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Quantitative Digital Autoradiography of Radionuclides in Human Tissues

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U.S. Transuranium and Uranium Registries

A unique resource for actinide dosimetry research
from whole-body retention to radionuclide microdistribution

USTUR

Established in 1968

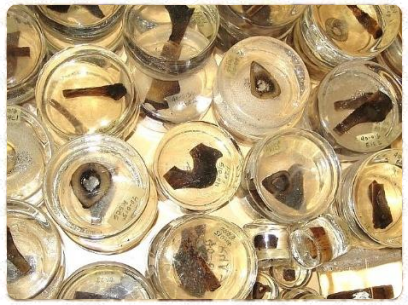
Occupationally exposed workers with documented actinide deposition

384	Enrolled Registrants
52	Whole-Body Donors
332	Partial-Body Donors

Voluntary, posthumous whole-body or partial-body tissue donors.

NHRTR

National Human Radiobiology Tissue Repository





- Archived whole-body and organ-specific tissue specimens from USTUR donors
- Preserved under controlled conditions
- Available for analysis and re-analysis as methods and technologies advance

Tissue Archive Includes

Bone · Liver · Lung · Kidney · … Many more

Research Across Scales

Systemic Retention
Whole-body burden and biokinetics

↓

Organ Retention
Organ-level burden and uptake

↓

Regional Distribution
Within-organ heterogeneity and localization

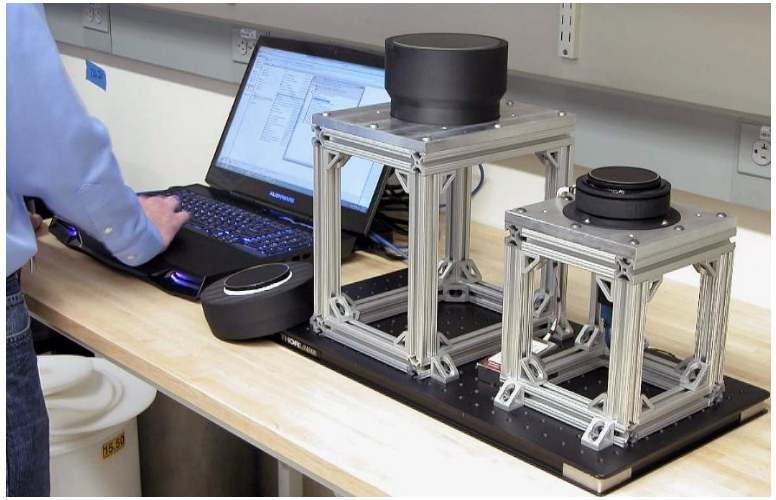
↓



Microdistribution
Cellular and subcellular localization

Advanced Digital Autoradiography

iQID: ionizing-radiation quantum imaging detector



Ionizing-radiation imaging:

- Gamma/X-rays
- Alpha particles
- Beta particles
- Neutrons
- Fission fragments



iQID Imaging Capabilities

Single-event imaging and particle discrimination across radiation types

Alpha particles
From ^{252}Cf and other alpha emitters

Fission fragments
From ^{252}Cf spontaneous fission

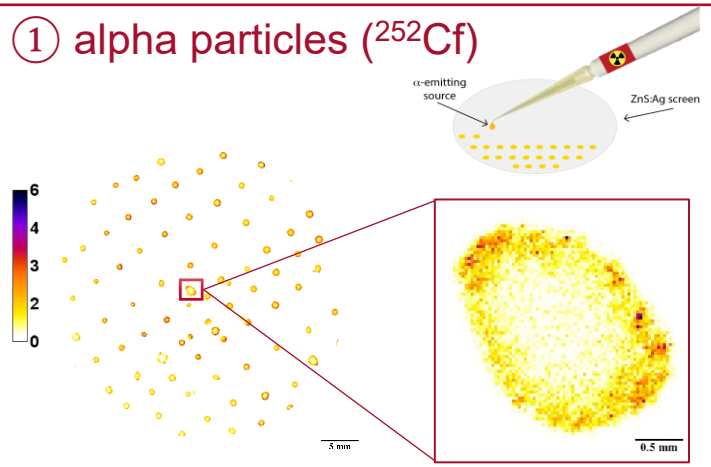
Beta particles
From ^{90}Y and ^{177}Lu beta emitters

Particle discrimination
Event-by-event classification of particle types

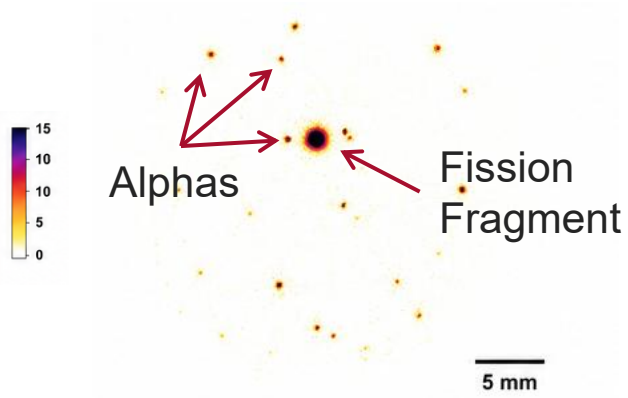
KEY TAKEAWAY

- Imaging of individual events
- Particle discrimination
- Foundation for quantitative alpha imaging

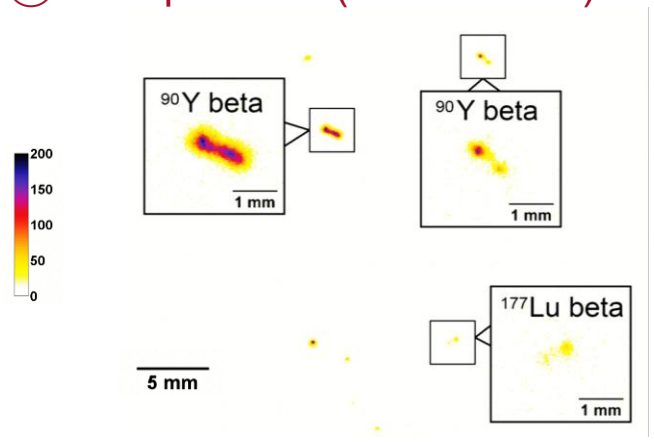
① alpha particles (^{252}Cf)



