Dose Quantities and Units

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Educational Objectives

1. How radiation dose can and should be expressed, merits and demerits of each quantity for cardiology practice
2. How representative fluoroscopy time, cine time are for dose to the patient and the staff
3. Simplified presentation of dose quantities

Patient dose variability in general radiology

1950s: "Adrian survey", UK
- Measures of glandular and red bone marrow doses with an ionisation chamber;
- First evidence of a wide variation in patient doses in diagnostic radiology
- Variation factor: 10

1980s: European countries
- Measures of dose by Kodak for simple and complex procedures
- Variation factor: 10 between patients; 5 between hospitals

1990s: Europe
- Initiation on patient doses to support the development of European guidelines on Quality Criteria for images and to assess reference levels
- ESD: 5 between hospitals

1990s: Europe
- Trials on patient doses to support the development of European guidelines on Quality Criteria for images and to assess reference levels
- Variation factor: 10 between hospitals

2000s: EANR, UK
- UK, national database with patient dose data from 400 hospitals
- Variation factor: 5 between hospitals

Patient doses in interventional procedures

- Also in cardiac procedures, patient doses are highly variables between centres
- Need for patient dose monitoring

Staff doses in interventional cardiology

- Large variability in staff exposure
- Need for staff dose monitoring

Dose quantities and Radiation units

- Dose quantities outside the patient’s body
- Dose quantities to estimate risks of skin injuries and effects that have threshold
- Dose quantities to estimate stochastic risks
**Why so many quantities?**

- 1000 W heater giving heat (IR radiation)
  - unit is the power which is related with emission intensity
- Heat perceived by the person will vary with so many factors: distance, clothing, temperature in room...
- If one has to go a step ahead, from perception of heat to heat absorbed, it becomes a highly complicated issue
- This is the case with X rays … and they can’t be perceived

**Dose quantities and Radiation units**

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**Radiation quantities**

- Used to describe a beam of x-rays:
  - Quantities to express total amount of radiation
  - Quantities to express radiation at a specific point

**Total radiation**

- Total photons
- Integral dose

**Radiation at a specific point**

- Photon fluence
- Absorbed dose
- Kerma
- Dose equivalent

**Radiation at a specific point**

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- x-ray beam emitted from a small source (point):
  - constantly spreading out as it moves away from the source
  - all photons that pass Area 1 will pass through all areas (Area 4)
  - the total amount of radiation is the same

\[ D_2 = D_1 \left( \frac{d_1}{d_2} \right)^2 \]

**Absorbed dose, D and KERMA**

- The KERMA (kinetic energy released in a material)
  \[ K = \frac{dE_{\text{trans}}}{dm} \]
  - where \( dE_{\text{trans}} \) is the sum of the initial kinetic energies of all charged ionizing particles liberated by uncharged ionizing particles in a material of mass \( dm \)

- The SI unit of kerma is the joule per kilogram (J/kg), termed gray (Gy).

- In diagnostic radiology, Kerma and D are equal (when we are far from interfaces: air-body, muscle-bone, etc).
Absorbed dose (air kerma) in X ray field can be measured with:
- Ionisation chambers,
- Semiconductor dosimeters,
- Thermoluminescent dosimeters (TLD).

Entrance dose to the patient in simulated clinical conditions:
- 20 cm of PMMA
- Ion chamber + electrometer = dosimeter
- Entrance surface dose (kerma) can be measured for the different clinical setup:
  - FOV
  - Focus to patient distance
  - Focus to image detector distance
  - Fluoroscopy mode (low, medium, high)
  - Cine mode (low, high)

Absorbed dose due to scatter radiation in a point occupied by the operator can be measured with a portable ionisation chamber.

Values of absorbed dose to tissue will vary by a few percent depending on the exact composition of the medium that is taken to represent soft tissue.

The following value is usually used for 80 kV and 2.5 mm Al of filtration:

\[ \text{Dose in soft tissue} = 1.06 \times \text{Dose in air} \]

The mean absorbed dose in a tissue or organ \( D_r \) is the energy deposited in the organ divided by the mass of that organ.

