SPECT Imaging of ^{155}Tb and Evaluation of the Impact of ^{156}Tb Contamination Using GATE 10

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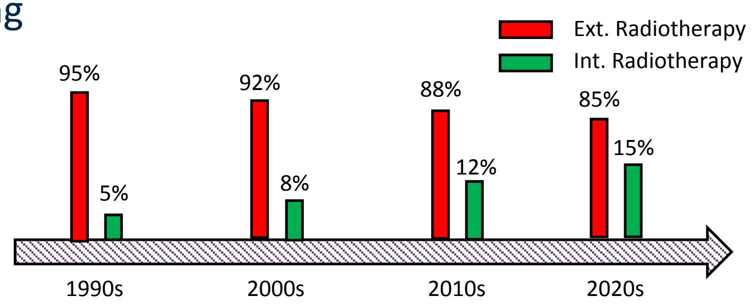
- Radiotherapy uses ionizing radiation to damage tumour cells while sparing normal tissues as much as possible.
  - External radiotherapy.
  - Internal radiotherapy.

➢ External radiotherapy remains the mainstream approach; internal radiotherapy is increasingly important for personalized treatment.

Why VIR : High precision, personalized treatment, targeting diffused tumors.

- Deliver maximum dose to target & minimum dose to surrounding.



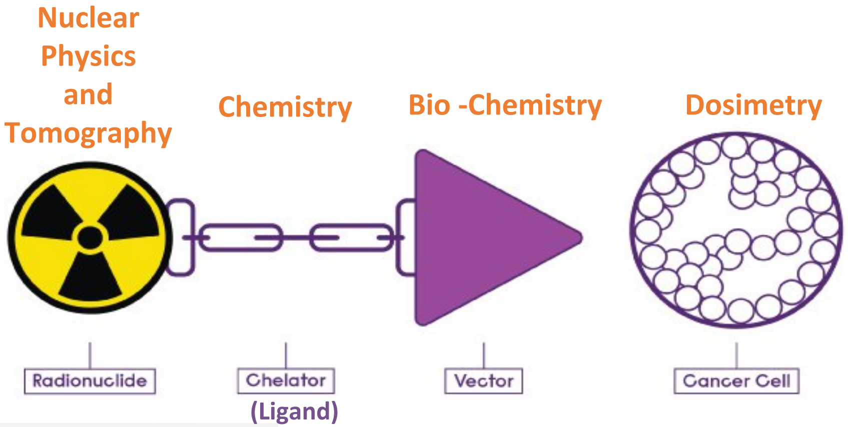
The utilization of internal vs external radiotherapy by patients in Europe and US over time.

DIrectory of RAdiotherapy Centres (DIRAC).

- Important to follow the bio distribution by SPECT or PET imaging.
- Interest in the theranostic (therapeutic + diagnostic) approach to ensure radionuclide delivery to the target.

➢ Requires development of new VIR radio-pharmaceuticals.

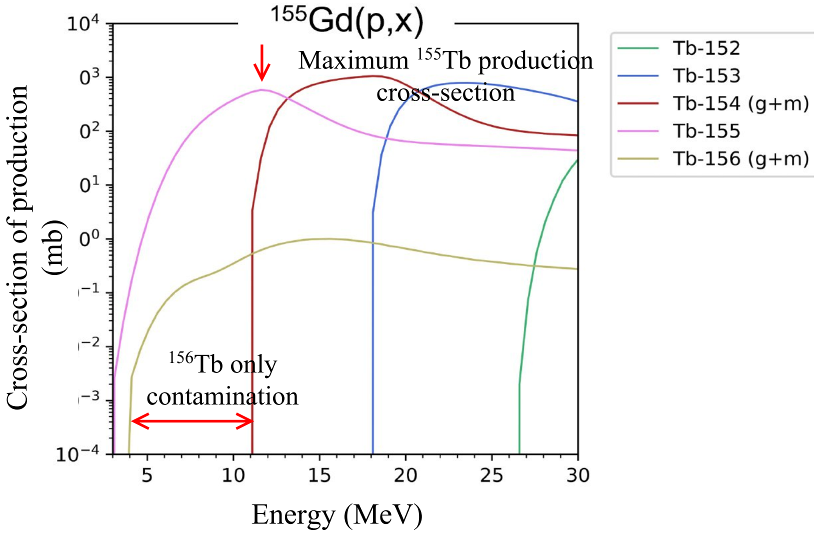
- Some available theranostic pairs: $^{64}Cu/^{67}Cu$, $^{44}Sc/^{47}Sc$, $^{86}Y/^{90}Y$.