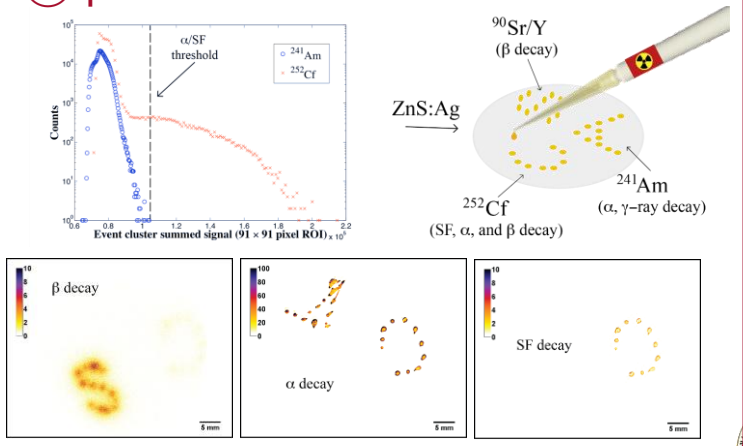
② fission fragments (^{252}Cf)



③ beta particles (^{77}Lu and ^{90}Y)



④ particle discrimination

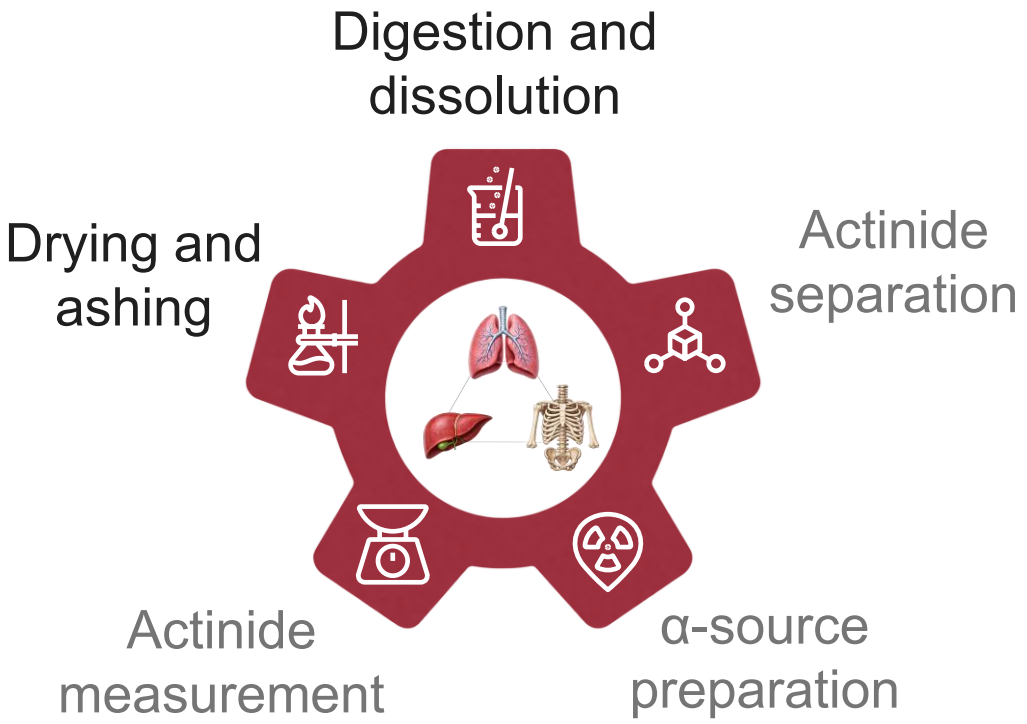


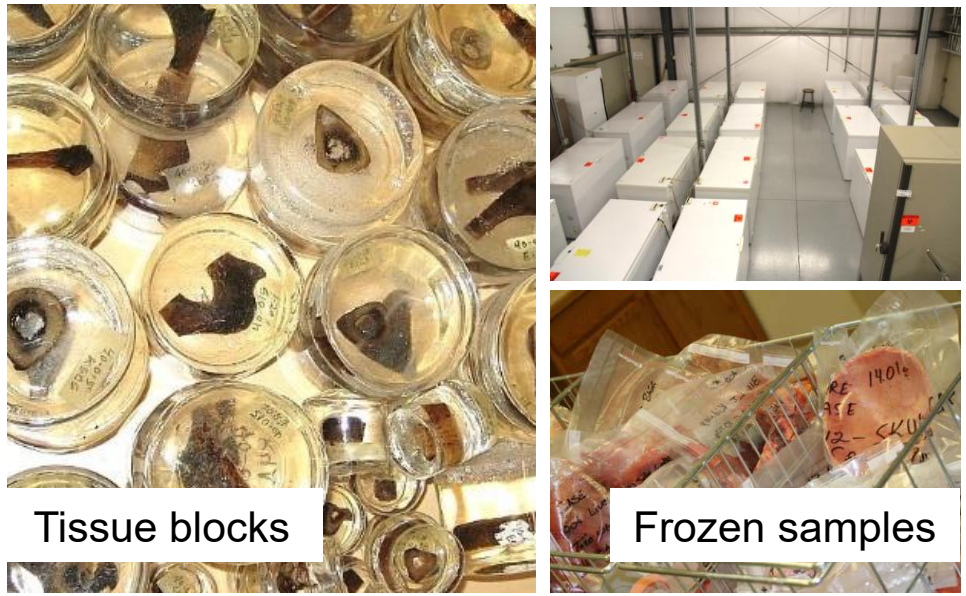
Miller BW, et al. Nucl Instrum Methods Phys Res A. 767 (2014): 146–152

Non-Destructive Analysis

Preserving the scientific value of archived tissues

- Radiochemical analysis provides accurate radionuclide quantification
- Standard analyses consume specimens
- Archived NHRTR specimens support future research
- Non-destructive analytical methods can extend their scientific value



