr>
<tr>
<td><strong>Photon and beta particles</strong></td>
<td>IEC 60846-1 [48] (H'(0.07)) and (H^*(10))</td>
<td>IEC 62387 [49] (H'(0.07)) and (H^*(10))</td>
</tr>
<tr>
<td><strong>Neutron</strong></td>
<td>IEC 61005 [51] (H^*(10))</td>
<td>...</td>
</tr>
</tbody>
</table>
Passive dosimetry

- Dedicated individual dosimetry designed to provide Hp(3)
  - Calibration in terms of Hp(3) (Bordy, 2011; Daures, 2011; Behrens, 2011; Ferrari, 2007; Gualdrini, 2011...)
  - Type test for eye dosimeters (Bordy, 2011; Bilski, 2011)
- Double dosimetry
  - Chest levels under the apron
  - Collar level above the apron
Double dosimetry

- Collar level over the apron -> eye dose assessment (ICRP 139, 2018)
- **Eye dose = Collar dose x F, F = 0.75 (0.4-0.9)**
- $H_{p}(3)/H_{p}(0.07)$ at collar level within ± 15% (>50 μSv)*
- Practical issues
  - Unavailable double dosimetry
  - Unknown position of the dosimeters
  - Irregular or erratic use, overuse
  - Variability in practice among the countries

*Vanhavere, 2011*
Active dosimetry

- Direct monitoring of eye dose
- Small detectors clipped onto spectacles
- Dose assessment in real time
- Dose per procedure
- Operational radiation protection
- May not be adequate for legal dosimetry?

Dosemeters have to be tested and suitable for use in clinical environment: beam quality, dose rate, pulsed radiation

(Struelens, 2011, Hupe 2018, ICRP 139, 2019)
Dosimetry in real time

- **Ambient monitors (C-arms)** *(Omar, et al, JRP, 2017)*
- Scatter dose levels in real time *(Vano, et al, Rad Meas 2011)*:
  - Educational role
  - Backup to personal dosimetry
  - Retrospective information and cumulative dose
  - Assessment of working habits, staff comparison
  - Correlation of dose rate with cumulative dose to staff
  - Correlation to patient dose for different procedures
Dosimetry in real time

- Computational dosimetry
  - Backup to personal dosimetry
  - Auditing the regular and proper use of personal dosimeters
  - Assessing the need for additional protection

- Computational technologies (not requiring dosimeters) together with personnel position sensing to assess personnel doses (ICRP 139, 2018)
Issues with passive and active dosimeters

• Ideally, dosimeters should be type tested and calibrated in terms of Hp(3) using an appropriate phantom
• The best position:
  – On the side of the head nearest to the radiation source
  – Behind the glasses (not very convenient)
  – Above the glasses (correction factor)
• However,...
Issues with passive and active dosimeters

- Must not interfere with the wearer’s vision
- Use of 3 or more dosemeters (reliability and consistency ?)

If the radiation field is well known, $H_p(3)$ can be estimated by the use of dosimeters calibrated in terms of $H_p(0.07)$ and $H_p(10)$ (ICRP 139, 2018)

Appropriate dosimetry arrangements: accuracy vs practicality
Retrospective dose assessment

• General assumptions on scattered dose levels
  1. Correlation to patient dose
  2. Scatter dose rate and typical exposure parameters (mainly in H*(10))
• Position of the operator and other staff members (modifying factors 0.2-1.0)
• Large uncertainty (order of magnitude):
  – Technical and physical factors, social desirability and memory bias...
  – Protective tools and their use...
  – Validation by means of measurements is needed (Pirchio et al, 2014)
Correlation of eye dose with patient dose

- Normalized eye dose per unit KAP based on local practice, as dominant influencing factors are (Antic, 2012; Krim 2011;...):

![](image)

X ray tube configuration, beam collimation, access route
Use of protective tools
If kept constant, correction is of practical use
### Eye dose normalized to respective KAP for interventional cardiology procedures for position of the first operator