- Terbium (Tb): promising theranostic element with four isotopes.

➡ Interest in ^{155}Tb-^{161}Tb potential theranostic couple (~similar $t_{\frac{1}{2}}$).

- Standard cyclotron production of ^{155}Tb out of ^{155nat}Gd induces co-production of ^{156}Tb ($t_{\frac{1}{2}}$ = 5.35 d) emitting high energy γ-rays:
  - ^{155}Tb SPECT images pollution.
  - Dosimeteric concerns.



Bouteculet M. De la cible de ^{155}Gd au ^{155}Tb, un radionucléide pour la santé. PhD thesis; 2025.

Isotope	Diagnosis	Therapy	1/2 life
^{149}Tb	? β+ 14.2%, γ	✓ (α)	4.12 h
^{152}Tb	✓ (β+)		17.48 h
^{155}Tb	✓ (γ)		5.32 d
^{161}Tb	? Low energy γ	✓ (β-)	6.96 d

γ - rays energy (keV)	
^{155}Tb	^{156}Tb
SPECT { 86.54 (32%) 105.3 (25.1%) 180.1 (7.5%) 262.3 (5.3%)	88 (18%) 199.2 (41%) 356.3 (13.6%) 534.3 (67%) 1065.1 (10.8%) 1154.1 (10.4%) 1222.4 (31%) 1421.7 (12%)

Naskar N, Lahiri S. Theranostic Terbium Radioisotopes: Challenges in Production for Clinical Application. Front Med (Lausanne). 2021 May 31;8:675014.

Objective and Methodology

- Evaluate by simulation the impact of contamination of ^{156}Tb on ^{155}Tb SPECT images in order to determine acceptable contamination limit, in terms of:
  - Quantitative SPECT imaging.
  - Dosimetry.

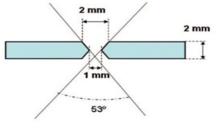
How?

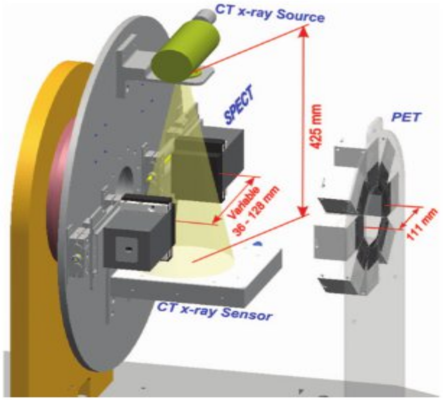
- SPECT imaging Monte Carlo (MC) simulation of ^{155}Tb phantom contaminated with 0-10% ^{156}Tb on two experimentally validated cameras:
  - Low energy camera: ALBIRA (BRUKER).
  - Medium energy camera: THIDOS (homemade high performance camera).
- Doimetry using mouse phantom simulation with experimental bio-kinetic data.