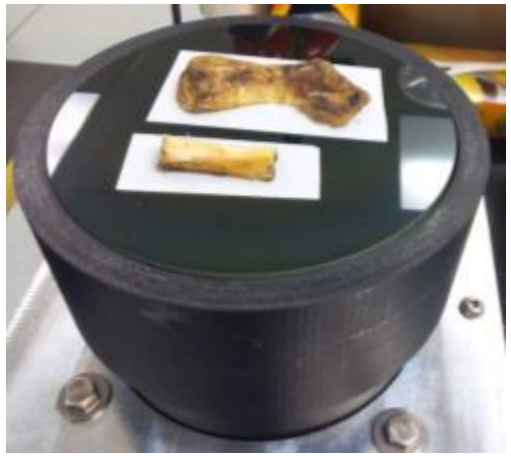


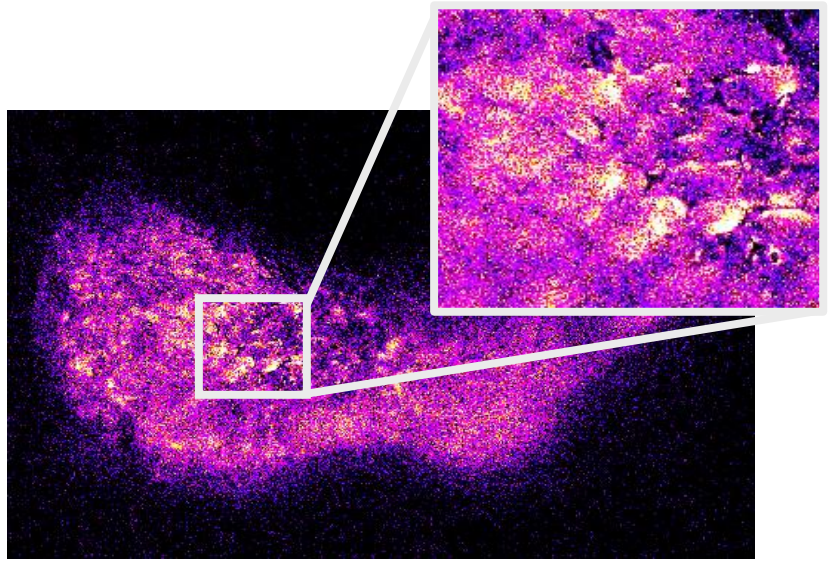
NHRTR sample collection

Spatial Distribution

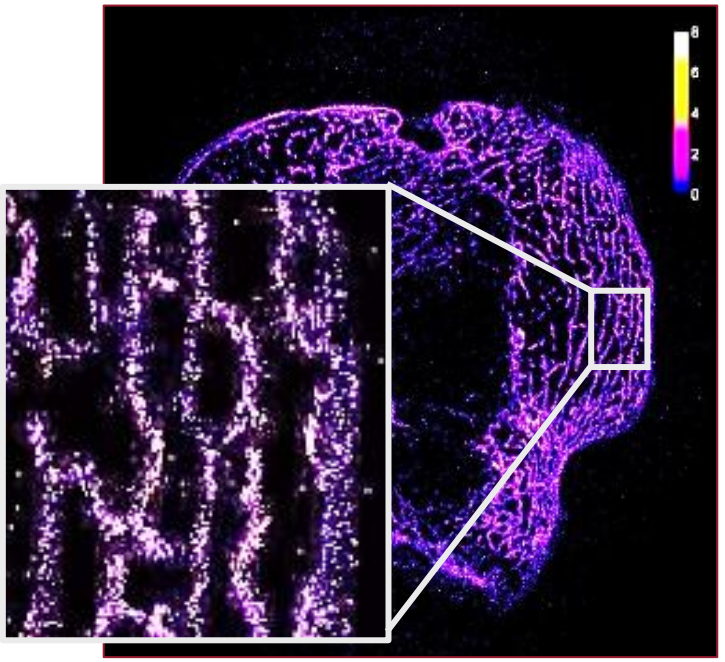
Feasibility studies at USTUR

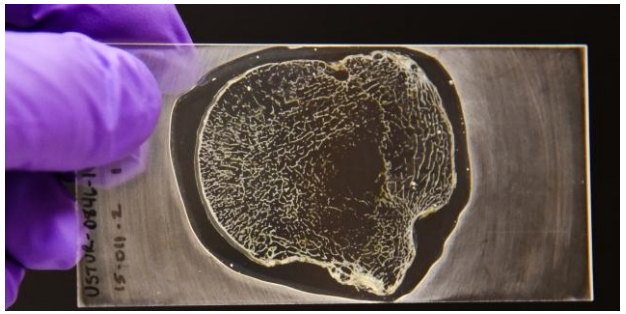
- Microdosimetry and radionuclide microdistribution studies
- Radiopharmaceutical and targeted alpha therapy research
- Source characterization and quality assurance
- Imaging of tissues with minimal sample preparation





Direct imaging with minimal sample preparation





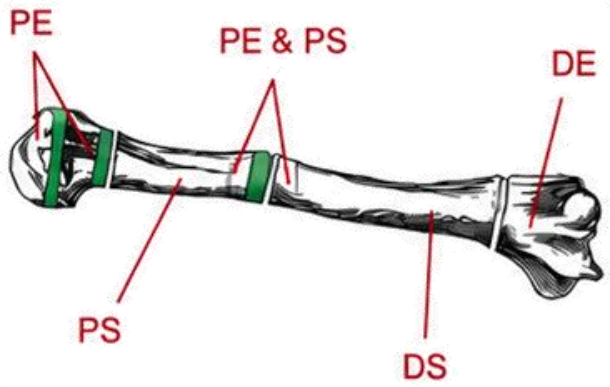
Thin sections enable higher spatial resolution

Tabatadze G, et al. Mapping ^{241}Am spatial distribution within anatomical bone structures using digital autoradiography. Health Physics (2019)