<table>
<thead>
<tr>
<th>Reference</th>
<th>Eye dose (µSv)</th>
<th>Eye dose/ $P_k (\mu Sv/(Gycm^2))$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antic, 2012</td>
<td>121±84 (4.5-370)</td>
<td>0.94±0.61</td>
</tr>
<tr>
<td>Donadille, 2011</td>
<td>52±77 (4-644)</td>
<td>1.0</td>
</tr>
<tr>
<td>Kim, 2008</td>
<td>170-439</td>
<td></td>
</tr>
<tr>
<td>Vano, 1998</td>
<td>170 (53-460)</td>
<td>3.3-6.0</td>
</tr>
<tr>
<td>Vano, 2013</td>
<td>-</td>
<td>10-11 (unprotected)</td>
</tr>
<tr>
<td>Efstathopoulos, 2012</td>
<td>13</td>
<td>1.37</td>
</tr>
<tr>
<td>Bor, 2009</td>
<td>72 (32-107)</td>
<td>0.86 (0.46-1.25)</td>
</tr>
<tr>
<td>Martin, 2009</td>
<td>66 (5-439)</td>
<td>1.0</td>
</tr>
<tr>
<td>Vanhavere, 2011</td>
<td>-</td>
<td>1.0</td>
</tr>
<tr>
<td>Pratt, 1993</td>
<td>15-53</td>
<td>-</td>
</tr>
<tr>
<td>Jacob, 2013</td>
<td>14-439</td>
<td>-</td>
</tr>
<tr>
<td>Koukororava, 2011</td>
<td>-</td>
<td>1.0</td>
</tr>
<tr>
<td>Duer, 2010</td>
<td>35±32 (pre year)</td>
<td>4.2 (unprotected)</td>
</tr>
<tr>
<td>Lie, 2008</td>
<td>23 (10-230)</td>
<td>0.4 (0.2-2.6)</td>
</tr>
<tr>
<td>Vano, 2009</td>
<td>-</td>
<td>7 (unprotected)</td>
</tr>
</tbody>
</table>
Correlation of eye dose with patient dose

- Useful as a surrogate measure of eye dose if measured dose using eye dosimeter is unavailable

Typically, 1 Gy·cm² to the patient resulted in:
- 10 μSv to the unprotected eyes of the primary operator
- 1 μSv when protective tools are used
Retrospective dose assessment

• Related to a “typical” procedure and *anticipated scatter dose*:
  – Consider past activity of an individual
  – Accuracy of information provided and assumptions made
  – Dose reduction factor due to use of protective tools (static vs clinical conditions)

<table>
<thead>
<tr>
<th>Professional group</th>
<th>Cumulative dose</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardiologists</td>
<td>25-1600 mSv</td>
<td>Jacob, 2012</td>
</tr>
<tr>
<td>Cardiologists</td>
<td>0.1-18.9 Sv</td>
<td>Vano, 2013</td>
</tr>
<tr>
<td>Cardiologists and support staff</td>
<td>0.1 to 21 Sv</td>
<td>Ciraj-Bjelac, 2010</td>
</tr>
<tr>
<td>Cardiologists and support staff</td>
<td>0.1-27 Sv</td>
<td>Vano, 2010</td>
</tr>
</tbody>
</table>
Current status of eye lens dose levels

- Eye doses vary considerably
  - Various dose methodologies and dose assessment approaches
  - Various combinations of protective tools
  - Reported mainly for the first operator and in some cases for nurses and radiographers
Current status of eye lens dose levels

