SENTINEL Coordinated Action
(Contract Number: 012909)

TRAINING COURSE ON RADIATION PROTECTION TRAINING FOR INTERVENTIONAL CARDIOLOGISTS AND RADIOLOGISTS

Budapest, 5 and 6 July 2006

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

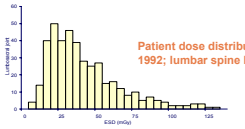
Patient dose variability in general radiology

1950s 'Adrian survey', UK
measures of gonadal and red bone marrow dose with an ionisation chamber; first evidence of a wide variation in patient doses in diagnostic radiology
(variation factor: 10,000)

1980s, European countries
measure of ESD with TLDs and DAP for simple and complex procedures
(variation factor: 30 between patients; 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)

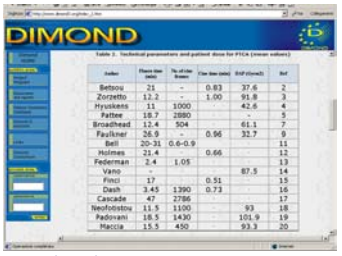
2000s, NRPB, UK
UK; National database with patient dose data from 400 hospitals
(variation factor: 5 between hospitals)



Patient dose distribution in EU survey 1992; lumbar spine Lateral projection

Patient doses in interventional procedures

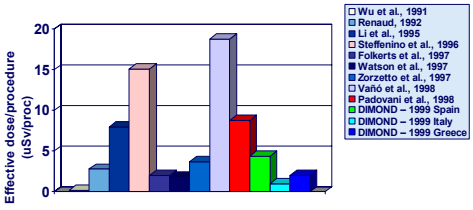
- Also in cardiac procedures, patient doses are highly variables between centres
- Need for patient dose monitoring



www.dimond3.org

Staff doses in interventional cardiology

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



Dose quantities and Radiation units

- Dose quantities <u>outside</u> the patient's body
- Dose quantities to estimate risks of <u>skin injuries</u> and effects that have threshold
- Dose quantities to estimate <u>stochastic risks</u>

Why so many quantities?

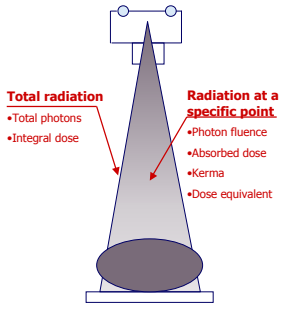
- 1000 W heater giving hear (IR radiation) - unit is the power which is related with emission intensity
- Heat perceived by the person will vary with so many factors: distance, clothing, temperature in room…
- If one has to go a step ahead, from perception of heat to heat absorbed, it becomes a highly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

Dose quantities and Radiation units

- 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

Radiation quantities

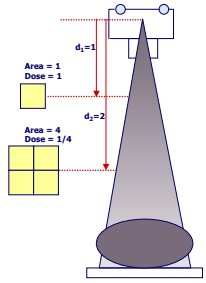
- Used to describe a beam of x-rays:
  - Quantities to express total amount of radiation
  - Quantities to express radiation at a specific point



Radiation quantities

- 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
  - The dose (concentration) of radiation is inversely related to the square of the distance from the source (inverse square law)

$$D_2 = D_1 * (d_1/d_2)^2$$



1 - Dose quantities and radiation units

Absorbed dose
The absorbed dose D, is the energy absorbed per unit mass

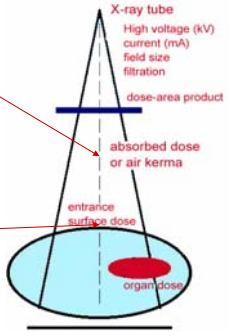
$$D = dE/dm$$

SI unit of D is the gray [Gy]

Entrance surface dose
includes the back scatter from the patient

$$ESD \cong D * BF$$

BF ranges from 1.2-1.4 as a function of field size



Absorbed dose, D and KERMA

- The KERMA (kinetic energy released in a material)

$$K = dE_{trans}/dm$$

  - where dE_{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).

