Methods of Dose Assessment to the Skeletal Tissues

ICRP Symposium on Radiological Protection Dosimetry

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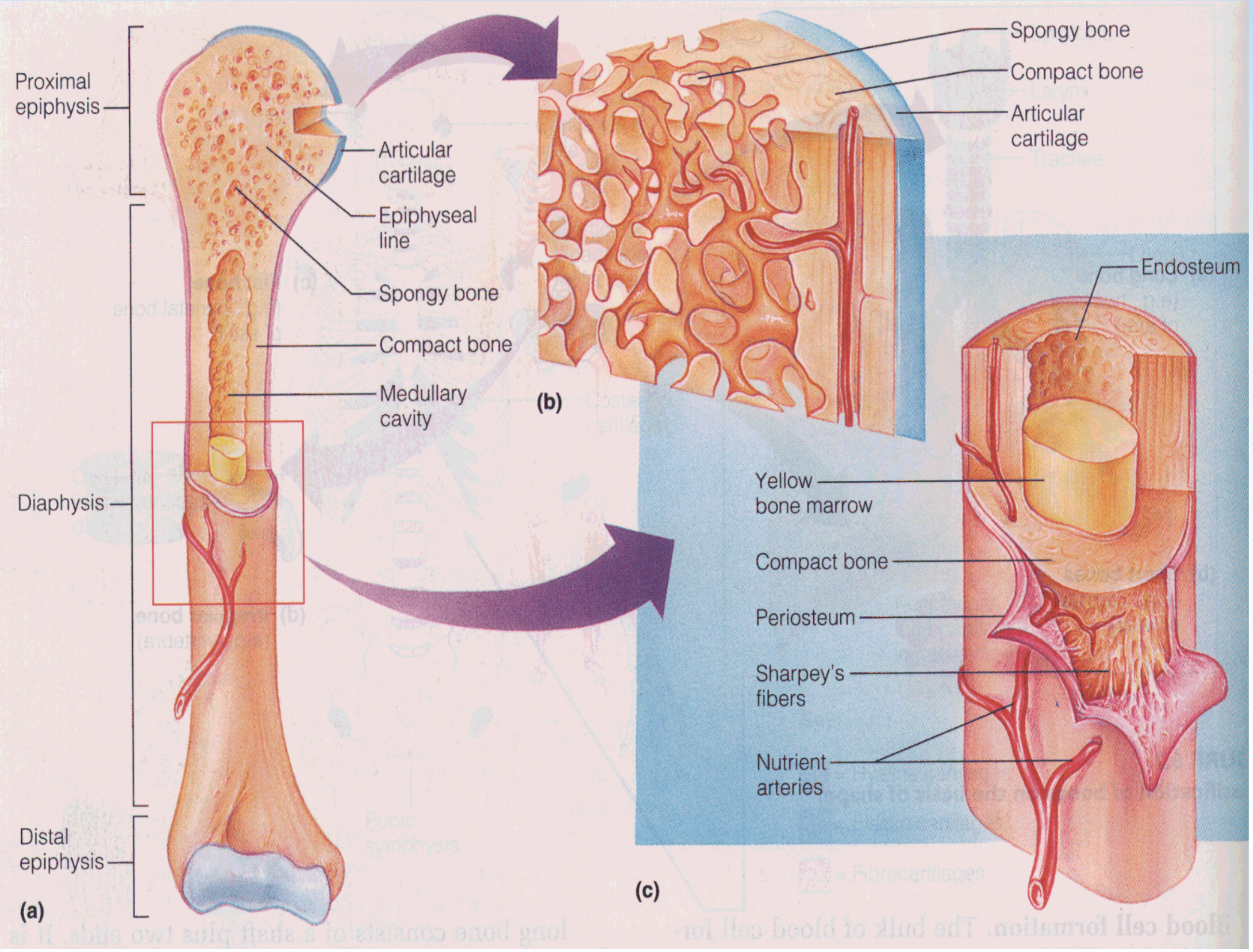
Human Skeleton 101



