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Implementation of ICRP computational reference phantoms in different exposure scenarios

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Overview

1. ICRP/ICRU adult reference computational phantoms
2. Red bone marrow dosimetry
3. EURADOS intercomparison exercise
4. Approach chosen and participation
5. Problems encountered
6. Summary and conclusions

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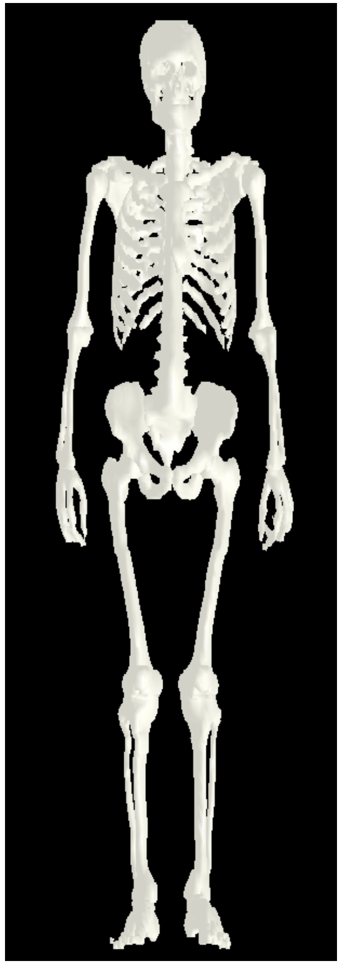
ICRP/ICRU adult reference computational phantoms

Reference computational phantoms – ICRP Publication 110



Male
176 cm, 73 kg
1.9 million voxels
Voxel size: 36.5 mm^3

140 Organ identification numbers

To be downloaded from
https://journals.sagepub.com/doi/suppl/10.1177/ANIB_39_2

Female
163 cm, 60 kg
3.9 million voxels
Voxel size: 15.2 mm^3

Features of the skeleton

Radiation-sensitive tissues in the skeleton:

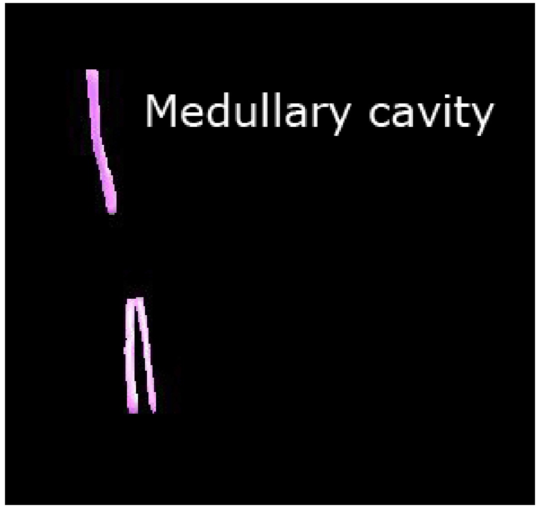
- Red (active) bone marrow
- Endosteum („bone surface“ or „shallow marrow“): 50µm thick layer covering
  - the surfaces of the bone trabeculae
  - the cortical surfaces of the medullary cavities in the shafts of all long bones

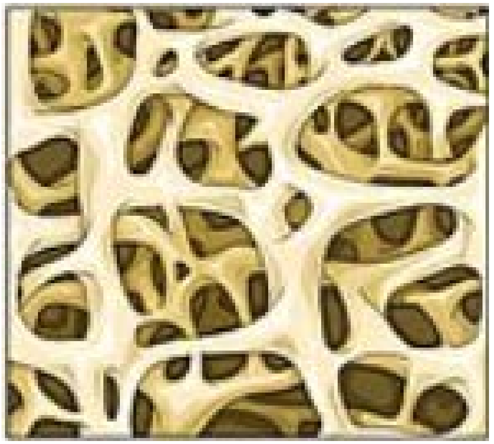
Tissues smaller than pixel resolution

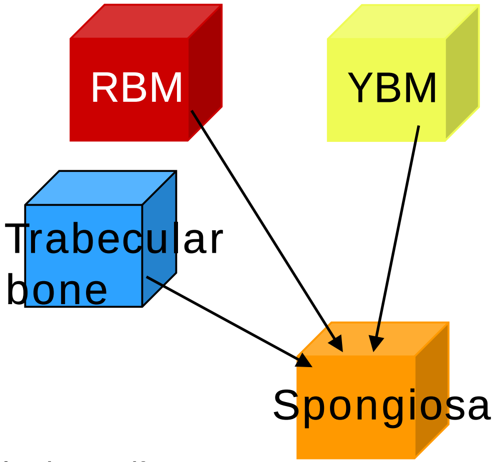
Sub-division of bones to accommodate these volumes (at macroscopic level)

Red bone marrow content and marrow cellularity given for 19 individual bones / bone groups (ICRP 70)