Dose measurement (I)

Absorbed dose (air kerma) in X ray field can be measured with

- Ionisation chambers,
- Semiconductor dosimeters,
- Thermoluminescentt dosimeters (TLD)

Dose measurement (I)

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
- Fluorosocpy mode (low, medium, high)
- Cine mode (low, high)

Dose measurement (II)

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

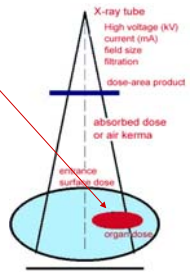
Absorbed dose in soft tissue and in air

- 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 :

Dose in soft tissue = 1.06 x Dose in air

Mean absorbed dose in a tissue or organ

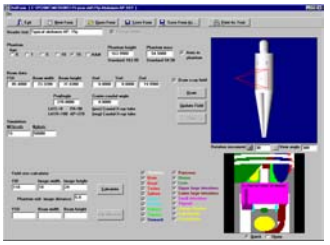
- The mean absorbed dose in a tissue or organ D_T is the energy deposited in the organ divided by the mass of that organ.



Organ dose evaluation

Organ doses cannot be measured on real patients.

- can be measured in antropomorphic phantoms simulating the esamination
- Can be calculated with dedicated software tools (interaction simulations of X-rays on a mathematical phantom)

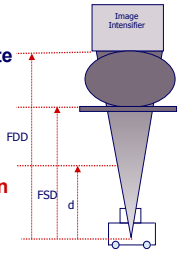


•Tapiovaara M, Lakkisto M and Servomaa A. A PC-based Monte Carlo program for calculating patient doses in medical x-ray examinations. Finnish Centre for Radiation and Nuclear Safety (STUK), Helsinki, 1997. http://www.stuk.fi/pcxmc

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**

FDD = focus-detector distance
FSD = focus-skin distance



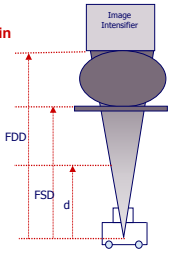
→ **measured entrance surface dose rate (air kerma rate) at FSD=70 cm: 18 mGy/min**

→ **dose rate at d= 50 cm: using the inverse square law**
$18 * (70/50)^2 = 18 * 1.96 =$ 35.3 mGy/min

Example 2: Entrance surface dose rate changes with image quality

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

FDD = focus-detector distance
FSD = focus-skin distance



1. **pulsed fluoro LOW → 47 mA,**
   → dose ratein in air (air kerma rate) = 18 mGy/min

   Dose rate at the patient skin including backscatter and conversion factor air to tissue:
   ESD= 18 * 1.3 *1.06 = 24.8 mGy/min

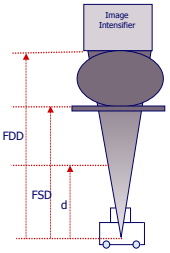
2. **pulsed fluoro NORMAL → 130 mA,**
   → dose rate = 52 mGy/min

   Dose rate at the patient skin including backscatter and conversion factor air to tissue :
   ESD= 52 * 1.3 *1.06= 71.6 mGy/min

Example 3: Entrance surface dose rate changes with patient thickness

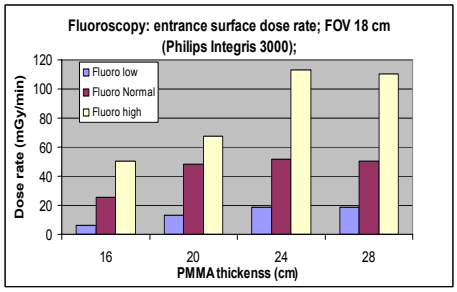
Fixed FOV=17 cm; pulsed fluoro= Low, 15 p/s; dose measured

FDD = focus-detector distance
FSD = focus-skin distance



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.)