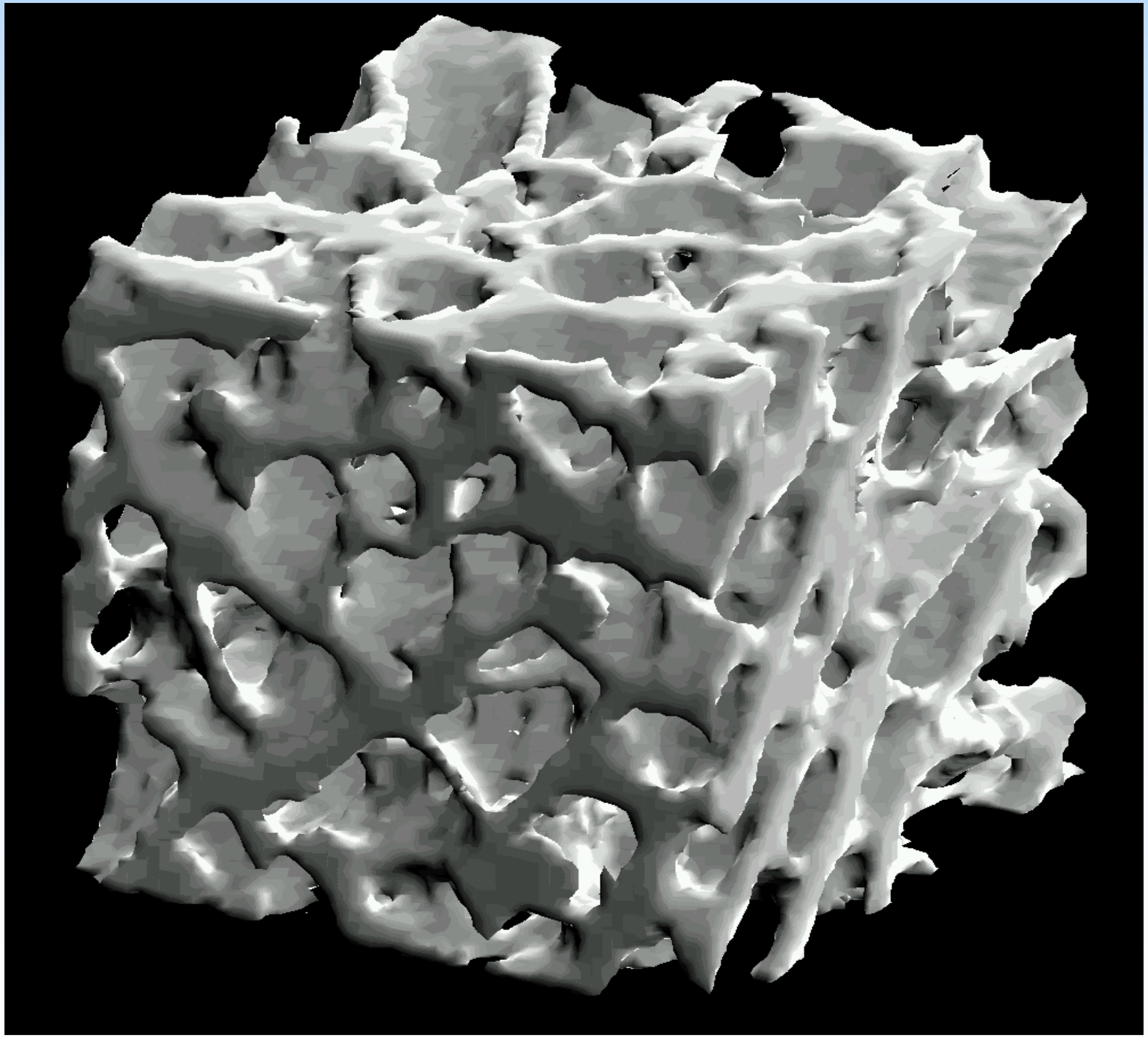
Cortical Bone

- hard bone
- compact bone
- 80% of mass

Trabecular Bone

- spongy bone
- cancellous bone
- 80% of surface area
- Home of bone marrow

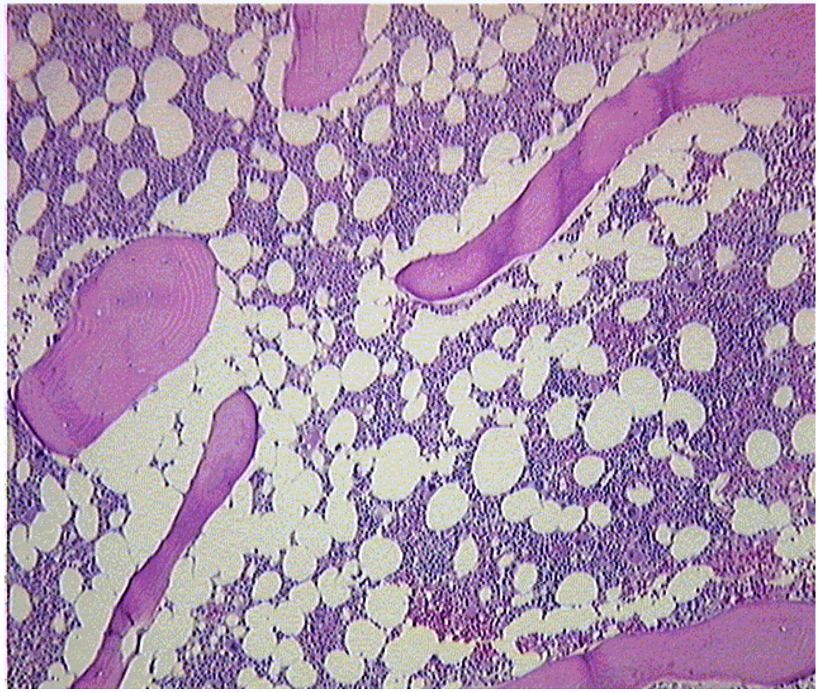
Core of Trabecular Bone



Representative section of trabecular bone from the lumbar vertebrae.