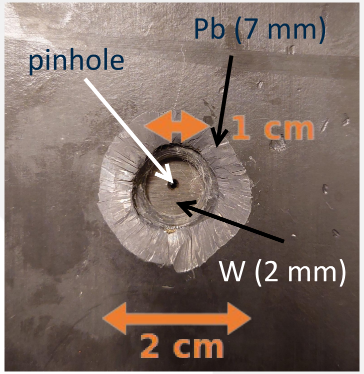
Part 1: SPECT Imaging Study

SPECT Cameras

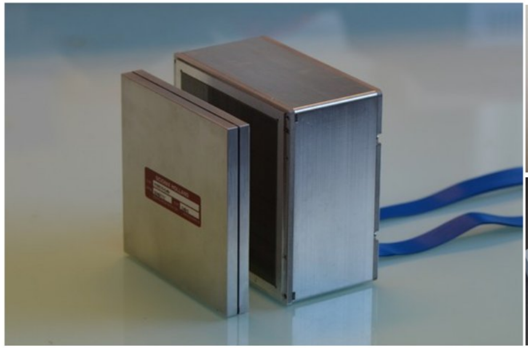
- **ALBIRA**[1] S108 small animal PET/SPECT/CT imaging system, at CHUV, Lausanne .
  - 2 rotating SPECT heads, 30 positions
  - 2 mm diameter tungsten single pinhole collimator.
  - 7 mm thick lead shielding.
  - Optimized for 140 keV (^{99m}Tc).
  - Intrinsic spatial resolution (FWHM) : 1.5 mm.
  - Energy resolution (FWHM): 17% at 140 keV.

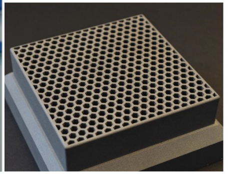






- **THIDOS**[2] is a medium-energy γ-camera developed at IJCLab for dosimetry control during internal radiotherapy.
  - Used as rotating SPECT head with 60 positions.
  - Tungsten parallel-hole collimator (HSR):
  - Optimized for 364 keV (^{131}I).
  - Intrinsic spatial resolution (FWHM) : 1.15 mm.
  - Energy resolution (FWHM): 8% at 356 keV.

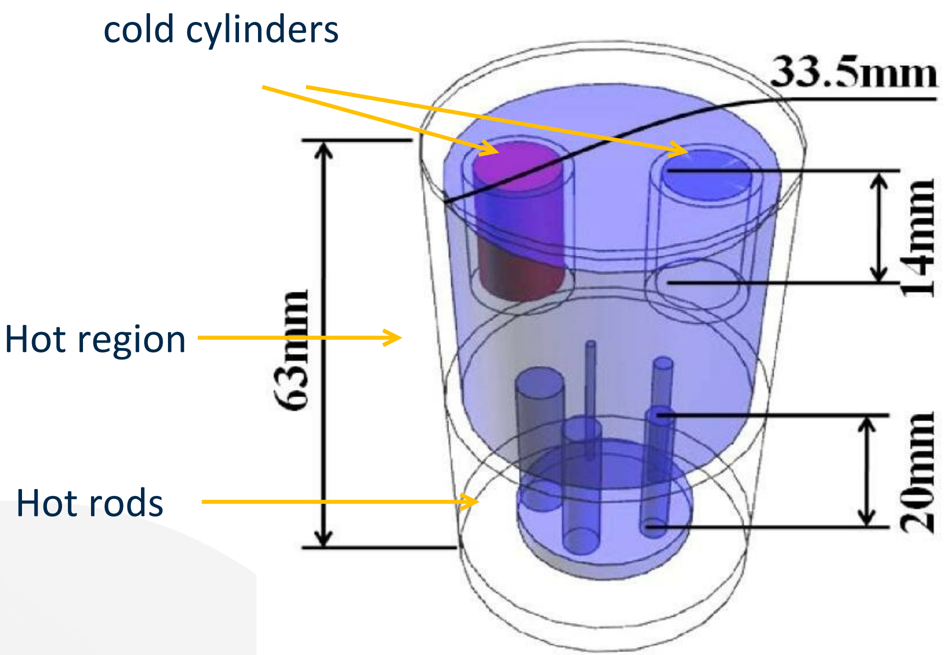




[1] Sánchez et al. Med. Phys, 40, No. 5, May 2013.

[2] Théo Bossis et al, A High-Resolution Portable Gamma-Camera for Estimation of Absorbed Dose in Molecular Radiotherapy.