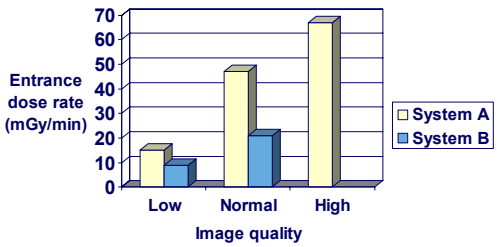


Entrance dose rates increase with:

→ fluoro image quality selected & patient thickness

Example 4: Equipment type

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

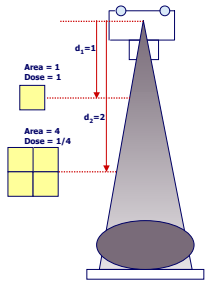


Entrance surface dose rates can be very different between systems !!!!!

1 - Dose area product (I)

- **DAP = D x Area**
  (or KAP = Kerma x Area)

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

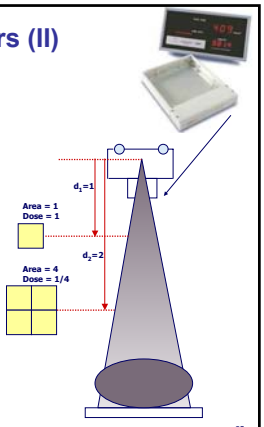


Attention to the different indications: Gy.cm², dGy.cm², cGy.cm², µGym²

1 Gy.cm² = 100 cGy.cm²
1 Gy.cm² = 100 µGym²
1 cGy.cm² = 1 µGym²

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

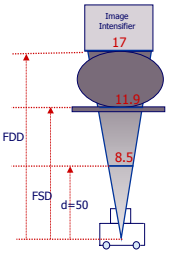
Patient thickness 24 cm, FOV=17 cm, FDD=100 cm, pulsed fluoro LOW → 95 kV, 47 mA, 15 pulse/s

FDD = focus-detector distance
FSD = focus-skin distance

→ Dose (kerma) in air in 1 min @ FSD=70 cm: 18 mGy
→ Area @ 70 cm: 11.9*11.9=141.6 cm²
DAP= 18 * 141.6 = 2549 mGycm² = 2.55 Gycm²

→ Dose in air 1 min @ FSD=50 cm: 18 * (70/50)² = 18 * 1.96 = 35.3 mGy
→ Area @ 50 cm: 8.5*8.5=72.2 cm²
DAP= 35.3 * 72.2 = 2549 mGycm² = 2.55 Gycm²

→ DAP is independent of focus to dosemeter distance
(without attenuation of x-ray beam)



Example 2: DAP (KAP) evaluations

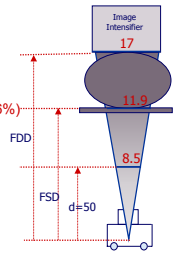
Patient thickness 24 cm, FOV=17 cm, FDD=100 cm pulsed fluoro LOW → 95 kV, 47 mA, 15 pulse/s

FDD = focus-detector distance
FSD = focus-skin distance

→ Dose in 1 min @ FSD=70 cm: 18 mGy
→ Area @ 70 cm: 11.9*11.9=141.6 cm²
DAP= 18 * 141.6 = 2549 mGycm² = 2.55 Gycm²

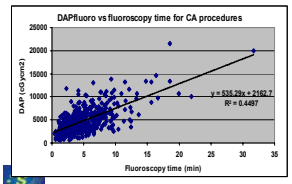
→ Area @ 70 cm: 15*15=225 cm²
DAP= 18 * 225 = 4050 mGycm² = 4.50 Gycm² (+76%)

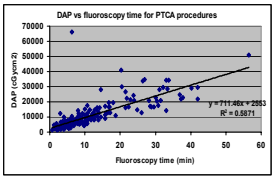
→ If you increase the beam area, DAP will increase proportionately



Other dose quantities outside the patient body

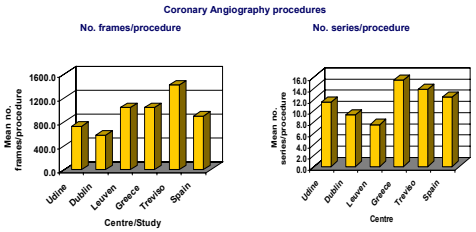
- **Fluoroscopy time:**
  - **has a weak correlation with DAP**
  - **But, in a quality assurance programme it can be adopted as a starting unit for**
    - **comparison between operators, centres, procedures**
    - **for the evaluation of protocols optimisation**
    - **and, to evaluate operator skill**