Organ doses cannot be measured on real patients.
- Can be measured in anthropomorphic phantoms simulating the examination
- Can be calculated with dedicated software tools (interaction simulations of X-rays on a mathematical phantom)
Example 1: Dose rate at different distances

Fixed FOV=17 cm & pt. thickness=24 cm
Pulsed fluoro LOW 15 pulses/s; 95 kV, 47 mA

- measured entrance surface dose rate (air kerma rate) at FSD=70 cm: 18 mGy/min
- dose rate at d=50 cm: using the inverse square law
  \[18 \times \left(\frac{70}{50}\right)^2 = 18 \times 1.96 = 35.3 \text{ mGy/min}\]

Example 2: Entrance surface dose rate changes with image quality

Fixed FOV=17 cm & patient thickness=24 cm
15 pulses/s, FSD=70 cm, 95 kV; measures performed in air

1. pulsed fluoro LOW \(\Rightarrow 47 \text{ mA}\),

- dose rate in air (air kerma rate) = 18 mGy/min
- Dose rate at the patient skin including backscatter and conversion factor air to tissue:
  \[\text{ESD} = 18 \times 1.3 \times 1.06 = 24.8 \text{ mGy/min}\]

2. pulsed fluoro NORMAL \(\Rightarrow 130 \text{ mA}\),

- dose rate = 52 mGy/min
- Dose rate at the patient skin including backscatter and conversion factor air to tissue:
  \[\text{ESD} = 52 \times 1.3 \times 1.06 = 71.6 \text{ mGy/min}\]

Example 3: Entrance surface dose rate changes with patient thickness

Fixed FOV=17 cm; pulsed fluoro=Low, 15 p/s; dose measured

1. Patient thickness 20 cm,

- Entrance surface dose rate at the patient skin including backscatter ESD=10 mGy/min

2. Patient thickness 24 cm,

- Entrance surface dose rate at the patient skin including backscatter ESD=25.2 mGy/min

3. Patient thickness 28 cm,

- Entrance surface dose rate at the patient skin including backscatter ESD=33.3 mGy/min

Example 3: Pt. Thickness (contd.)

Entrance dose rates increase with:
- fluoro image quality selected & patient thickness

Example 4: Equipment type

Entrance surface dose rates, FOV=17 cm, PMMA=20 cm

- Dose area product (I)

\[\text{DAP} = D \times \text{Area}\]

(or KAP = Kerma \times \text{Area})

the SI unit of DAP (KAP) is the Gy.cm²

Attention to the different indications:

- Gy.cm², dGy.cm², cGy.cm², \(\mu\)Gy.cm²

1 Gy.cm² = 100 dGy.cm²
1 Gy.cm² = 100 cGy.cm²
1 cGy.cm² = 1 \(\mu\)Gy.cm²

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Dose quantities and units

1 – DAP meters (II)

- DAP is independent of source distance:
  - D decrease with the inverse square law
  - Area increase with the square distance
- DAP is usually measured at the level of tube diaphragms

Example 1: DAP (KAP) evaluations

<table>
<thead>
<tr>
<th>Patient thickness 24 cm, FOV=17 cm, FDD=100 cm, pulsed fluoro LOW</th>
<th>95 kV, 47 mA, 15 pulse/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dose in 1 min @ FSD=70 cm: 18 mGy</td>
<td></td>
</tr>
<tr>
<td>Area @ 70 cm: 11.9*11.9=141.6 cm²</td>
<td></td>
</tr>
<tr>
<td>DAP= 18 * 141.6 = 2549 mGycm² = 2.55 Gycm²</td>
<td></td>
</tr>
<tr>
<td>Dose in air 1 min @ FSD=50 cm: 18 * (70/50)² = 35.3 mGy</td>
<td></td>
</tr>
<tr>
<td>Area @ 50 cm: 8.5*8.5=72.2 cm²</td>
<td></td>
</tr>
<tr>
<td>DAP= 35.3 * 72.2 = 2549 mGycm² = 2.55 Gycm²</td>
<td></td>
</tr>
<tr>
<td>DAP is independent of focus to dosemeter distance (without attenuation of x-ray beam)</td>
<td></td>
</tr>
</tbody>
</table>