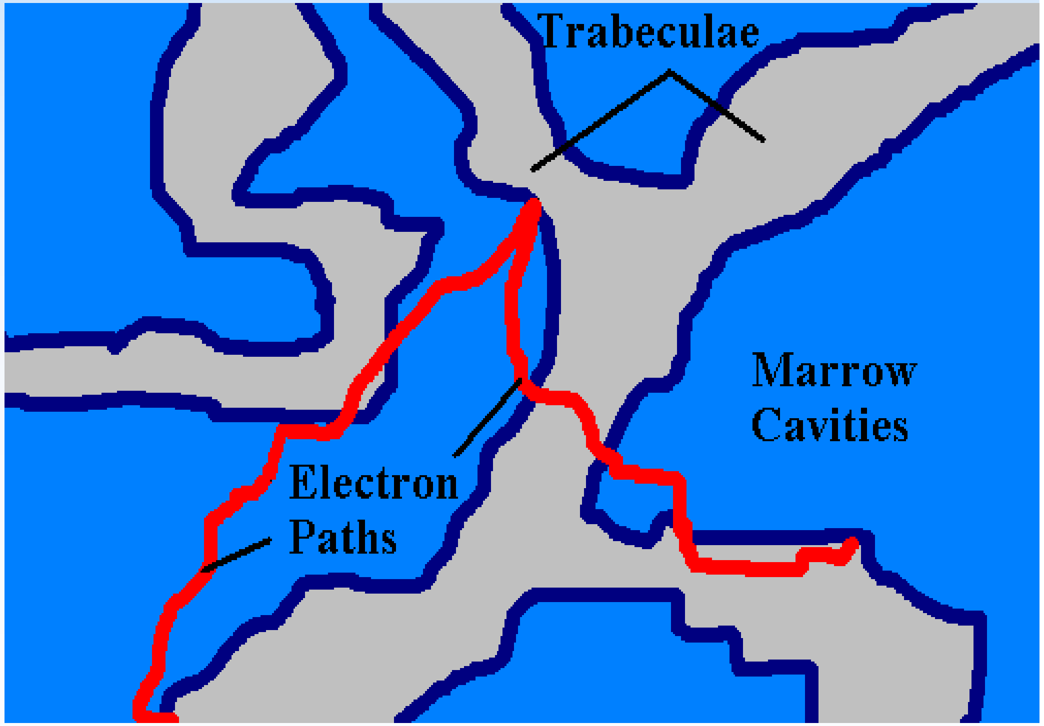
Bone Marrow

- Active Marrow (Red)
  - Home of the blood forming stem cells
  - Radiosensitive tissue
- Inactive Marrow (Yellow)
  - Adipose tissue (fat)
- Osteoprogenitor cells
  - Bone 'endosteum'



Why does the skeleton require special treatment?

- Small sizes of trabecular and marrow cavity regions
- Anisotropic structure of contrasting media
- Structure of bone and marrow composition varies throughout the body



Specific Absorbed Fractions

The radiation-weighted S coefficient [Sv (Bq-s)$^{-1}$] for a radionuclide is calculated as:

$$S_w(r_T \leftarrow r_S) = \sum_R w_R \sum_i E_{R,i} Y_{R,i} \boxed{\Phi\left(r_T \leftarrow r_S, E_{R,i}\right)}$$

$E_{R,i}$ is the energy of the i^{th} radiation of type R emitted in nuclear transformations of the radionuclide;

$Y_{R,i}$ is the yield of the i^{th} radiation of type R per nuclear transformation, [(Bq s)$^{-1}$];

w_R is the radiation weighting factor for radiation type R; and

$\Phi\left(r_T \leftarrow r_S, E_{R,i}\right)$ is the SAF, defined as the fraction of energy $E_{R,i}$ of radiation type R emitted within the source tissue r_S that is absorbed per mass in the target tissue r_T (kg^{-1}).

$$\Phi\left(r_T \leftarrow r_S, E_{R,i}\right) = \frac{\varphi\left(r_T \leftarrow r_S, E_{R,i}\right)}{m_T}$$

Skeletal Target Regions

- Osteoprogenitors – dose is averaged over the first 50 μm of soft tissue adjacent to the bone surface.
  - Also called bone endosteum or shallow marrow

- Red marrow or Active marrow

Skeletal Source Regions

- Red (active) marrow
- Yellow (inactive) marrow

- Trabecular bone
  - Surface
  - Volume
- Cortical bone
  - Surface
  - Volume

Applications of skeletal dosimetry

- Radiations externally incident on the body
  - Photons (secondary electrons)
  - Neutrons (recoiling protons)

- Radiations emitted from within the skeleton
  - Electrons
  - Alpha particles

Historical Approaches

- Electrons
  - University of Leeds - *basis for ICRP 30 decisions*
    - FW Spiers et al (1968 – 1976)
  - Eckerman (1985), Eckerman & Stabin (2000)
  - Bolch et al (1996 – present)

- Alphas
  - Thorne 1976, 1977 - *basis for ICRP 30 decisions*
  - Watchman et al 2005
  - Hunt et al 2007

Latest skeletal data being adopted by ICRP

- Replace the ICRP 30 non-energy dependent assumptions with energy dependent data
- Photon dose response functions
  - Johnson et al (2011)
  - Hough et al (2011)
- Neutron dose response functions
  - Bahadori et al (2011)
  - Jokisch et al (2011)
- Electron specific absorbed fractions
  - Hough et al (2011)
- Alpha specific absorbed fractions
  - Jokisch et al (in preparation)

