Dosimetry in Radiodiagnostic Procedures, Risk Issues and Research Needs

Renato Padovani
Medical Physics Dpt, S. Maria della Misericordia University Hospital, Udine, Italy
Objectives

• To discuss present status of dosimetry in diagnostic and interventional radiology and radiation risk assessment and to identify possible research and action needs
Content

• Examination frequencies and population exposures in Europe
• Dosimetry status and needs
• Radiation risk assessment and research needs
• Optimisation of exposure status and action needs
DoseDataMed2 EC project (2012): frequency X-ray procedures

- > 1.5 proc/year
- <0.7 proc/year

Large variability for high dose procedures (CT, IR)
DoseDataMed2 EC project (2012): collective effective dose for X-ray procedures (mSv/person.year)

Overall total collective effective dose per 1,000 of population, mSv

- > 1.5 mSv/year
- <0.5 mSv/year

Legend:
- Blue: Plain radiography
- Red: Fluoroscopy
- Green: Computed tomography
- Purple: Interventional radiology
DDM2: European figure

- Europe has lowest mean dose level if compared with US (~3 mSv/y) or Japan (~2 mSv/y)
- Large differences with regards to justification and optimisation levels
Question rising

• Which has been the impact of 15 years of research, actions, ME Directive and EC guidelines in Europe?
  – Several actions and research projects:
    • Development of DRLs concepts, referral criteria, optimisation tools, equipment with dose information, etc
    • Several guidelines (education and training, audit, etc.)
  – Development of safety culture in radiology area
    • Implementation of QA programmes, patient dose monitoring, DRLs assessment and use
    • Development of a category of medical physicists experts in diagnostic imaging
    • IEC and DICOM developments

• But, in Europe we have still large differences in the justification and optimisation of radiological procedures
Patient dosimetry status and needs
Status of patient dosimetry

- ICRU 74 and IAEA Dosimetry in Diagnostic Radiology: An International Code of Practice (TRS 457, 2007) have given advices to harmonise dosimetry practice:
  - better definition of dose quantities:
    - equipment-specific
    - and, patient specific
- ICRP 103 and 110
  - Voxel phantoms for organ dose assessment
    - Great improvement from the presently used mathematical antropomorphic phantoms
Equipment specific dose quantities
(names and symbols, ICRU 74)

• Incident air kerma, $K_i$

• Entrance surface air kerma $K_e = K_i B$
  unit: Gy

• X-ray tube output $Y(d) = K(d)/P_{it}$
  unit: GyC$^{-1}$

• Air kerma-area product $P_{KA}$
  unit: Gym$^2$
  $$P_{KA} = \int_{A} K(x, y) dx dy$$

• Air kerma-length product $P_{KL}$
  unit: Gym
  $$P_{KL} = \int_{L} K_{air}(z) dz$$

• Computed Tomography Kerma Index, $C_{100}$
  unit: Gy
  $$C_{100} = \frac{1}{50} \int_{-50}^{+50} K(z) dz$$

→ IEC standards, MED requirements
Patient specific dose quantity

- The absorbed dose $D$, is the energy absorbed per unit mass.

→ Organ dose is expressed as an mean absorbed dose to an organ/tissue
Organ dose

• Methods to assess mean organ dose:
  – To measure organ dose in a physical anthropomorphic phantom
  – To simulate with the Monte Carlo method the irradiation of a phantom (mathematical or voxel)
    • Conversion coefficients normalised to equipment specific dose quantities
Computational anatomical phantoms

• To evaluate the energy deposition in organs from internal and external radiation exposures.

• **Mathematical phantoms:**
  - Mathematical expressions describing the shape and position of idealised body organs (Oak Ridge National Laboratory (Fisher and Snyder, 1967, 1968; Snyder et al., 1969, 1978; Cristy, 1980; Cristy and Eckerman, 1987) for the Medical Internal Radiation Dose (MIRD) Committee)
  
  – From the original adult MIRD phantom, **paediatric phantoms** were derived to represent infants and children of various ages (Cristy, 1980).
  
  – **Hermaphrodite models**, **male and female adult mathematical models** called Adam’ and ‘Eva’ were introduced (Kramer, 1982)
Computational anatomical phantoms

• ‘Tomographic’ or ‘voxel’ phantoms
  – Large number of volume elements (voxels) for a detailed representation of human anatomy
    (Zankl et al., 1988; Zubal et al., 1994, 1996; Dimbylow, 1996; Caon et al., 1999; Xu et al., 2000; Zankl and Wittmann, 2001; Petoussi-Henss et al., 2002; Zaidi and Xu, 2007)
  – Voxel phantoms can be used for a wide spectrum of applications.