**Total dose**
- range from less than **0.1 to 1100 µSv**

**Dose rate**
- from **1 to 22 mSv/h** (fluoroscopy)
- from **12 to 235 mSv/h** (DSA)
## Typical dose levels

<table>
<thead>
<tr>
<th>Type of Procedure</th>
<th>Eye Lens Dose per Procedure (μSv)</th>
<th>Eye Lens Dose / $P_{KA}$ (μSv/Gy cm²)</th>
<th>Measurement Details</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Various interventional radiology procedures, with protective tools</td>
<td>47 (0-557)</td>
<td>1.19</td>
<td>25 procedures, few cases per procedures</td>
<td>[15]</td>
</tr>
<tr>
<td>Hepatic chemoembolization</td>
<td>270-1,070 / 16-64 (unprotected / protected)</td>
<td>-</td>
<td>With phantom, different acquisition modes</td>
<td>[36]</td>
</tr>
<tr>
<td>Iliac angioplasty</td>
<td>250-1,110 / 15-66 (unprotected / protected)</td>
<td>-</td>
<td></td>
<td>[36]</td>
</tr>
<tr>
<td>Neuroembolization (head)</td>
<td>1,380-5,600 / 83-336 (unprotected / protected)</td>
<td>-</td>
<td></td>
<td>[36]</td>
</tr>
<tr>
<td>TIPS creation</td>
<td>410-1,860 / 25-112 (unprotected/ protected)</td>
<td>-</td>
<td></td>
<td>[36]</td>
</tr>
<tr>
<td>Anesthesiology, various procedures</td>
<td>44</td>
<td>0.278-1.305</td>
<td>Simulations, 31 cases</td>
<td>[37]</td>
</tr>
<tr>
<td>Gastroenterology, ERCP</td>
<td>90/10 (unprotected, overcouch/undercouch)</td>
<td>0.98-1.4/14-21 (unprotected, undercouch/overcouch)</td>
<td>62 cases</td>
<td>[38]</td>
</tr>
<tr>
<td>Vascular surgery, EVAR</td>
<td>10 (unprotected)</td>
<td>-</td>
<td>149 cases</td>
<td>[39]</td>
</tr>
<tr>
<td>Urology, various procedures</td>
<td>26 (unprotected)</td>
<td>-</td>
<td>20 cases</td>
<td>[40]</td>
</tr>
<tr>
<td>Urology, percutaneous renal calculus removal</td>
<td>100 (unprotected)</td>
<td>-</td>
<td>102 cases</td>
<td>[41]</td>
</tr>
<tr>
<td>Orthopedic surgery, various procedures</td>
<td>50 (unprotected)</td>
<td>-</td>
<td>204 cases</td>
<td>[42]</td>
</tr>
<tr>
<td>CT fluoroscopy, various procedures</td>
<td>7-48</td>
<td>-</td>
<td>220 cases</td>
<td>[17]</td>
</tr>
<tr>
<td>CT-guided interventions</td>
<td>3.5 (0.2-39.9)</td>
<td>0.47-0.84</td>
<td>89 cases</td>
<td>[16]</td>
</tr>
<tr>
<td>Various procedures</td>
<td>-</td>
<td></td>
<td>1,300 cases</td>
<td>[43]</td>
</tr>
</tbody>
</table>

Note: EVAR = Endovascular aneurysm repair; ERCP = Endoscopic retrograde cholangio-pancreatography; $P_{KA}$ = kerma-area product; TIPS = Transjugular intrahepatic portosystemic shunt.
## Typical dose levels

<table>
<thead>
<tr>
<th>Type of Procedure</th>
<th>Eye Lens Dose Per Procedure (µSv)</th>
<th>Eye Lens Dose / ( P_{KA} ) (µSv/Gy cm²)</th>
<th>Measurements Details</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interventional cardiology, first operator, various procedures, dose with protective tools</td>
<td>121 ± 84 (4-5-370)</td>
<td>0.94 ± 0.61</td>
<td>35 cases</td>
<td>[13]</td>
</tr>
<tr>
<td></td>
<td>52 ± 77 (4-644)</td>
<td>1.0</td>
<td>646 cases</td>
<td>[44]</td>
</tr>
<tr>
<td></td>
<td>3.3-1,040</td>
<td></td>
<td>Literature survey, phantom and clinical, 3,1532 cases per survey</td>
<td>[34]</td>
</tr>
<tr>
<td></td>
<td>170 (53-460)</td>
<td>3.3-6.0</td>
<td>83 cases</td>
<td>[45]</td>
</tr>
<tr>
<td></td>
<td>13 (0-61)</td>
<td>1.37</td>
<td>7 cases</td>
<td>[15]</td>
</tr>
<tr>
<td></td>
<td>72 (32-107)</td>
<td>0.86 (0.46-1.25)</td>
<td>166 cases</td>
<td>[14]</td>
</tr>
<tr>
<td></td>
<td>66 (5-439)</td>
<td>1.0</td>
<td>Literature survey, 26 studies included</td>
<td>[12]</td>
</tr>
<tr>
<td></td>
<td>15-53</td>
<td>1.0</td>
<td>1,300 cases</td>
<td>[32]</td>
</tr>
<tr>
<td></td>
<td>23 (10-230)</td>
<td>0.4 (0.2-2.6)</td>
<td>144 cases</td>
<td>[46]</td>
</tr>
<tr>
<td></td>
<td>35 ± 32 (per year)</td>
<td>4.2</td>
<td>using collar dosimeter</td>
<td>[48]</td>
</tr>
<tr>
<td>Interventional cardiology, first operator, various procedures, dose without protective tools</td>
<td>-</td>
<td>10-11</td>
<td>EPD, 1,969 cases</td>
<td>[49]</td>
</tr>
<tr>
<td></td>
<td>300-2,500</td>
<td>3.2-3.4</td>
<td>Multicentric phantom study, different complexities</td>
<td>[35]</td>
</tr>
</tbody>
</table>