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**



DIMOND trial on CA procedures (2001)

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)

3rd level "Patient risk" — **Level 2 + DAP + Maximum Skin Dose (MSD)**

2nd level "Clinical protocol" — **Level 1 + No. images + fluoroscopy time**

1st level "Equipment performance" — ***Dose rate*** **and dose/image** ***(BSS, CDRH, AAPM)***

Reference levels in interventional cardiology

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

Procedure:	CA	PTCA
DAP (Gycm²)	57	94
Fluoroscopy time (min)	6	16
No. of frames	1270	1355

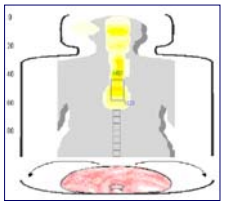
DIMOND EU project. E.Neofotistou, et al, Preliminary reference levels in interventional cardiology, J.Eur.Radiol, 2003

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

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

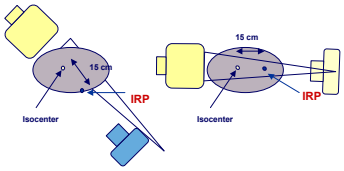


Methods for maximum local skin dose (MSD) assessment

- 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)

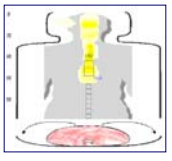
Methods for MSD (cont.): on-line methods (I)

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

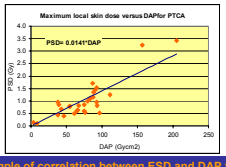


Methods for MSD (contd.): on-line methods (II)

- Dose distribution calculated by the angio unit using all the geometric and radiographic parameters (C-arm angles, collimation, kV, mA, FIID, …)



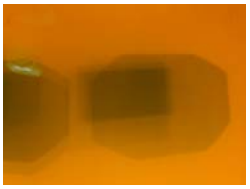
- Correlation MSD vs. DAP:
  - Maximum local skin dose has a weak correlation with DAP
  - For specific procedure and protocol, installation and operators a better correlation can be obtained and MSD/DAP factors can be adopted for an approximate estimation of the MSD



Example of correlation between ESD and DAP for PTCA procedure in the Udine cardiac centre

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

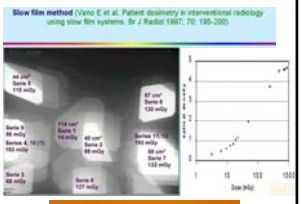
- Point measurements: thermoluminescent detectors (TLD)
- Area detectors: radiotherapy portal films, radiochromic films, TLD grid
  - Large area detectors exposed during the cardiac procedure: between tabletop and back of the patient



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

2 – 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
  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

Exercise 2: Evaluation of MSD

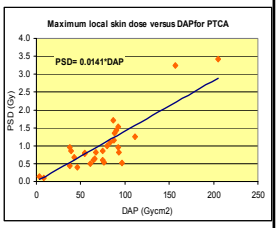
An crude estimation of MSD during the procedure can be made from the correlation between MSD and DAP in PTCA procedure:

Example:

A PTCA with DAP= 125 Gycm²

MSD= 0.0141*DAP =
= 0.0141*125= 1.8 Gy

(linear regression factor is characteristic of the installation, procedure and operator)



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**

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

$$H = D * w_R$$

the SI unit of H is the Sievert [Sv]

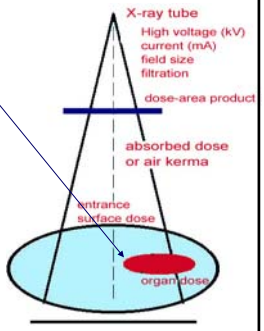
For X-rays is $w_R=1$

→ For x-rays H = D !!

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.