Example 2: DAP (KAP) evaluations

<table>
<thead>
<tr>
<th>Patient thickness 24 cm, FOV=17 cm, FDD=100 cm, pulsed fluoro LOW</th>
<th>95 kV, 47 mA, 15 pulse/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dose in 1 min @ FSD=70 cm: 18 mGy</td>
<td></td>
</tr>
<tr>
<td>Area @ 70 cm: 15*15=225 cm²</td>
<td></td>
</tr>
<tr>
<td>DAP= 18 * 225 = 4050 mGycm² = 4.50 Gycm² (+76%)</td>
<td></td>
</tr>
<tr>
<td>If you increase the beam area, DAP will increase proportionately</td>
<td></td>
</tr>
</tbody>
</table>

Other dose quantities outside the patient body

- Fluoroscopy time:
  - has a weak correlation with DAP
  - But, in a quality assurance programme it can be adopted as a starting unit for:
    - comparison between operators, centres, procedures
    - for the evaluation of protocols optimisation
    - and, to evaluate operator skill

Other dose quantities outside the patient body

- Number of acquired images and no. of series:
  - Patient dose is a function of total acquired images
  - There is an evidence of large variation in protocols adopted in different centres

Reference levels

Reference levels: an instrument to help operators to conduct optimised procedures with reference to patient exposure

Required by international (IAEA) and national regulations

For complex procedures reference levels should include:

- more parameters
- and, must take into account the protection from stochastic and deterministic risks (Dimond)
**Reference levels in interventional cardiology**

- From a survey conducted in several cat labs in Europe, reference levels have been derived.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>CA</th>
<th>PTCA</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAP (Gycm²)</td>
<td>57</td>
<td>94</td>
</tr>
<tr>
<td>Fluoroscopy time (min)</td>
<td>6</td>
<td>16</td>
</tr>
<tr>
<td>No. of frames</td>
<td>1270</td>
<td>1355</td>
</tr>
</tbody>
</table>


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**Dose quantities and Radiation units**

1. Dose quantities outside the patient’s body
2. Dose quantities to estimate risks of skin injuries and effects that have threshold
3. Dose quantities to estimate stochastic risks

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**Interventional procedures: skin dose**

- In some procedures, patient skin doses approach those used in radiotherapy fractions
- In a complex procedure skin dose is highly variable
- Maximum local skin dose (MSD) is the maximum dose received by a portion of the exposed skin

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**Methods for maximum local skin dose (MSD) assessment**

- **On-line methods:**
  - Point detectors (ion chamber, diode and Mosfet detectors)
  - Dose to Interventional Radiology Point (IRP) via ion chamber or calculation
  - Dose distribution calculated
  - Correlation MSD vs. DAP
- **Off-line methods:**
  - Point measurements (thermo luminescent detectors (TLD)
  - Area detectors (radiotherapy portal films, radiochromic films, TLD grid)

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**Methods for MSD (cont.): on-line methods (I)**

- Point detectors (ion chamber, diode and Mosfet detectors)
- Dose to Interventional Radiology Point (IRP) via ion chamber or calculation

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**Methods for MSD (contd.): on-line methods (II)**

- Dose distribution calculated by the angio unit using all the geometric and radiographic parameters (C-arm angles, collimation, kV, mA, FIID, …)
- Correlation MSD vs. DAP:
  - Maximum local skin dose has a weak correlation with DAP
  - For specific procedure and protocol, installation and operators a better correlation can be obtained and MSD/DAP factors can be adopted for an approximate estimation of the MSD