- Sub-division of these 19 bones into 2 different identification numbers each (cortex and spongiosa)
- Homogeneous spongiosa volume composed by bone-specific fractions of bone marrow (red, yellow) and trabecular bone
- Long bones need medullary cavities as third component







Left: microscopic structure of trabecular bone (from https://en.wikipedia.org/wiki/Trabecula); right: three components making up the spongiosa composition

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Red bone marrow dosimetry (as recommended in ICRP Publication 116)

Red bone marrow dosimetry (ICRP Publication 116)

1. Electrons (directly ionizing): homogeneous energy deposition => marrow dose well approximated by average spongiosa dose

Mass-weighted average of spongiosa doses

$$D_{skel}(AM) = \sum_{x} \frac{m(AM, x)}{m(AM)} D(SP, x) \tag{3.1}$$

with

$D_{skel}(AM)$: skeletal-averaged absorbed dose to active marrow

$m(AM,x)$: mass of active marrow in skeletal site *x*

$m(AM)$: mass of active marrow summed across the entire skeleton

$D(SP, x)$: absorbed dose to spongiosa in bone site *x*

and similarly for endosteum

Red bone marrow dosimetry (ICRP Publication 116)

2. Photons and neutrons (indirectly ionizing)

Energy ranges, for which secondary charged-particle equilibrium does not exist across the marrow cavities

a. Photons:

- below ≈200 keV: more photo-electric events in denser bone trabeculae than in marrow
- => absorbed dose to marrow tissues enhanced due to secondary electrons generated in bone trabeculae that deposit energy in the adjacent marrow tissues

b. Neutrons:

- below ≈150 MeV: more recoil protons born in marrow tissues than in bone trabeculae
- => absorbed dose to marrow tissues suppressed due to recoil particles traversing marrow spaces, with residual energy being lost to surrounding trabeculae

Red bone marrow dosimetry (ICRP Publication 116)

2. Photons and neutrons (indirectly ionizing)

Method proposed in ICRP Publication 116 for photons: usage of dose response functions

(D4) The absorbed dose to tissue r_T in bone site x, $D(r_T, x)$ is thus determined as the integral of the product of the bone-specific energy-dependent photon fluence $\Phi(E, r_S, x)$ and the bone-specific energy-dependent dose–response function $\mathcal{R}(r_T \leftarrow r_S, x, E)$:

$$D(r_T, x) = \int_E \Phi(E, r_S, x)\mathcal{R}(r_T \leftarrow r_S, x, E)dE \quad \text{(D.3)}$$

$$D_{skel}(r_T) = \sum_x \frac{m(r_T, x)}{m(r_T)} D(r_T, x) \quad \text{(D.9)}$$

and similarly for neutrons

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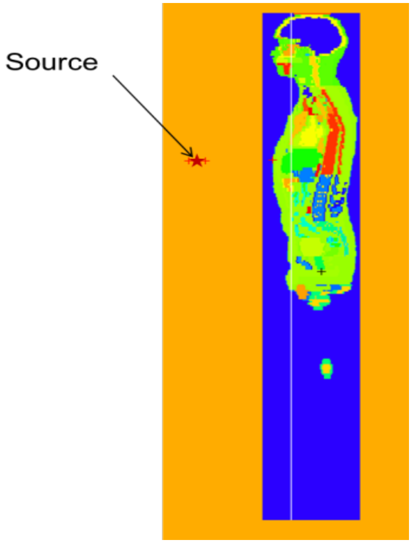
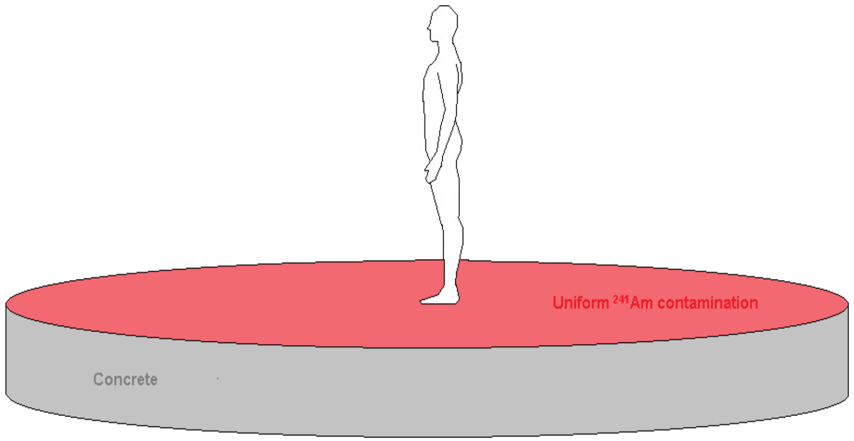
EURADOS intercomparison exercise