➔ ICRP 110: ... phantoms will be used by ICRP in establishing radiation protection guidance, e.g. effective dose coefficients and other secondary dosimetric quantities.
Example: Absorbed dose per air kerma to Stomach from an Anterio-Posterior photon exposure for male and female ICRP 110 phantoms

- Different MC codes used
- Comparison with previous conversion coefficients (.) (ICRP 74)

→ Progresses mainly to improve accuracy of exposure and risk assessment to workers and population

→ Development for patient dose assessment are possible:
  - to develop phantoms patient-specific (e.g. different age, obese patients, pregnant women, etc)
  - to improve accuracy in patient exposure assessment
Dosimetry needs: equipment-specific dose information

• **Computed Tomography**
  – Dose quantity
    • CTDI is a dose quantity related to specific geometrical phantoms (CT dosimetry phantoms)
      – For the wide beams used in some MSCT the quantity is inaccurate
    • CTDI is not a real equipment specific and it is not a patient specific
      – A new CT dosimetry methodology should be probably necessary
  – Information from the CT of the angular current modulation is not always available
    • IEC should require availability of angular current modulation and DICOM should export the data

• **Interventional radiology**
  – Real time skin dose distribution not yet available to monitor in skin dose in high dose IR procedures
    • Patient skin models and patient-to-equipment registration methods have to be develop and implemented in IR equipment
Dosimetry needs: equipment-specific dose information

• ConeBeam CT
  – A solid dosimetry is not available
    • KAP is used, but x-ray beam is not fully intercepted by the patient body
    • A better dosimetry method should be developed
Dosimetry needs: patient specific dosimetry

• To develop patient models aiming to compute organ doses in the different procedure
  – Patient models
    • Age/Size/Gender specifics
      e.g. paediatric, obese patient models, pregnant women, etc.
    • Models for specific applications:
      – Interventional radiology: patient skin model to compute skin dose distribution and peak skin dose
      – Mammography: average glandular dose
    • Models to take into account the different irradiation modalities:
      – Tomosynthesis
      – CT
      – ConebeamCT
Dosimetry needs: implementation of patient specific dosimetry

• To implement in radiological equipment patient specific dosimetry
  – CT
    • organ dose patient-specific taking information from CT images
  – IR
    • from the patient skin model, patient-to-equipment registration, to compute and provide the real time skin dose map
  – Mammography
    • Average glandular dose (AGD) is calculated for standard breast, equipment software is not using the information on breast composition (glandularity) derived from the automatic exposure system
    • A more solid dosimetry can be implemented
Dosimetry needs: risk assessment and communication

- Effective dose is a fortunate synthetic quantity to quantity workers and population exposures and compare with limits
- Today cumulative effective dose is frequently adopted to quantify population exposures, also for medical exposures, when age classes, gender, pathology can modify substantially risk factors!

➔ Probably we need a similar synthetic quantity to properly express patient radiation exposure
  – should be age/gender/(pathology?) specific

➔ Or do we need to develop a quantity to assess the risk in a form that can be understood by the patient and can be compared with other risks?
Optimisation of radiological procedures
Optimisation tools: DRLs

• Status of Diagnostic Reference Levels (DRLs)
  – Required by MED
  – Present situation in Europe is given by DDM2 study:
    • Several countries have adopted the (old) EC DRLs
    • Most Countries have never updated DRLs
    • Very few Countries have DRLs for high dose/risk procedures (paediatric CT, interventional radiology)
    • Few information on the effective use of DRLs in EU countries
    • General thinking is that the compliance with DRLs certifies an optimised practice!
  – No great impact of DRLs is seen in most of EU countries (see DDM2)
Optimisation tools: DRLs

• The need:
  – To redefine DRLs: role, assessment and use
  – To add a second quantity, like Achievable Reference Level (ARLs) ?
    • It can be easier to understand the purpose of DRLs to identify unacceptable practices
  – Regulatory needs
    • More stringent requirements from regulations
      – periodic dose assessment and communication to regulatory bodies, ...
    • Development of national /regional patient dose archives
    • External audits
Optimisation tools: the clinical protocol

• To develop and implement in the radiological equipment intelligent tools supporting staff in planning a procedure:
  – To develop models and objective procedures on how to set the pre-programmed dose levels in an optimal way.
  – We should find the ‘task’ to be optimized
    • Example:
      The task: high contrast visualisation of thin linear structure, moving on a cardiac background.
      The aim: to develop an algorithm to apply on the object (like a model observer or another relevant SNR), and access to raw data to calculate such a model observer
Optimisation in interventional procedures