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**Example of correlation between ESD and DAP for PTCA procedure in the Udine cardiac centre**
Methods for MSD (contd.): off-line (I)

- Point measurements: thermoluminescent detectors (TLD)
- Area detectors: radiotherapy portal films, radiochromic films, TLD grid
  - Large area detectors exposed during the cardiac procedure: between tabletop and back of the patient

Example of dose distribution in a CA procedure shown on a radiochromic film as a grading of color

Methods for MSD (contd.): off-line (II)

- Area detectors:
  * Dose distribution is obtained through a calibration curve of Optical Density vs. absorbed dose
  * Radiotherapy films:
    - require chemical processing
    - maximum dose 0.5-1 Gy
  * Radiochromic detectors:
    - do not require film processing
    - immediate visualisation of dose distribution
    - dose measurement up to 15 Gy

Exercise 1: Evaluation of MSD

A PTCA of a patient of 28 cm thickness, 2000 images acquired, 30 min of fluoroscopy:

- System A:
  - 2000*0.4 mGy/image = 0.8 Gy
  - 30 min * 33 mGy/min = 0.99 Gy
  - Total cumulative dose = 1.79 Gy

- System B:
  - 2000*0.6 mGy/image = 1.2 Gy
  - 30 min * 50 mGy/min = 1.5 Gy
  - Total cumulative dose = 2.7 Gy

Cumulative skin dose is a function of system performance and image quality selected

Dose quantities and Radiation units

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Dose quantities for stochastic risk

- Detriment:
  - Radiation exposure of the different organs and tissues in the body results in different probabilities of harm and different severity
  - The combination of probability and severity of harm is called “detriment”.
  - In young patients, organ doses may significantly increase the risk of radiation-induced cancer in later life
Dose quantities for stochastic risk

Equivalent dose (H)

The equivalent dose \( H \) is the absorbed dose multiplied by a dimensionless radiation weighting factor, \( w_R \), which expresses the biological effectiveness of a given type of radiation

\[ H = D \times w_R \]

the SI unit of \( H \) is the Sievert \([\text{Sv}]\)

For X-rays is \( w_R = 1 \)

\[ \text{For x-rays} \quad H = D \]

Mean equivalent dose in a tissue or organ

The mean equivalent dose in a tissue or organ \( H_T \) is the energy deposited in the organ divided by the mass of that organ.

Dose quantities for stochastic risk

Mean equivalent dose in a tissue or organ

The mean equivalent dose in a tissue or organ \( H_T \) is the energy deposited in the organ divided by the mass of that organ.

Dose quantities for stochastic risk

Tissue weighting factor

To reflect the detriment from stochastic effects due to the equivalent doses in the different organs and tissues of the body, the equivalent dose is multiplied by a tissue weighting factor, \( w_T \),

<table>
<thead>
<tr>
<th>ORGAN / TISSUE</th>
<th>( W_T )</th>
<th>ORGAN / TISSUE</th>
<th>( W_T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone marrow</td>
<td>0.12</td>
<td>Lung</td>
<td>0.12</td>
</tr>
<tr>
<td>Bladder</td>
<td>0.35</td>
<td>Oesophagus</td>
<td>0.03</td>
</tr>
<tr>
<td>Bone surface</td>
<td>0.01</td>
<td>Skin</td>
<td>0.01</td>
</tr>
<tr>
<td>Breast</td>
<td>0.01</td>
<td>Stomach</td>
<td>0.12</td>
</tr>
<tr>
<td>Colon</td>
<td>0.12</td>
<td>Trachea</td>
<td>0.01</td>
</tr>
<tr>
<td>Gonad</td>
<td>0.38</td>
<td>Remainder</td>
<td>0.98</td>
</tr>
<tr>
<td>Liver</td>
<td>0.96</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Dose quantities for stochastic risk

Effective dose, \( E \)

The equivalent doses to organs and tissues weighted by the relative \( w_T \) are summed over the whole body to give the effective dose \( E \)

\[ E = \sum T w_T H_T \]