Quantitative Analysis

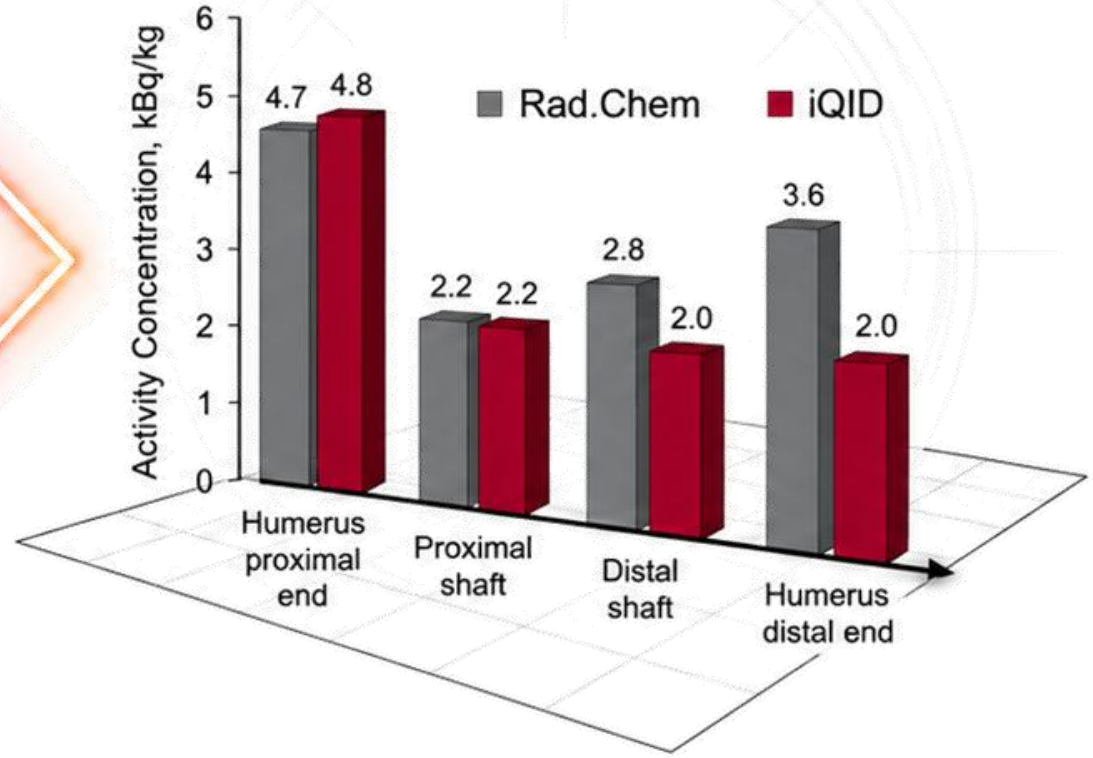
Surface activity and activity concentration

Surface activity mapping
(Bq mm^{-2})



iQID Digital Autoradiography

Activity concentration estimation
(Bq g^{-1})



Bone	Surface activity, mBq mm^{-2}	
	Average	Max
Humerus		
Proximal end	0.198	0.251
Proximal shaft	0.074	0.031

Geometric Efficiency Challenge

From counts to activity concentration

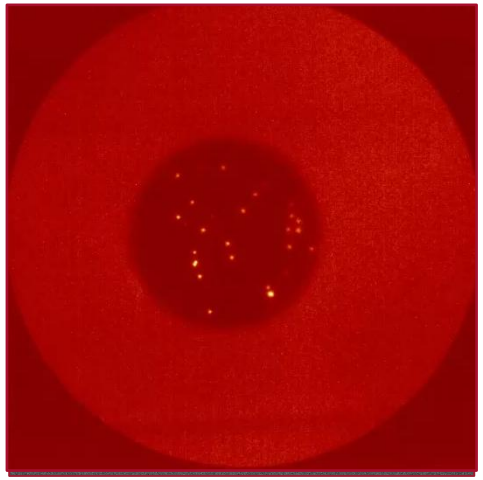
How can geometric efficiency be accurately determined for heterogeneous tissue samples?

$$\text{Activity} = \frac{R_N}{\varepsilon_i \varepsilon_g}$$

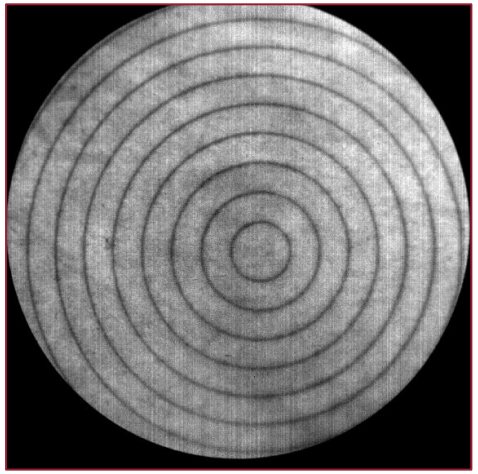
- **Detector diameter:** 40 mm
- **Source:** ^{242}Pu, ^{239}Pu, ^{241}Am
- **Activity:** 4.3 Bq
- **Intrinsic efficiency:** 92%
- **Spatial resolution:** 19.5×19.5 µm



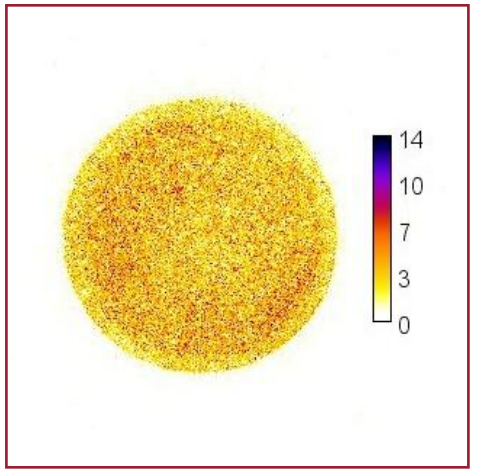
Calibration setup



Shadow image



Scale setup



Final image

Radium Dial Painter Bones

Cortical and trabecular bone samples for quantitative ^{226}Ra analysis

Case 03-666

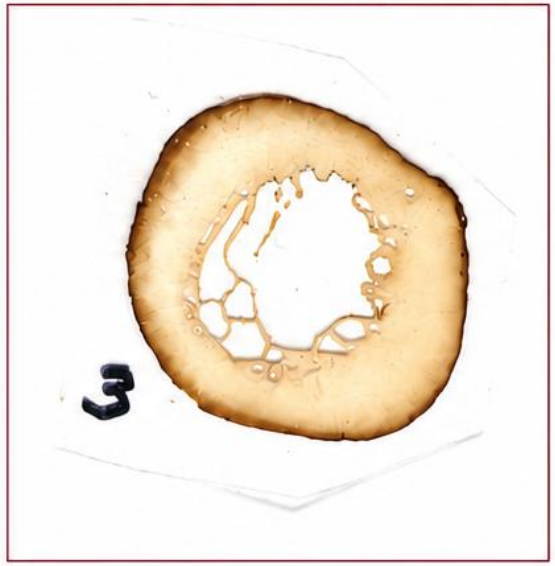
- **Duration of employment:** 6.7 y
- **Estimated intake of ^{226}Ra:** 58.9 MBq
- **Estimated intake of ^{228}Ra:** 8.6 MBq
- **Age at the time of death:** 24 y