1. Deterministic risks should not be a post procedure surprise.
2. A center doing interventional cardiac work and never observing any deterministic risks in their patients is probably not trying hard enough. (S. Balter, US)

• The need:
  – Real time skin dose maps:
    • from the patient skin model, patient-to-equipment registration, to compute and provide the real time skin dose map
  – Patient dose archives
    • To identify repeated procedures
    • To compute cumulative exposures, including skin dose maps, and to transfer the information also to the to x-ray equipment
    • To identify patient for clinical follow-up
Optimisation in interventional procedures: staff exposure

• Status of staff exposure in IR (from ISEMIR, IAEA):
  – Not harmonised monitoring,
  – Low compliance with rules by the staff
  – The actual exposures are probably not known in several hospitals
  – Dated technology (passive dosimeters) applied to staff monitoring
  – New dose limit for eye lens of 20 mSv/y in EU BSS

• The need:
  – To improve staff monitoring:
    • Dosimetry: models to assess eye doses, computational dosimetry
    • Technologies:
      – active dosimeters, electronic archives providing real time information,
      – integration of staff and patient exposures
  – To improve dosimetry practices
    – Inspection/audit
    – Exposure monitoring: to integrate national dose archives with personal data
      (e.g. clinical tasks & workload)
Optimisation tools: large patient dose archives

• Status of standards
  – DICOM has developed and is updating the RDSR (Radiation Dose Structured Report)
  – IHE has developed the REM profile (Radiation Exposure Monitoring Integration Profile, draft 2008) thinking to a patient dose tracking tool at the department/hospital level
  – Some examples of dose archives implemented in small network of hospitals

• Present developments allows to develop dose archives at regional/country level to easily:
  – provide periodic information to radiological staff
  – provide cumulative doses to individual patient
  – compare practice/protocols between clinics/hospitals
  – assess and update DRLs/ARLs
  – support clinical audits
Level of knowledge of exposure and risk levels in specific group of patients and applications
Repeated exposures: CT

• Repeated exposure to head and neck CT is significantly associated with increased risk of cataracts Mei-Kang Yuan et al., Taiwan (AJR, September 2013, Vol. 201:3pp. 626-630).

• Magnitude of repeated exposures in a hospital (Udine, 2013):
  – 2.4% of patients submitted to CT examination have received a cumulative DLP > 6700 mGycm (100 mSv for a reference adult man)
    • A 71 y patient has performed 8 CTs with a cumulative DLP of 516000 mGycm (415 mSv)
    • Another patient 28 y old has performed 8 CTs with a cumulative DLP of 917000 mGycm (209 mSv)
Risk Assessment in diagnostic radiology

- Very few information on risk are available for specific group of patients/pathologies
  - Adult chronic disease patients with repeated procedures, sometimes for the whole life:
    - ESKD (end stage kidney disease),
    - IBD (inflammatory bowel disease),
    - CAD (coronary artery disease),
    - HT (heart transplant)
Risk Assessment in diagnostic radiology

• For paediatric patients, only studies reporting cumulative effective dose!
  – Paediatric patients with pathologies with positive outcome and long life expectation and repeated x-ray and nuclear medicine procedures:
    • Lymphoma
    • Crown disease, cystic fibrosis, hydrocephalous,
    • CHD (congenital heart disease),
    • haemophilia, bleeding disorders
Needs for risk assessment in IR & CT

• Dose and dose-rate effectiveness factor (DDREF). ICRP combines the LNT model with a value of 2 for the DDREF and considers it a prudent basis for the practical purposes of radiological protection, ... should be applied to chronic exposures at dose rates less than 6 mGy/h averaged over the first few hours. ICRP refers (paragraph A62 of the 2007 recommendations) that: “When dose rates are lower than around 0.1 Gy/hour there is repair of cellular radiation injury during the irradiation”.

• In IR procedures, dose and dose rates can be higher. During a cine frame a skin dose of 1 mGy can be imparted in <10 ms → dose rate of 360 Gy/h
• .. also in CT dose rate is of the same order of magnitude

→ radiation risk factors could be higher
Summary

- In the 80s-90s European outcomes from researches and regulations have been the basis for the implementation of actions, rules and safety culture in medical exposure
  - These developments have been taken as models at worldwide level

- It is necessary another great effort to fulfil the job to provide harmonised practice to all European patients
  - Developing optimisation methods and implement them in existing and new coming practices
  - Improving knowledge on low dose radiation risks
  - Developing communication strategies

These will allow to continue to be ahead in this field worldwide level