\( w_T \): weighting factor for organ or tissue \( T \)

\( H_T \): equivalent dose in organ or tissue \( T \)

Dose quantities for stochastic risk

Stochastic risk

Stochastic risk (death from exposure) is calculated multiplying effective dose \( E \) by the risk factor specific for sex and age at exposure

Stochastic Risk = \( E(Sv) \times f \)

Example: Effective dose assessment in cardiac interventional procedures

1. Organ doses and \( E \) can be calculated using FDA conversion factors (FDA 95-8289; Rosenstein) when the dose contribution from each x-ray beam used in a procedure is known.
2. Complutense University (Madrid) computer code allows to calculate in a simple manner organ doses and \( E \) (Rosenstein factors used).
Example: PCXMC - Organ and effective dose evaluation (STUK Monte Carlo simulation tool)

Software tool (STUK, Finland):
PCXMC simulates the interaction of X-rays on a mathematical phantom

http://www.stuk.fi/pcxmc

Example 1

Effective dose quantity allows to compare different type of radiation exposures:
- Different diagnostic examination
- Annual exposure to natural background radiation

Example 2: Effective dose assessment in cardiac procedures

For a simple evaluation, E can be assessed from total DAP using the conversion factor 0.17-0.23 mSv/Gycm² (evaluated from NRPB conversion factors for heart PA, RAO and LAO projections)

Example:
CA to a 50 y old person performed with a DAP=50 Gycm²
- Effective dose E = 50 * 0.2 = 10 mSv = 0.01 Sv
- Stochastic risk: R=0.01 Sv * 0.05 deaths/Sv = 0.0005 (5/10000 procedures)

Comparison of different type of procedures:
Udine cardiac center: CA : mean DAP=30 Gycm² → E = 6 mSv
PTCA:mean DAP=70 Gycm² → E = 14 mSv
MS-CT of coronaries → E ≈ 10 mSv

Staff Dosimetry

- Typical staff doses
- Staff dosimetry methods

Many variables affect level of staff exposure

- type of equipment and equipment performance
- distance from the patient
- beam direction
- use of protective screens
- type of procedure
- radiology technique
- operator skill
- training
Staff dosimetry in interventional radiology

- Exposure is not uniform:
  - with relatively high doses to the head, neck and extremities
  - much lower in the regions protected by shieldings

Dose quantities and dose limits

- **Dose quantities:**
  - Effective dose
  - Equivalent dose to most exposed part of the body (hands, feet, eye lens)

- **Dose limits** (nationally regulated) for exposed workers are:
  - Effective dose ($E$): 20 mSv/year
  - Equivalent dose ($H$) to eye lens: 150 mSv/year
  - Equivalent dose ($H$) to skin and extremities: 500 mSv/year

- **Dose limits** (nationally regulated) for non exposed workers and population is:
  - Effective dose ($E$): 1 mSv/year

Personal dosimetry methods

- **Effective dose evaluation**
  - Single dosimeter worn:
    - above the apron at neck level (recommended) or under the apron at waist level
  - or, two dosimeters worn (recommended):
    - one above the apron at neck level
    - another under the lead apron at waist level

- **Equivalent dose to:**
  - Special dosimeters for:
    - Hands
    - Feet
    - Eye lens

Exercise 1: annual staff exposure

- Operator 1: 1000 procedures/year
  - $20 \mu Sv/proc$.
  - $E = 0.02 \times 1000 = 20 \text{ mSv/year}$ = annual effective dose limit

- Operator 2: 1000 proc/year
  - $2 \mu Sv/proc$.
  - $E = 0.002 \times 1000 = 2 \text{ mSv/year}$ = 1/10 annual limit

Summary

- **Different dose quantities are able:**
  - to help practitioners to optimise patient exposure
  - to evaluate stochastic and deterministic risks of radiation

- **Reference levels in interventional radiology** can help to optimise procedure

- **Staff exposure** can be well monitored if proper and correct use of dosimeters are routinely applied