Two Methods Used

Pathlength-based transport

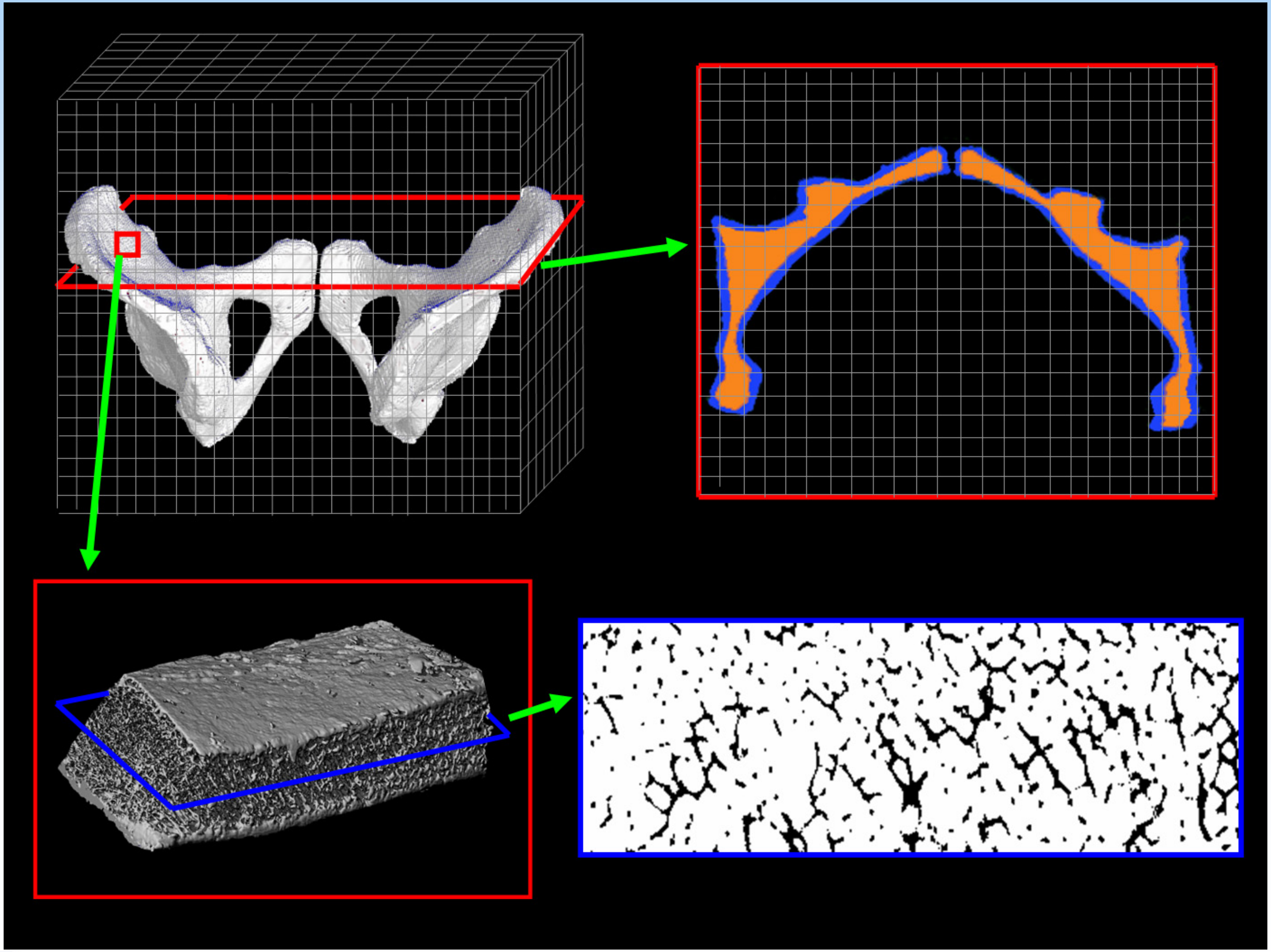
- Measure distributions of straight-line pathlengths across bone and marrow segments of micro-CT images of trabecular bone
- Sample from the distributions and couple to CSDA range/energy data

Paired-image radiation transport

- Use two images:
  - micro-CT of trabecular core
  - CT of entire skeletal site to capture macroscopic structure
- Perform 3D radiation transport using EGSnrc

In both methods, additional techniques are required to define the endosteum target and apportion the marrow cavity into red and yellow constituents.

