Interface- and skeleton dosimetry

CPD/ST- and PhD course
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Fundamental quantities
Kerma and Collision kerma

Kerma

\[ K = \frac{dE_{tr}}{dm} = \int_0^{\infty} \frac{\mu_{tr}}{\rho} \psi_{hv} dh \nu \]

Collision kerma

\[ K_{col} = \frac{dE_{tr}}{dm} (1 - g) = \int_0^{hv} \frac{\mu_{en}}{\rho} \psi_{hv} dh \nu \]

\[ g = \text{fraction of energy transferred to kinetic energy } E_{tr} \text{ of charged particles lost to bremsstrahlung in slowing down} \]

In diagnostic radiology

\[ K \approx K_{col} \]

In charged particle equilibrium CPE

\[ D = K_{col} \]
Introduction to interface dosimetry

What characterizes an interface?

At the interface absorbed dose is delivered by secondary electrons generated by photons in two media $Z_1$ and $Z_2$ within regions delimited by the maximum ranges $R_1$ and $R_2$ on both sides. These regions are characterized by dose gradients.
Fundamental quantities
Air kerma and absorbed dose to air

Absorbed dose and kerma at a PMMA-air interface

For air cavities inside a PMMA phantom ‘absorbed dose to air’ deviates from air kerma – CPE does not exist!

Consequences for recent definitions of application specific quantities

From IAEA CoP (2007), p 22
Theory by Spiers

The theory was originally developed for bone marrow dosimetry in x-ray diagnostics. It is based on a simplified transport theory.

Assumptions
1. Isotropic emission of secondary electrons
2. Electrons in $Z_2$ travel in straight paths with $R = 0.7 \cdot R_{\text{CSDA}}$
3. Energy imparted per unit length of straight path
   
   \[
   \frac{dT}{dR} = \frac{1}{m} \left( \frac{1}{A} \right)^{1/m} \cdot R^{(1/m-1)}
   \]

4. Length of the straight path in $Z_1$

   \[
   \frac{R_2}{R_1} = \frac{R_{\text{CSDA,2}}}{R_{\text{CSDA,2}}}
   \]
Theory of Spiers
continued

The following expression is obtained (derivation details omitted)

\[ D_{\text{det}}(P, T_0) = D_{\text{det,BGL}} G(P, T_0) + D_{\text{det,eq}} [1 - G(P, T_0)] \]

- Detector medium = medium Z₂ (medium of interest)
- G(P,T₀) = geometry function for electrons with initial energy T₀ describes dose gradient at the interface.
- The shape of the dose gradient depends on assumption 3
- If medium Z₁surrounds medium Z₂ the latter forms a cavity within walls of medium Z₁
When detector medium $Z_2$ is surrounded by medium $Z_1$, the mean absorbed dose in the detector can be derived

$$D_{\text{det}}(T_0) = D_{BGL} G(T_0) + D_{\text{det,eq}} [1 - G(T_0)]$$

Averaging over the energy spectrum of secondary electrons

$$D_{\text{det}} = D_{BGL} \overline{G} + D_{\text{det,eq}} \overline{G}'$$

$$\overline{G} = \overline{G}'$$ if the spectra of initial kinetic energies of the secondary electrons are equal for the two media

Note the similarity with Burlins cavity theory!
Theory by Spiers

continued

Geometry function $G$ at plane interface

- The shape of $G$ depends on the assumptions made for the length of the straight electron path and energy imparted along this range
- $G=0.5$ at a point close to the plane interface

- At the plane interface the absorbed dose is the sum of 0.5 of the dose to a B-G cavity inside medium $Z_1$ and 0.5 of the dose under CPE to medium $Z_2$
Theory by Spiers
continued

Geometry function $G$ at points on the surface and centre of a spherical cavity

Point on surface

Point at centre

$D/r_0$ $D/r_0$
Bone marrow dose for Iliac Crest

From King and Spiers (1985) Br J Radiol 58, 345-356

Iliac crest

A: Cylindrical cavities
B: Improved theory
C: Experimental results
D: Spherical cavities
Experiments
x-ray diagnostic beam

Irradiation geometry
Teflon phantom, 0.1 mm LiF dosimeters

Derivation of absorbed dose distribution using successive layers of 5 µm mylar film

Dosemeter is thick compared to the dose gradient
Experiments
x-ray diagnostics

Interfaces to high atomic number materials in x-ray diagnostics

Absorbed dose, relative units
Depth, mg/cm²

100 kV
Pb
Sn
Cu
Al

200 kV

Absorbed dose, relative units
Depth, mg/cm²

Comparison with theory

Comparison with Spiers theory at Al interface

Alm Carlsson 1973 Acta Radiol Suppl 332

Histogram: measurements
Dotted line: theory
Comparison with theory

Comparison with Spiers theory at Pb interface

Aim Carlsson 1973 *Acta Radiol* Suppl 332
Multiple scattering of electrons
Consequence for interface dosimetry

Alternative way to interpret the overestimate of the Spiers theory

Spencer's famous energy dissipation functions

**Spiers assumption**

\[
\frac{R_2}{R_1} = \frac{R_{CSDA,2}}{R_{CSDA,2}}
\]

Does it hold?