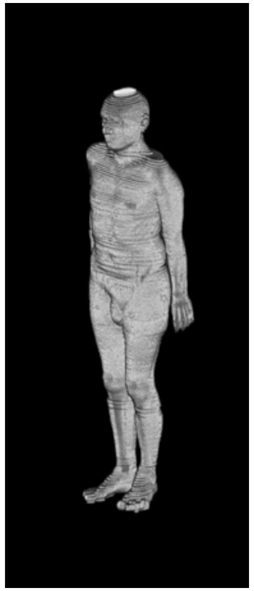
EURADOS intercomparison exercise

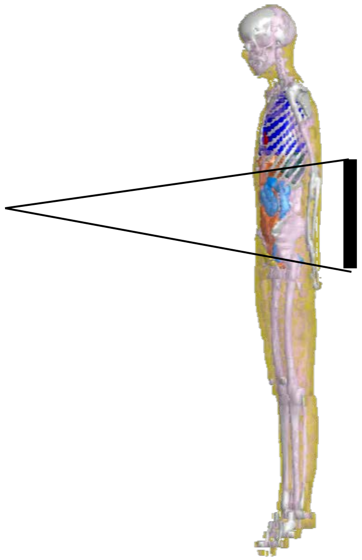
6 different exposure situations (tasks)

- Co-60 point source AP
- 10 keV neutron point source AP
- Ground contamination with Am-241
- Exposure in a cloud of N-16
- X-ray examinations
  - Chest PA
  - Abdomen AP
- Internal dosimetry
  - Monoenergetic photons
  - Monoenergetic electrons
  - Two specific radionuclides









What did we want to test?

Correct combination of the voxel phantoms with radiation transport code

Understanding of dose quantities

- Organ absorbed dose, organ absorbed dose rate, organ equivalent dose rate
- Effective dose
- Absorbed fraction, specific absorbed fraction, S value (internal exposures)

Method for red bone marrow dosimetry (ICRP recommendation)

- Fluence-to-dose response functions (photons, neutrons)
- Mass-average of mean spongiosa dose coefficients (electrons)

Normalisation quantities

- Air kerma free in air
- Kerma-area product
- Activity concentration

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Approach chosen and participation

Approach chosen

- Each task supervised by a member of EURADOS WG6
- Master solution
  - Established by the responsible person
  - Correctness ascertained by second/third calculations by other members supporting the task
- Task specifications announced on the EURADOS website and distributed to various mailing lists
- Participants invited to solve one or several tasks, according to their knowledge, interest, and time to be devoted to the participation
- Solutions to be entered into templates provided for each task (to ease evaluation of the results) and sent to responsible person
- Feedback to participants provided and revised solutions invited
- Co-authorship for papers describing the specific tasks offered to participants

Participation

- Intercomparison exercise well-received by the computational dosimetry community
- 32 participants (or teams) from 17 countries solved at least one task
- Some participants solved several or even all tasks
- Monte Carlo codes used:
  - FLUKA
  - Geant4
  - MCNP family
  - PenEasy
  - TRIPOLI
  - VMC

Solutions

- Agreement of initial solutions with master solutions very variable
  - Agreement within a few percent
  - Deviation by factors or orders of magnitude
- Many problems could be solved by feedback between participants and the responsible person
- Initial errors due to
  - Simple carelessness
  - Misunderstanding concerning the normalisation quantity
  - Lacking knowledge of dose quantities, such as effective dose
  - Lacking knowledge of ICRP recommended bone dosimetry methods
- Revised solutions in most cases in (much) better agreement

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Problems encountered

Problems with participants' solutions

- Omitted quality assurance of results
  - Plausibilty considerations
    - Homogeneous exposure conditions result in similar magnitudes of organ doses
    - Value for single intermediate energy unlikely entirely outside the range of values for other energies
  - Comparison with literature values for similar exposure conditions
- Changes applied for revision of results not disclosed
  - Appropriateness cannot be judged
  - Reasons for initially erroneous solution remain unclear
    - No additional insights can be gained into possible similar errors to be expected in future similar exercises
    - No insights can be gained that might help other participants

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Summary and Conclusions

Summary and Conclusions

- EURADOS intercomparison exercise conducted with tasks of practical interest in medical physics as well as occupational and environmental radiation protection.
- Correct simulation of proposed tasks requires knowledge of the physical quantities involved and the ability to combine the ICRP/ICRU reference computational phantoms correctly with radiation transport codes.
- Main scope of the intercomparison exercise was to offer an open forum for discussion and training in the field of computational dosimetry.
- In some cases, no knowledge about potential miscomprehensions could be gained due to the participants not disclosing how they improved their computational procedure.
- Sometimes lack of awareness was found of the necessity to quality assure computational results (plausibility checks or comparison with literature data for similar exposure conditions).
- Such studies are beneficial to the field of computational dosimetry:
  - Direct training of participants via feedback with the task organisers
  - Availability of representative dose values for various exposure conditions that may aid future novice users in the quality assurance of their methods