Model of the Pelvis



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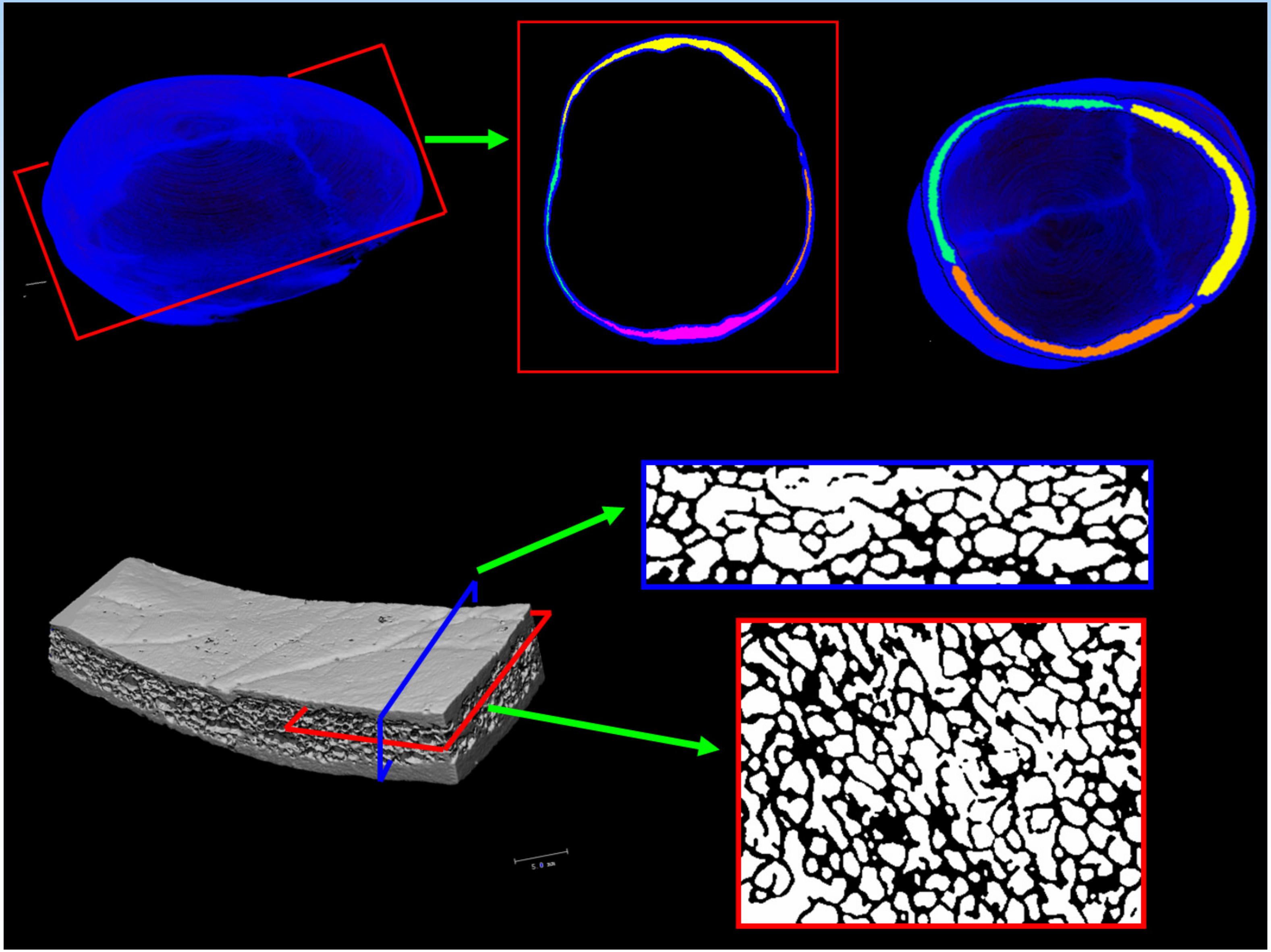
