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

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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”

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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


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Approaches to eye dosimetry

Passive dosimetry

Active dosimetry

Retrospective dosimetry

Scatter dose levels
Correlation between patient dose indices and eye dose

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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]</td>
<td>IEC 62387 [49]</td>
</tr>
<tr>
<td></td>
<td>$H'(0.07)$ and $H^*(10)$</td>
<td>$H'(0.07)$ and $H^*(10)$</td>
</tr>
<tr>
<td><strong>Neutron</strong></td>
<td>IEC 61005 [51]</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>$H^*(10)$</td>
<td></td>
</tr>
</tbody>
</table>

IEC 61526 [50] $H_p(0.07)$ and $H_p(10)$

ISO 21909 [52] $H_p(10)$
Passive dosimetry

- Dedicated individual dosimetry designed to provide $H_p(3)$
  - Calibration in terms of $H_p(3)$ (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)**
- $Hp(3)/Hp(0.07)$ at collar level within ± 15% ($>50 \mu Sv$)*
- 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)

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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, $Hp(3)$ can be estimated by the use of dosimeters calibrated in terms of $Hp(0.07)$ and $Hp(10)$ (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;...):

\[
\text{Eye dose} \propto \text{KAP}
\]

X-ray tube configuration, beam collimation, access route

Use of protective tools

If kept constant, correction is of practical use

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### 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/ $P_{KA}$ (µSv/(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>Koukorava, 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·cm$^2$ to the patient resulted in:

10 μSv to the unprotected eyes of the primary operator
1 μSv when protective tools are used

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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)

Max/Min : 2000
### 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>[36]</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>0.278-1.305</td>
<td>Simulations, 31 cases</td>
<td>[37]</td>
</tr>
<tr>
<td>Anesthesiology, various procedures</td>
<td>90/10 (unprotected, overcouch/undercouch)</td>
<td>0.98-1.4/14-21 (unprotected, overcouch/undercouch)</td>
<td>62 cases</td>
<td>[38]</td>
</tr>
<tr>
<td>Gastroenterology, ERCP</td>
<td>50 (unprotected)</td>
<td>-</td>
<td>149 cases</td>
<td>[39]</td>
</tr>
<tr>
<td>Vascular surgery, EVAR</td>
<td>10 (unprotected)</td>
<td>-</td>
<td>20 cases</td>
<td>[40]</td>
</tr>
<tr>
<td>Urology, various procedures</td>
<td>26 (unprotected)</td>
<td>-</td>
<td>102 cases</td>
<td>[41]</td>
</tr>
<tr>
<td>Urology, percutaneous renal calculus removal</td>
<td>100 (unprotected)</td>
<td>-</td>
<td></td>
<td>[42]</td>
</tr>
<tr>
<td>Orthopedic surgery, various procedures</td>
<td>50 (unprotected)</td>
<td>-</td>
<td>204 cases</td>
<td>[43]</td>
</tr>
<tr>
<td>CT fluoroscopy, various procedures</td>
<td>7-48 (0.2-39.9)</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>-</td>
<td>89 cases</td>
<td>[16]</td>
</tr>
<tr>
<td>Various procedures</td>
<td>-</td>
<td>0.47-0.84</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&lt;sub&gt;KA&lt;/sub&gt; (μSv/Gy cm&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>Measurements Details</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intervventional cardiology, first operator, various</td>
<td>121 ± 84 (4.5-370)</td>
<td>0.94 ± 0.61</td>
<td>35 cases</td>
<td>[13]</td>
</tr>
<tr>
<td>procedures, dose with protective tools</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, 3-1,532 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></td>
<td>-</td>
<td>1,300 cases</td>
<td>[32]</td>
</tr>
<tr>
<td></td>
<td>15-53</td>
<td>1.0</td>
<td>164 cases</td>
<td>[46]</td>
</tr>
<tr>
<td></td>
<td>23 (10-230)</td>
<td>0.4 (0.2-2.6)</td>
<td>144 cases</td>
<td>[47]</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>Intervventional cardiology, first operator,</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>various procedures, dose without protective tools</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<sub>KA</sub> = kerma-area product.
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

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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 (μSv/Gycm²):**

  - 0.98-1.43
  - 14 - 21

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

- ERCP (O’Conor et al, 2013)
- $\text{Hp}(3)/\text{KAP} (\mu\text{Sv}/\text{Gycm}^2)$:
  
  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 @ overcoach geometry

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

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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

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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

<table>
<thead>
<tr>
<th>Organ</th>
<th>Dose/DAP (µGy Gy⁻¹ cm⁻²)</th>
<th>DAP per month a (Gy cm²)</th>
<th>Dose per cardiology procedure (µGy)</th>
<th>No. of cardiology procedures per month a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eye</td>
<td>1</td>
<td>2000</td>
<td>80</td>
<td>25</td>
</tr>
<tr>
<td>Thyroid b</td>
<td>1.5 (0.2)</td>
<td>120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hand (percutaneous procedures)</td>
<td>40</td>
<td>1000</td>
<td>300</td>
<td>16</td>
</tr>
<tr>
<td>Hand (femoral access)</td>
<td>5</td>
<td></td>
<td>(40)</td>
<td>(100)</td>
</tr>
<tr>
<td>Leg b</td>
<td>10 (2)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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.
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

Betti, EJMP, 2019
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**
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