**NOTE:** EPD = electronic personal dosimeter; \( P_{KA} \) = kerma-area product.

Ciraj-Bjelac, O, JACR, 2016
Factors influencing dose to the eye lens

**Patient related factors**
- Clinical problem (fluoroscopy time and number of images)
- Size of the patient

**Equipment related factors**
- Geometry of the X-ray tube (undercouch/overcouch)
- Use of biplane systems
- Performance characteristics of X-ray system, including the settings
- The scatter radiation distribution

**Practice related factors**
- Use of protective tools
- Position vs. X-ray tube and patient, projections used, exposure setting, collimation, access route...
- Workload and physician’s experience and skill
Favorable undercouch configuration: **dose reduction factor: 2-27** (Carinou, 2011)
X-ray tube geometry & eye dose

- ERCP (O’Conor et al, 2013)
- $Hp(3)/KAP$ ($\mu$Sv/Gycm$^2$):

0.98-1.43

14 - 21

Endoscopic retrograde cholangiopancreatography (ERCP)
X-ray tube geometry & eye dose

- ERCP (O’Conor et al, 2013)
- Hp(3)/KAP ($\mu$Sv/Gycm$^2$):

The highest values are related to the overcouch x-ray tube geometry and the absence of ceiling suspended screens and glasses.

Endoscopic retrograde cholangiopancreatography (ERCP)
Protective tools @ overcoatch geometry

Gastrointestinal procedures: scenting and enteroclysis*
*Clinical center of Serbia, unpublished data

All
Without protection
With protection

\[ y = 0.0636x - 27.464 \]
\[ R^2 = 0.7882 \]

\[ y = 0.0335x + 5.6041 \]
\[ R^2 = 0.9765 \]
Practice related factors: protective tools

Use of ceiling screens
• Positioned just above patients and position of the operator behind
• **Dose reduction factor: 2-7**
• For LLAT projection move the screen towards the operator (x-ray tube)**
• Biplane systems: additional lateral shielding

Lead glasses, properly fitted
Key factors:
• Position and head of orientation
• Beam projection
• Scatter radiation from gaps beneath the glasses and BS from the head
• **Dose reduction factor: 1.4 – 10**
• Important: large glass with lateral coverage and good fit to face

Efficiency of protection tools

• Strong dependence on orientation and design, factor 1.4-9, (Sturchio, 2013)
• Rule of thumb:
  – Use of leaded glasses alone reduced the lens dose rate by a factor of 5 to 10; scatter-shielding screens alone reduced the dose rate by a factor of 5 to 25. Use of both simultaneously is even more efficient than either used alone, reducing the dose rate by factor of 25 or more.

Should be used by staff members in the interventional room
Practice related factors

Position of the operator
- Largely determined by the procedures performed
  - Radial vs femoral access in cardiology procedures
  - Percutaneous procedures in interventional radiology
- Radial artery route vs femoral access route
- Dose difference by a factor 2-7 (Carionu, 2011)

X-ray tube angulation
- Technique related factors
- Left lateral projection associated with higher doses (Kong, 2014)
- Not well defined geometry
Dose management strategy

- **Use of protective tools**, undercoach x-ray tube geometry, keep away from the X ray tube and patient
- **Maintaining x-ray equipment in optimum operating condition** (pulsed fluoroscopy, minimizing fluoroscopy time, limiting radiographic images, collimation and reduced use of magnification)
- **Training** in radiation protection (use of active dosimeters and awareness of the radiation dose levels)
Eye lens monitoring arrangements

• Number of situations requiring specific eye lens monitoring is likely to increase
Estimation of dose levels

Prior to routine individual monitoring

- Need for IM?
- Method?
- Interval of routine monitoring?