These bone sections are archived in the National Human Radiobiology Tissue Repository (NHRTR) at USTUR.

Selected Bone Samples

K5C1: femur (L) middle shaft (MS)

Q8B1: 7th thoracic (T7) vertebral body



K5C1



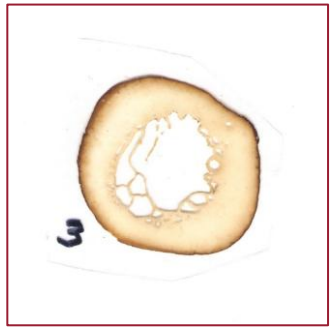
Q8B1

Image Acquisition

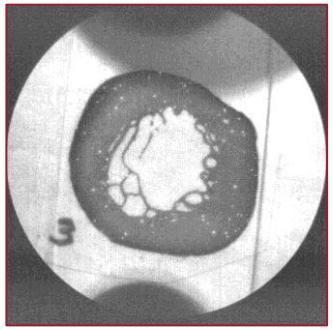
Workflow for quantitative activity mapping

K5C1 Femur (L) middle shaft (MS)

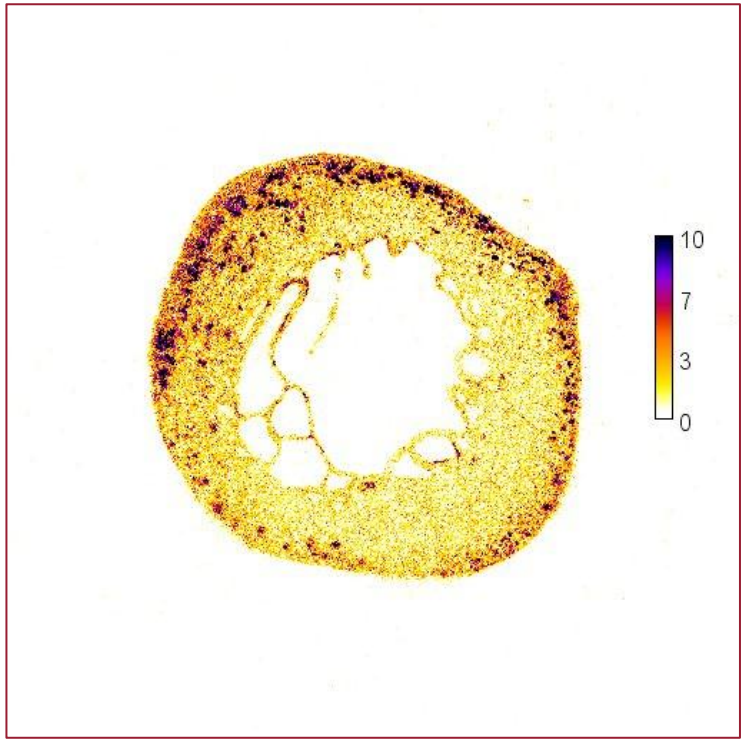
Digital Scan



Shadow Image



iQID Image



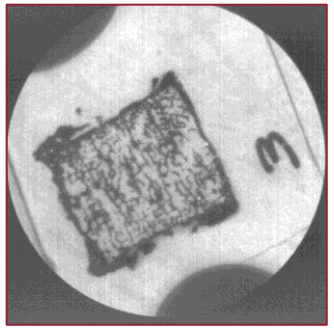
Imaging time: 15 h

Q8B1 7th thoracic vertebral body

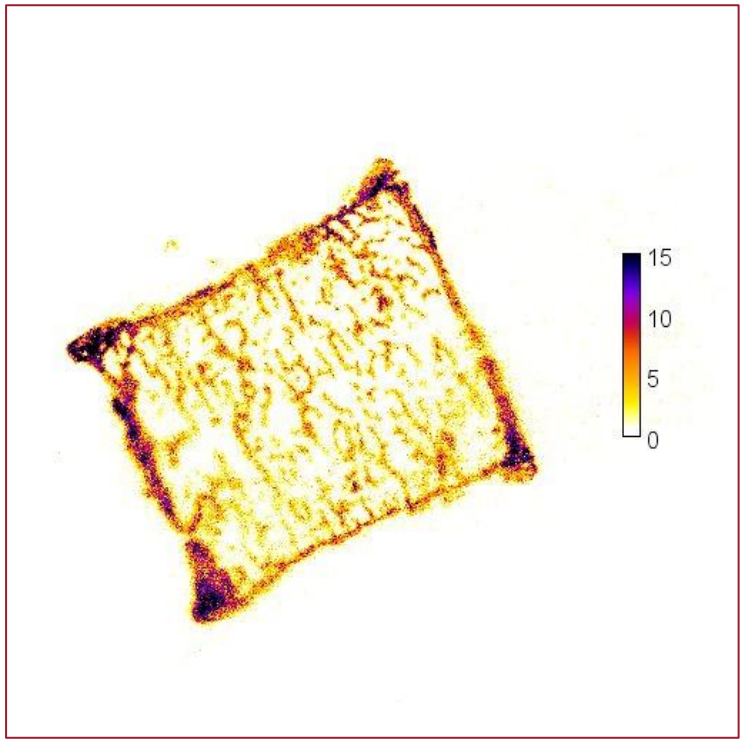