Distance from source as fraction of \(r_{CSDA}\)
Monte Carlo simulations using coupled photon-electron transport through trabecular bones

Figure 1. (a) Five electron trajectories in a bone marrow (BM) micro voxel that has a BSC layer adjacent to trabecular bone (TB). For trajectory 1, which starts and ends in BM, the entire energy is scored into RBM. In a similar way, the entire energy deposited by trajectory 2 is collected as a contribution to the BSC equivalent dose. For trajectories 3 (starts in BSC, ends in BM) and 4 (starts in BM, ends in BSC), the energy is divided between RBM and BSC according to the path-length in the two sub-volumes. Even for trajectories such as 5, which starts in BSC, traverses the BM volume, and ends in BSC, the contributions to the RBM and BSC equivalent dose are computed according to the path-lengths in the two sub-volumes. Part (b) illustrates the problem of accurate computation of energy deposition for condensed history charged particle transport. Trajectory 1, although starting and ending in BM, may have portions of the curved path going through the BSC sub-volume. In a similar way, trajectory 2, which starts and ends in the BSC layer, has a portion traversing the BM sub-volume. Trajectories 3 and 4, although having the same initial and final position, have different path-lengths in the BSC and BM sub-volumes.

BSC = bone surface of about 10 micrometer thickness
BM = bone marrow
EGSnrc transport code
Model for calculating dose to bone marrow

Kramer et al. (2006)
Phys Med Biol 51, 6265-6289

Contains a nice review on the history of skeletal dosimetry from Spiers 1949 until 2006

Figure 2. The use of a cluster of eight micro matrices with 15% trabecular bone volume extracted from a 3D-microCT image scanned at a resolution of 30 µm for skeletal dosimetry in spongiosa.
Trabecular bone samples—five different skeletal regions

Bone marrow cavities are in the range between 50-2000 micrometer depending on the site in the skeleton

Kramer et al. 2010
Phys Med Biol 55, 163
Creation of a reference phantom of a newborn

Cassola et al. (2013) J Radiol Prot 33, 669

Figure 5. From left to right: image of a newborn formalised cadaver from the department of anatomy of the UFPE; cadaver image imported into Blender and filled with mesh organs; UFPE newborn mesh body surface; ICRP89 newborn (ICRP 2002, p. 70); and ICRP newborn imported into Blender and filled with mesh organs.
Skeleton part of the reference new born phantom

Cassola *et al.* (2013)  
J Radiol Prot 33, 669
Reference phantoms newborn and 1 year old

Cassola et al. (2013)
J Radiol Prot 33, 669

Figure 8. Voxelised phantoms from left to right: surfaces and segmented skeletons showing cortical bone, cartilage and medullary cavities for P00 and P01, lymphatic nodes for P00 and organs for P01.
Comparison of the reference and BABY models

**BABY** phantom constructed from CT images of 8 week cadaver

**Reference phantom** based on data from ICRP 89 (2002), Ann ICRP 32 (3-4)

- BABY 4.2 kg/57 cm
- Reference 3.5 kg/50.5 cm

Organ doses at CT examination (one rotation (1 cm slice) at liver center): Most differences <10% except for kidneys and stomach, known to have quite different positions in the abdominal region. Average differences 10.4% (80 kV) and 10.8% (125 kV)

Cassola *et al.* (2013)  
J Radiol Prot 33, 669
Reference adult phantoms

Kramer et al. 2010
Phys Med Biol 55, 163

Figure 1. Surfaces: MASH polygon mesh, MASH voxelized, FASH polygon mesh and FASH voxelized, from left to right.
Adult female reference phantom (FASH3) with skeleton

Red bone marrow dose FAX06 phantom

Kramer et al. (2007) Phys Med Biol 52, 6697
Bone surface dose FAX06 phantom

Kramer et al. (2007) Phys Med Biol 52, 6697
Thank you for your attention!