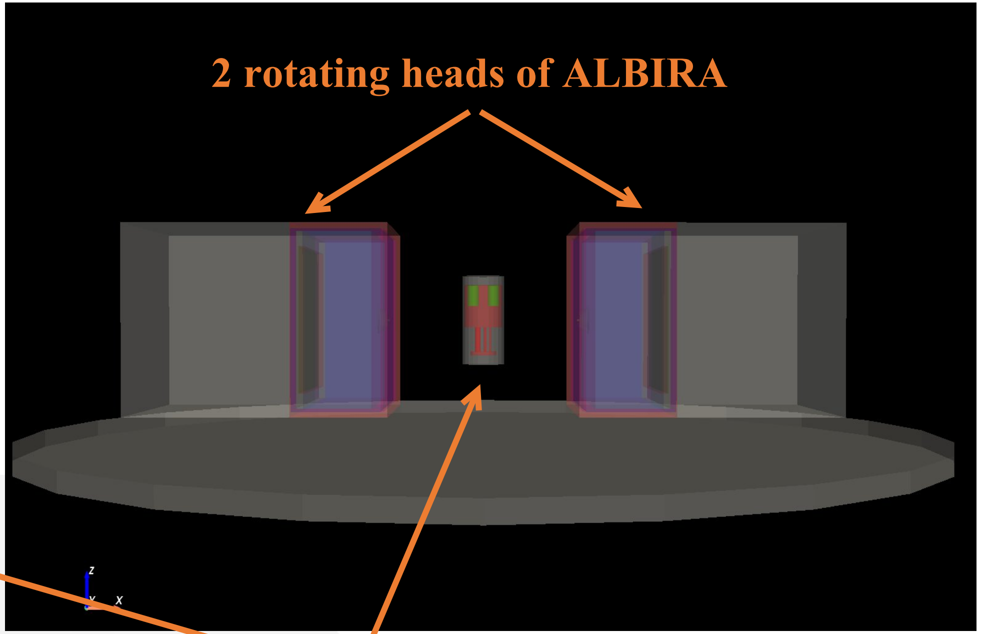
- **Phantom**: NEMA NU 4-2008, a standard small-animal imaging phantom designed for quantitative performance evaluation.[1]
  - Includes rods (1–5 mm) for spatial resolution testing.
  - Cold and uniform regions for contrast, uniformity, and SNR analysis.



[1] NEMA Standards Publication NU 4-2008 Performance Measurements of Small Animal Positron Emission Tomographs National Electrical Manufacturers Association 1300 N. 17th Street, Suite 1752 Rosslyn, VA 22209.

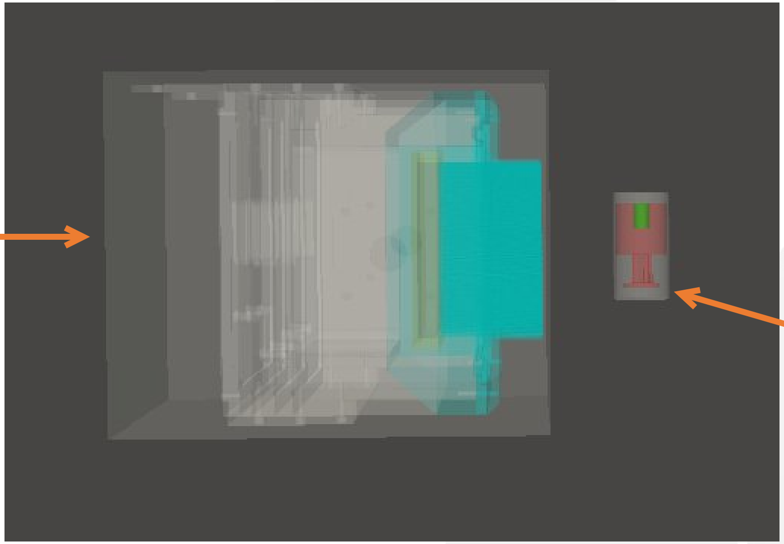
- **Monte Carlo simulation** performed GATE 10 for both imaging and dosimetry.
- With GATE 10: Reproduced cameras parts and movement, phantom and all sources (isotopes and contaminants).