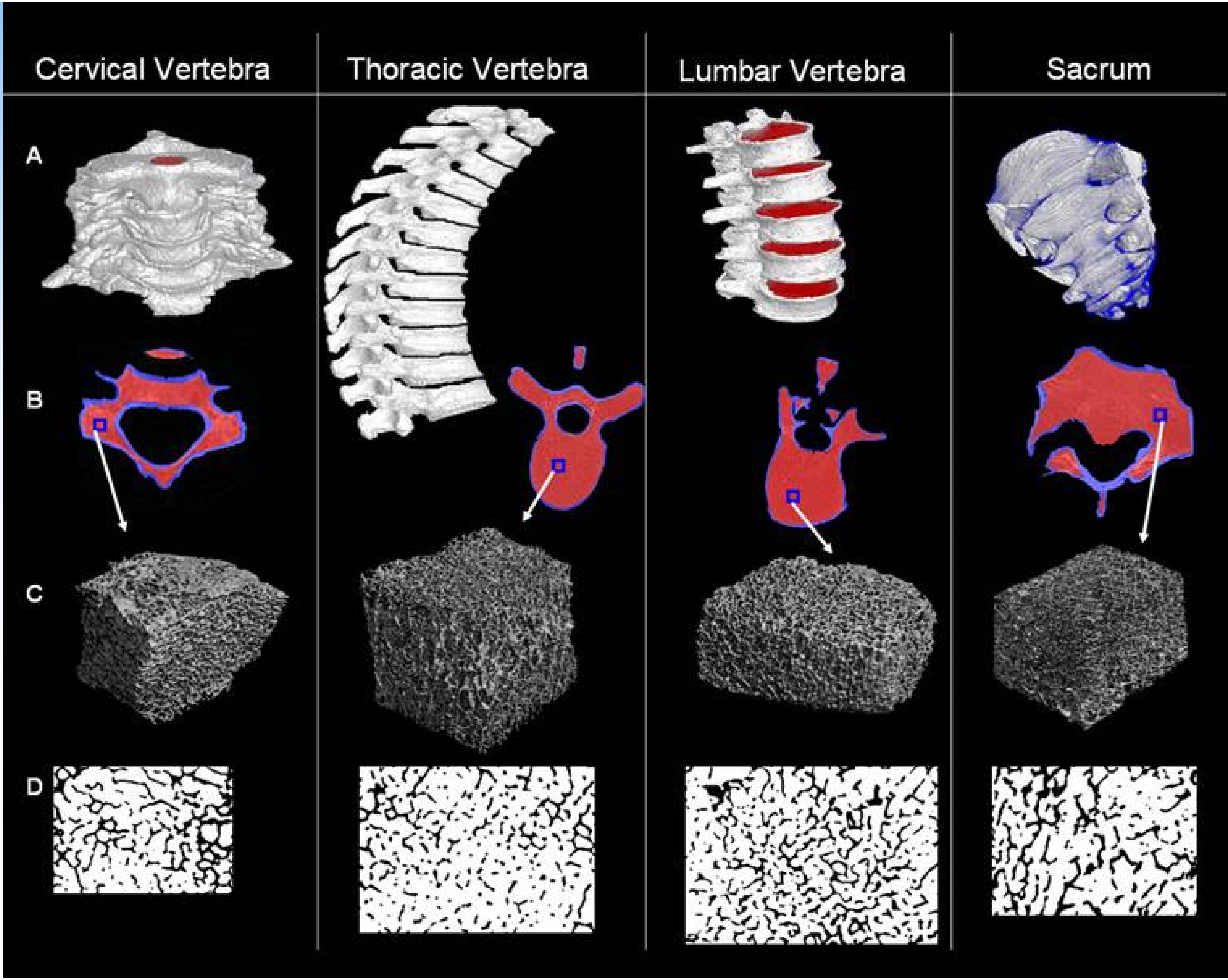
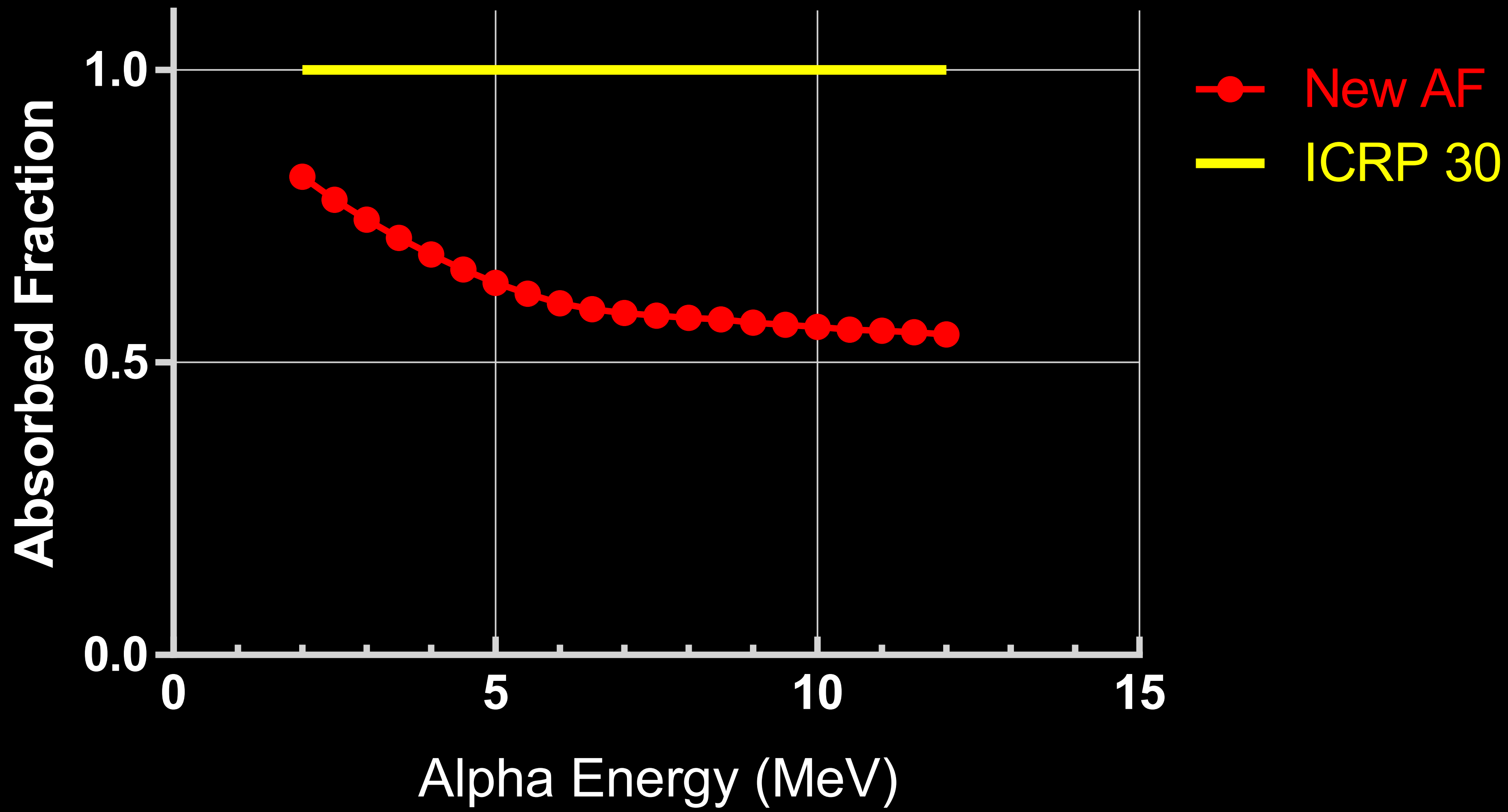
Model of the Cranium