Digital Scan



Shadow Image



iQID Image



Imaging time: 17 h

Image-Based Source Geometry Construction

Image segmentation and ROI-specific count extraction

1 **Digital Scan** — *Anatomical reference*

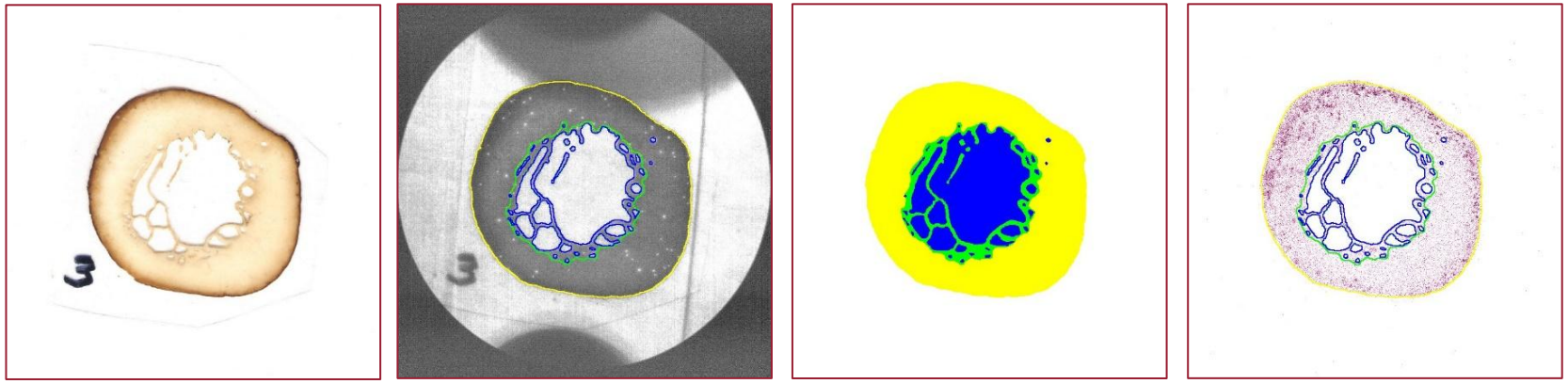
2 **Coregistration** — *Shadow image aligned to anatomy*

3 **ROI Definition** — *Specimen-specific source geometry*

4 **Count Extraction** — *Region-specific counts*

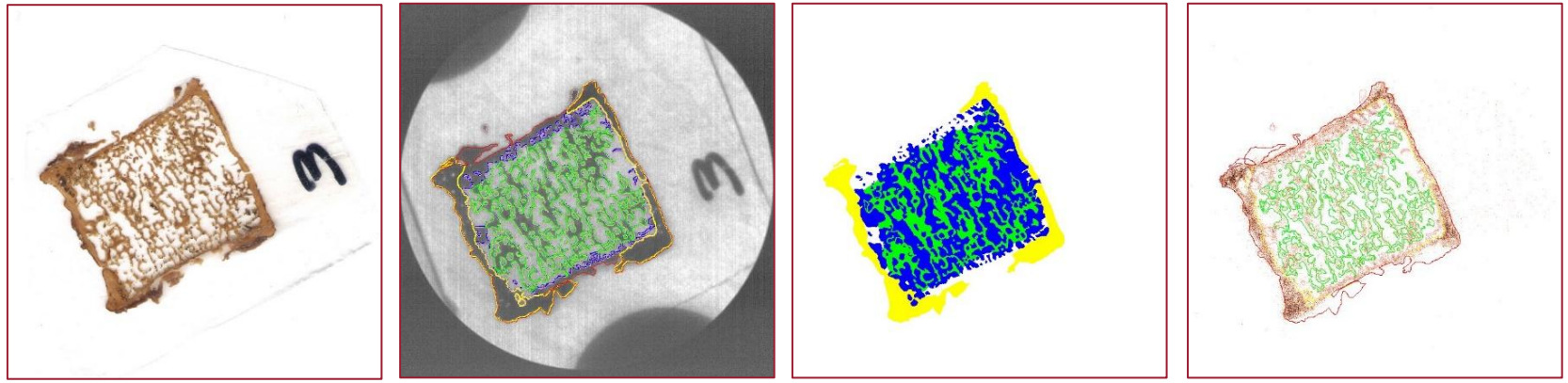
K5C1

Femur (L) middle shaft (MS)



Q8B1

7th thoracic vertebral body



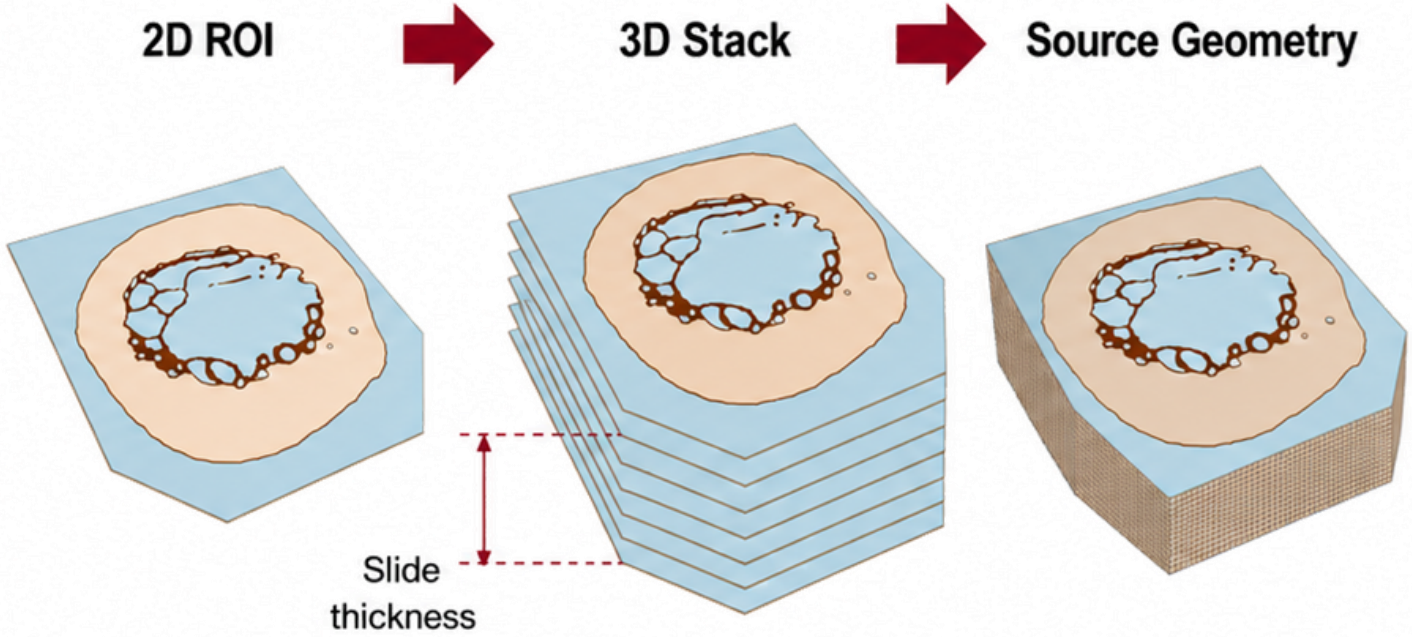
- Cortical bone
- Trabecular bone
- Medullary cavity