ALBIRA, Geometric volume



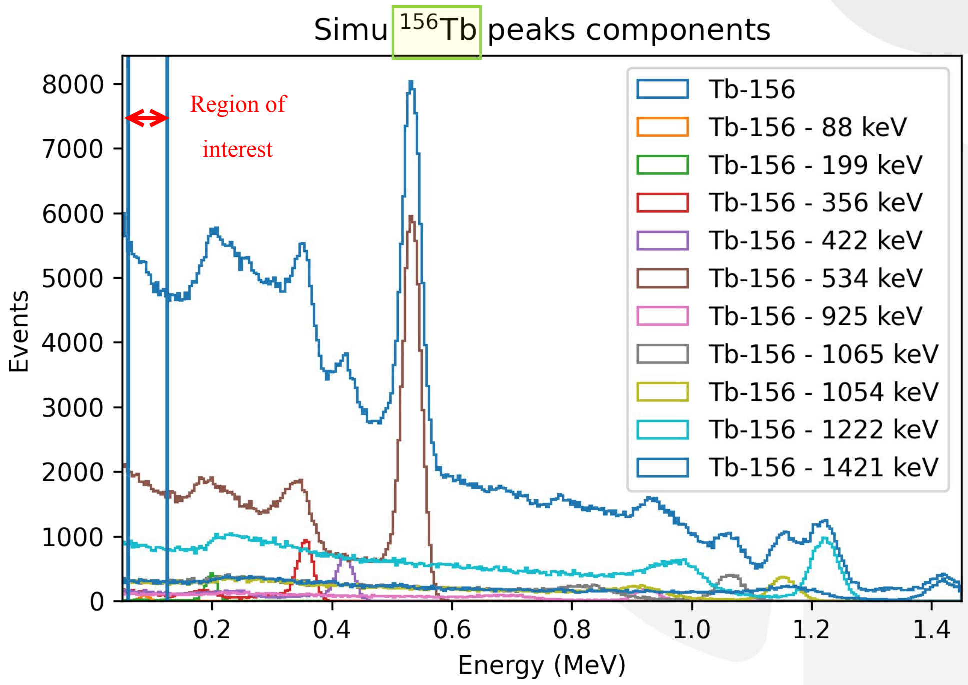
THIDOS, Mechanic volume (stl)