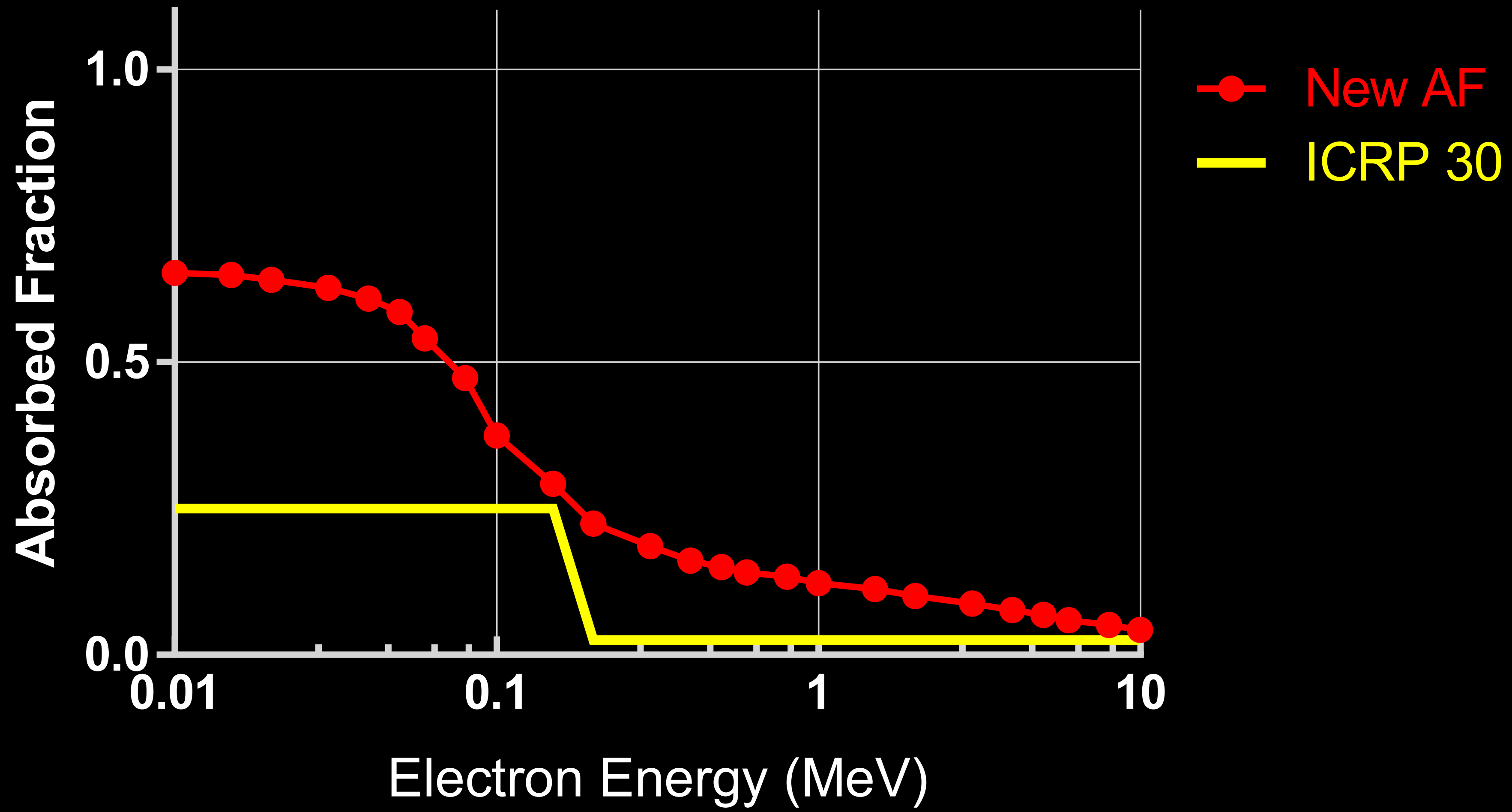


Cervical Vertebra
Thoracic Vertebra
Lumbar Vertebra
Sacrum
A
B
C
D

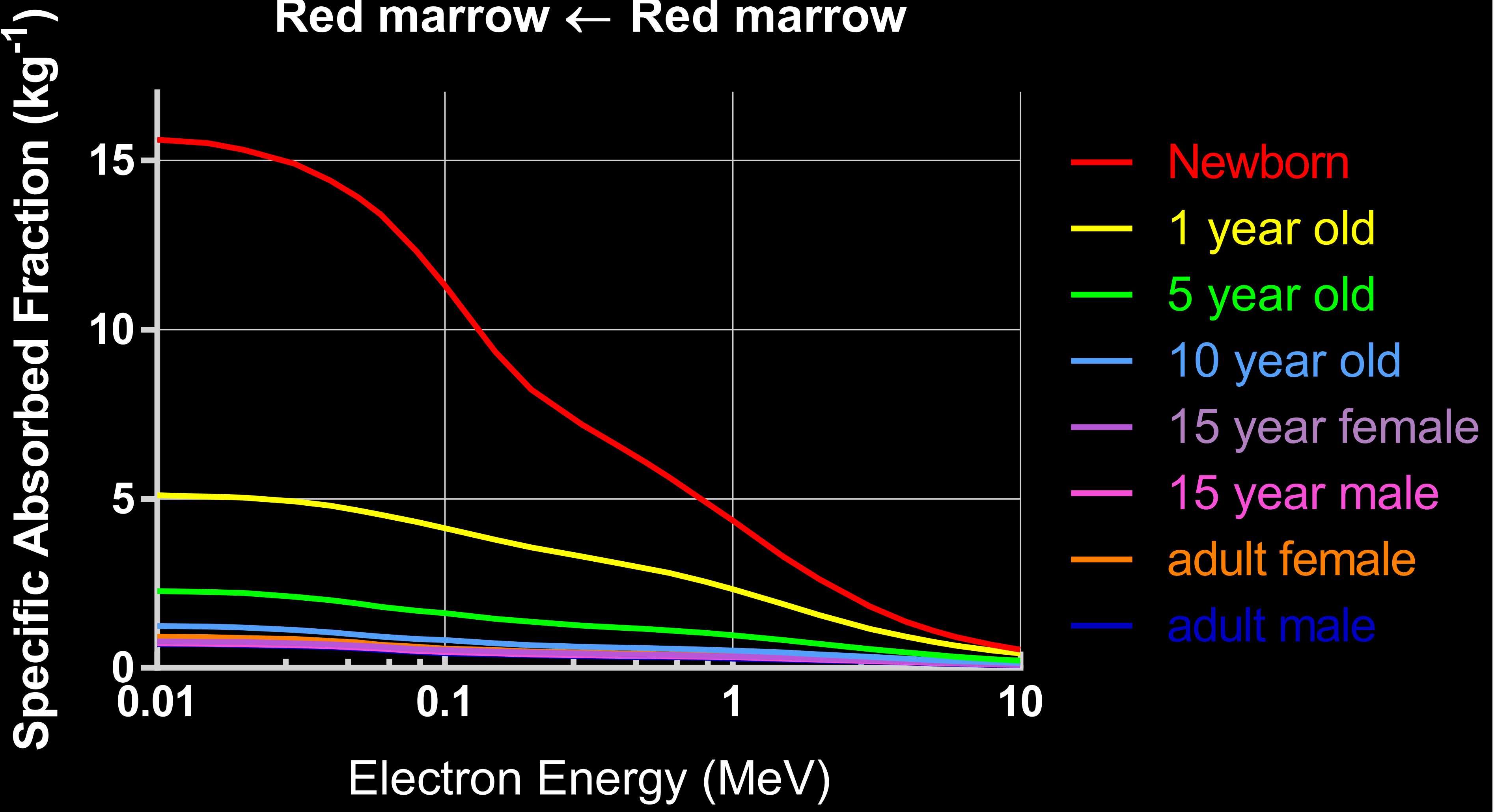
Alpha particle Skeletal-Averaged AF
Adult Male
R-marrow ← R-marrow