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,

ORGAN / TISSUE	W_T	ORGAN / TISSUE	W_T
Bone marrow	0.12	Lung	0.12
Bladder	0.05	Oesophagus	0.05
Bone surface	0.01	Skin	0.01
Breast	0.05	Stomach	0.12
Colon	0.12	Thyroid	0.05
Gonads	0.20	Remainder	0.05
Liver	0.05		

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

$$E = \Sigma_T w_T.H_T$$

w_T : weighting factor for organ or tissue T

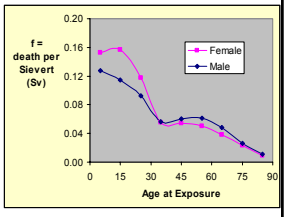
H_T : equivalent dose in organ or tissue T

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) * f



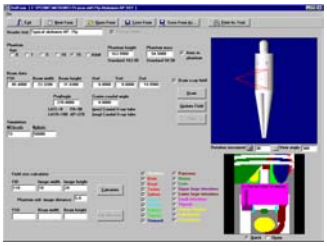
Example: Effective dose assessment in cardiac interventional procedures

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

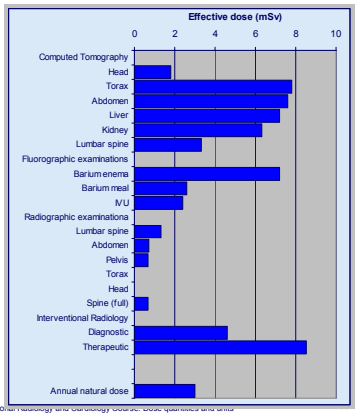


•Tapiovaara M, Lakkisto M and Servomaa A. A PC-based Monte Carlo program for calculating patient doses in medical x-ray examinations, Finnish Centre for Radiation and Nuclear Safety (STUK), Helsinki, 1997. http://www.stuk.fi/pcxmc.

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**

→ **Stocastic 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

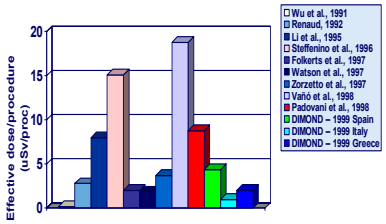
MS-CT of coronaries → E ≅ 10 mSv

Staff Dosimetry

- **Typical staff doses**
- **Staff dosimetry methods**

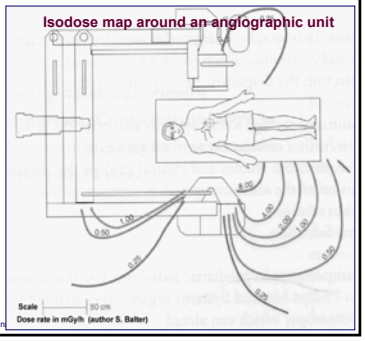
Staff doses per procedure

- High variability of staff dose per procedure as reported by different authors
- Correct staff dosimetry and proper use of personal dosimeters are essential to identify poor radiation protection working conditions



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

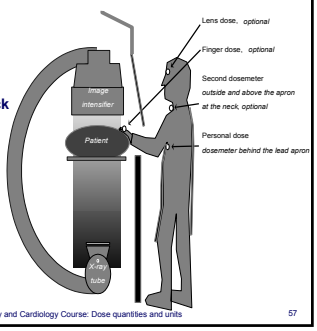
- Exposure is not uniform:
  - with relatively high doses to the head, neck and extremities
  - much lower in the regions protected by shieldings

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 extrimities: 500 mSv/y
- 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

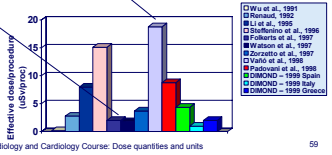


Staff dosimetry methods (comments)

- Assessment of *E* is particularly problematic due to the conditions of partial body exposure
- Use of dosimeter worn outside and above protective aprons results in significant *overestimates of E*.
- On the other hand the monitor under the protective apron significantly *underestimates* the effective dose in tissues outside the apron.
- 2 dosimeter are reccomended
- Multiple dosimeters (more than 2) are too costly and impratical.

Exercise 1: annual staff exposure

- Operator 1: 1000 procedures/year
  - 20 µSv/proc
  - E= 0.02*1000 = 20 mSv/year = annual effective dose limit
- Operator 2: 1000 proc/year
  - 2 µSv/proc
  - E= 0.002*1000=2 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