Sample Geometry Modeling

From anatomical ROIs to sample-specific source geometries

Geometry Construction

- Anatomical regions segmented from digital scans
- ROIs exported from ImageJ
- ROIs stacked using measured slide thickness
- Specimen-specific 3D source geometries generated in Python
- Bone volume and mass calculated from geometry and tissue density



K5C1

Bone volume:
0.047 cm³

Bone mass:
0.089 g

Q8B1

Bone volume:
0.030 cm³

Bone mass:
0.057 g

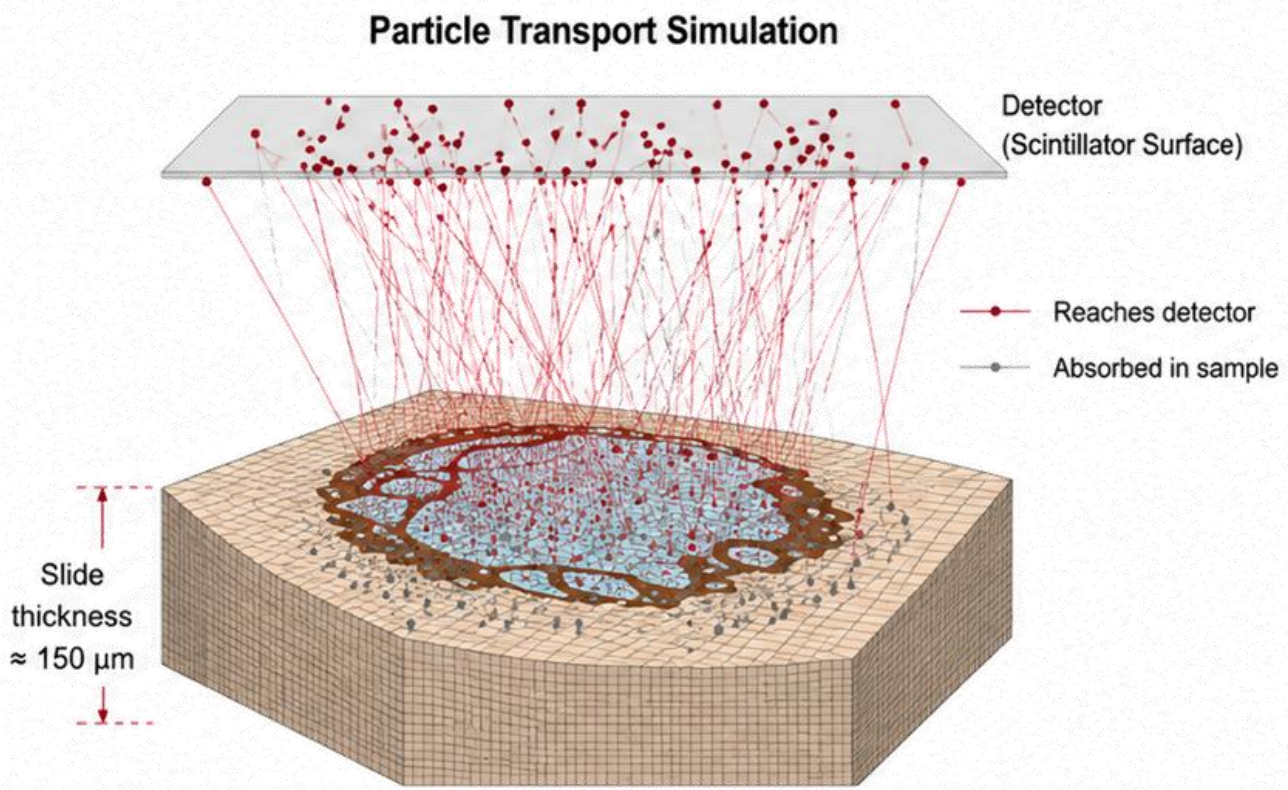
Each specimen required a unique 3D source geometry to accurately determine geometric efficiency (ε_g).

Geometric Efficiency Calculation

Monte Carlo alpha-particle transport simulation

Simulation Inputs

- 3D source geometry from segmented ROIs
- Slide thickness ≈ 150 µm
- Bone density = 1.92 g cm^{-3}
- Intrinsic efficiency = 92%
- Activity distribution derived from iQID image (non-uniform)
- Isotropic alpha emission



Geometric Efficiency (ε_g)

$$\varepsilon_g = \frac{N_{detected}}{N_{emitted}}$$

Geometric efficiency is the fraction of emitted alpha particles that reach the detector surface and are detected.

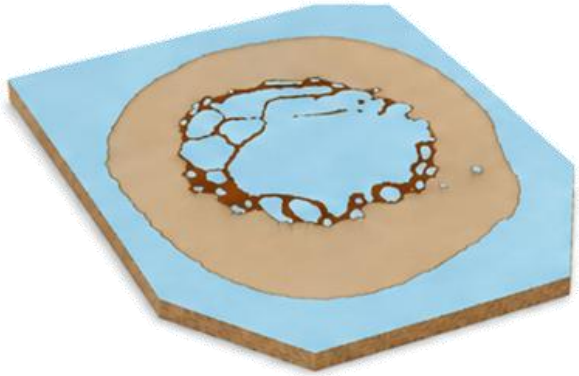
Geometric efficiency is determined by the specimen's geometry and activity distribution.