Electron Skeletal-Averaged AF
Adult Female
Endosteum ← T-bone-surface



Electron Skeletal-Averaged SAF
Red marrow ← Red marrow



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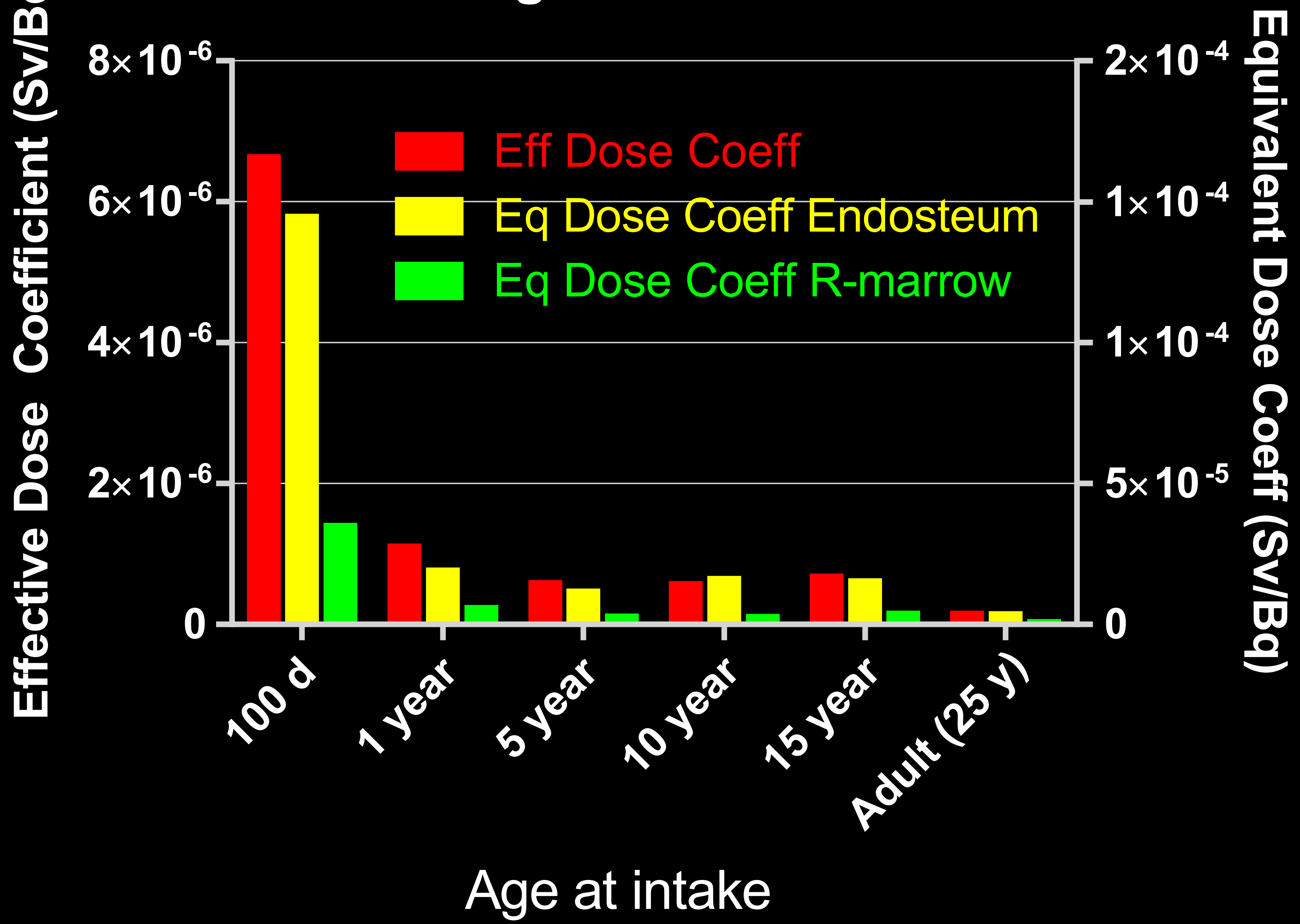
Ra-226 Ingestion Dose Coeffs



Conclusions

- The ICRP is implementing new specific absorbed fraction data for the skeleton
- New considerations include:
  - Marrow cellularity impact on the AF as well as the target mass
  - Energy dependent values for electrons and alphas
  - Skeletal structural data expanded and is now based on a full set of samples from cadavers at each age

Thank you for your attention.

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