Workplace monitoring
Literature data
Simulations
Individual monitoring for a limited time
When is monitoring needed?

- Recommendation of dose monitoring (Martin, 2011):
  - 1-2 mSv/month, initial monitoring to establish dose levels
  - 2-3 mSv/month, regular monitoring should be considered
  - >3 mSv/month, regular monitoring is required

- Recommendation of dose monitoring (IAEA, 2011; IRPA, 2017):
  - If annual equivalent dose to the lens is likely to exceed a dose of the order of (5-6) mSv
When is monitoring needed?

- **Recommendation of dose monitoring (Martin, 2011):**
  
  - 1-2 mSv/month, initial monitoring to establish dose levels
  
  - 2-3 mSv/month, regular monitoring should be considered
  
  - >3 mSv/month, regular monitoring is required

- **Recommendation of dose monitoring (IAEA, 2011):**

  If annual equivalent dose to the lens is likely to exceed a dose of the order of 5 mSv

---

**Table 6. Indicators for deriving dose estimates for use in risk assessments**

| Organ                     | Dose/DAP (µGy Gy⁻¹ cm⁻²) | DAP per month (Gy cm²) | Dose per cardiology procedure (µGy) | No. of cardiology procedures per month
|---------------------------|--------------------------|------------------------|-------------------------------------|----------------------------------------
| Eye                       | 1 | 2000 | 80 | 25
| Thyroidb                 | 1.5 (0.2) | 120 | 100 |
| Hand (percutaneous procedures) | 40 | 1000 | 300 | 16
| Hand (femoral access)    | 5 | (40) |
| Legb                     | 10 (2) | (100) |

DAP, dose–area product.

aWorkload for which dose monitoring should be considered. It is likely to be required for an individual with a workload double this value.

bDoses in brackets relate to where protection is being used.

---

Martin, BJR, 2011

13th EURADOS Winter School, Florence, 30 January 2020
Fluoroscopy guided procedures

- Interventional cardiology

- Interventional neuroradiology
  - Eye dose per procedure: 248/18 µSv, with and without glasses
  - Number of procedures for 20 mSv/y: 119/602, with and without glasses

- Fluoroscopy (gastro, gynecology, urology..)
  - (0.1-0.5) mSv/procedure
  - Average: 13 mSv/y

Tavares, Int Neurorad, 2016
Bahruddin, JJP, 2016
Routine eye lens monitoring

• May be necessary in:
  – Interventional radiology and cardiology
  – For use of fluoroscopy used outside the imaging departments

• Take into account:
  – Energy and angle of incident radiation
  – Geometry of the radiation field
  – Use of personal protective equipment
How to use of a dedicated eye lens dosimeter?

- The position should be as close as possible to the eye (preferably in contact with the skin)
- Detector should face the radiation source
- In interventional procedures:
  - On the side closest to the x-ray tube
  - Behind the glasses (not very convenient)
  - Above the glasses (correction factor)
If use of a dedicated eye lens dosimeter is impractical?

- Dosimeter at trunk or thyroid level above the protective tools
  - Correction factor of 0.75 (!)
- Large uncertainty
- Caution, if the measured dose levels are close to the dose limits
In the absence of any dose measurement

• Eye lens dose could be estimated from patient dose, using the conversion from $P_{KA}$ to eye lens dose of:
  - 1 $\mu$Sv/Gy cm$^2$ (protective tools are used)
  - 10 $\mu$Sv/Gy cm$^2$ (without protection)
• Even larger uncertainty and variability
Conclusions

• **Accurate dose measurements** are a prerequisite for investigation of low dose effects to the lens of the eye
• **Dedicated and calibrated dosimeters**
• Question of **what dose monitoring is appropriate** for an interventional facility is not straightforward
• Possible options: active, passive dosimetry and link to patient dose indices (with larger uncertainty)
Conclusions

• Optimistic situation with eye protection
  – If radiation protection devices (most importantly protective screens or lead glass barriers) are not used, the risk for eye injuries is elevated

If radiation protection devices and techniques are properly used, **one can keep the radiation dose to eye lens at optimal level**