Results: Geometric Efficiency

Monte Carlo-derived geometric efficiency

K5C1 – Femur Shaft

Specimen Geometry



Geometric Efficiency (ε_g)

3.35%

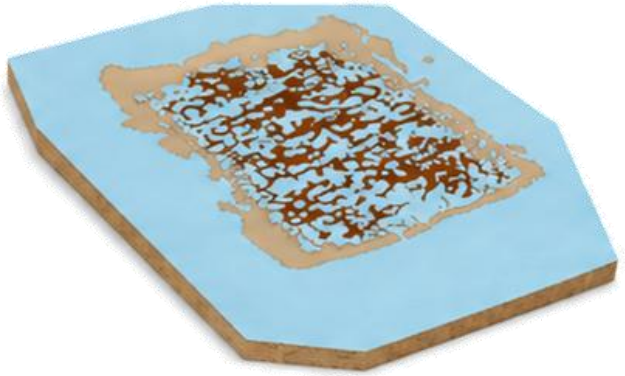
(± 0.02%)

Bone mass
0.089 g

Slide thickness
≈ 150 µm

Q8B1 – Vertebral Body

Specimen Geometry



Geometric Efficiency (ε_g)

3.36%

(± 0.02%)

Bone mass
0.057 g

Slide thickness
≈ 150 µm

The femur shaft and vertebral body specimens yielded nearly identical geometric efficiencies (~3.35%).

Simulation Details

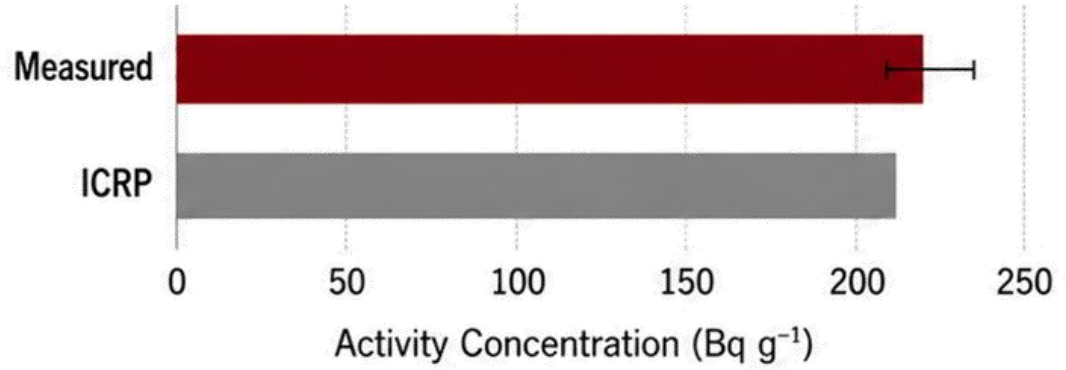
- Ra-226 α spectrum sampled by yield (4.784 MeV: 94.4%, 4.601 MeV: 5.6%)
- Non-uniform source distribution from iQID image
- 10^8 particle histories simulated per specimen
- Intrinsic detector efficiency: 92%
- Detector positioned in contact with slide surface

Geometric efficiency (ε_g) = fraction of emitted alpha particles reaching the detector surface

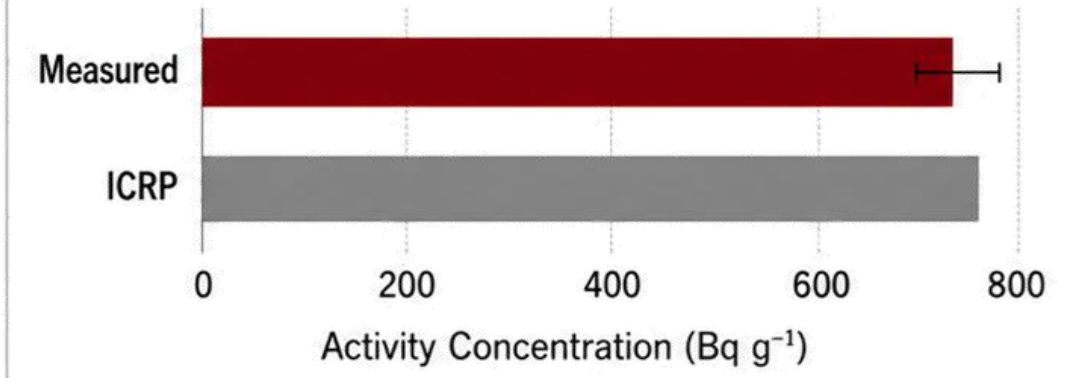
Results: Activity Concentration

Geometry-corrected iQID measurements versus ICRP biokinetic model predictions

Femur Shaft	
Measured (iQID):	219 ± 1 Bq g^{-1}
ICRP Model:	213 Bq g^{-1}
Difference:	+2.8%



Vertebral Body	
Measured (iQID):	714 ± 2 Bq g^{-1}
ICRP Model:	731 Bq g^{-1}
Difference:	-2.3%



Geometry-corrected iQID activity concentrations agreed with ICRP model predictions within 3% at both skeletal sites.

Key Findings & Future Work

This study demonstrates iQID-based quantitative analysis of radionuclides in human bone

- Generated specimen-specific 3D source geometries.
- Applied Monte Carlo-derived geometric efficiency corrections.
- Geometry-corrected activity concentrations agreed with ICRP predictions within 3%.
- iQID enables quantitative activity estimation and spatial mapping.
- Non-destructive methodology preserves valuable archived tissues.

Future Work

- Expand to additional donors and skeletal sites.
- Quantify activity in cortical and trabecular bone.
- Extend to other alpha emitters and dosimetry applications.

Digital autoradiography combined with Monte Carlo modeling enables non-destructive, quantitative, anatomically resolved measurements of alpha-emitting radionuclides in human bone.

Thank you!