1 rotating head of THIDOS

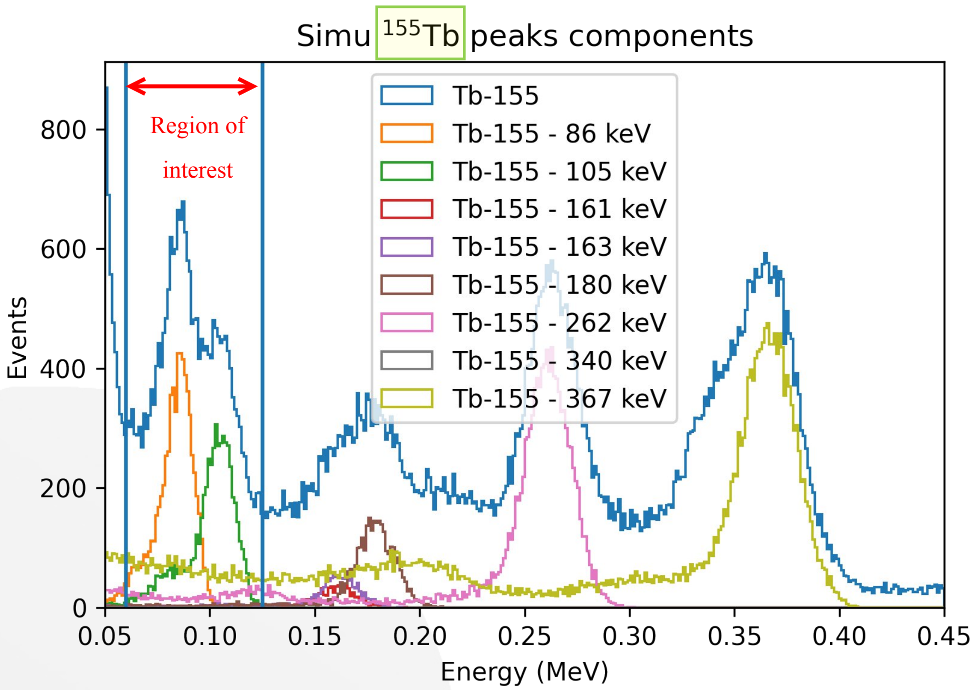


Phantom

- We can dissemble rays contribution for each isotope through simulation.
- ➢ High contribution of 156Tb high energy rays within region of interest (figures for ALBIRA).



Careful! Different Scales



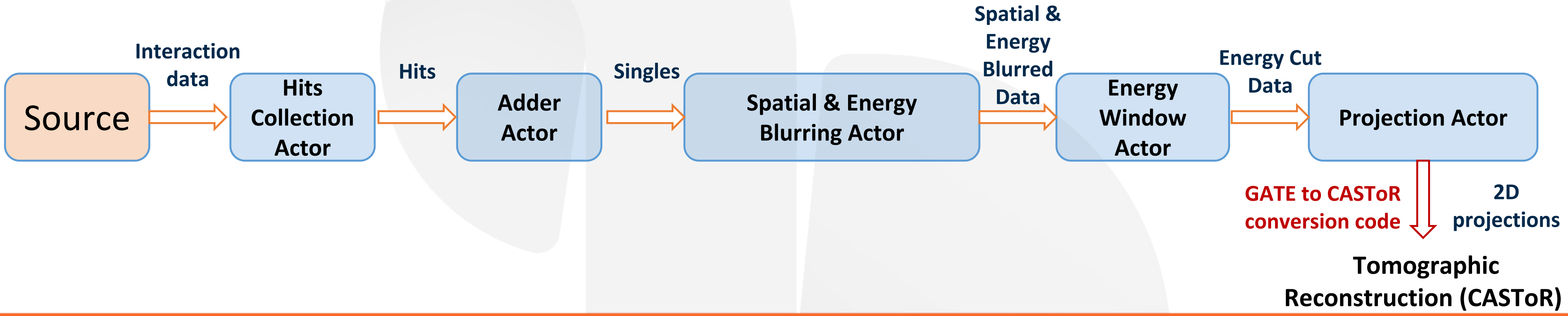
David Sarrut et al 2021 Phys. Med. Biol. 66 10TR03.

GATE 10 Simulation Main Components

- Used PHID source (Photon from Ion Decay).
  - ➢ PHID files of ^{154}Tb, ^{155}Tb, ^{156}Tb, ^{161}Tb and ^{139}Ce (atomic relaxation and isomeric transition) were created (to be shared).
  - Not available for voxelized volumes.
    - ➢ Used Ion source with decay or discrete spectrum.

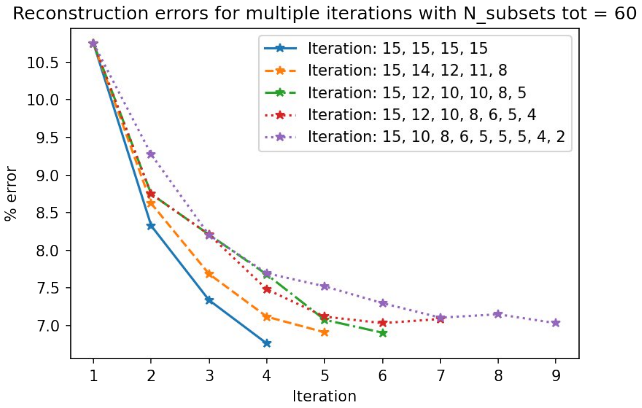
- Used (add_dynamic_parametrisation) for cameras rotation and translation.

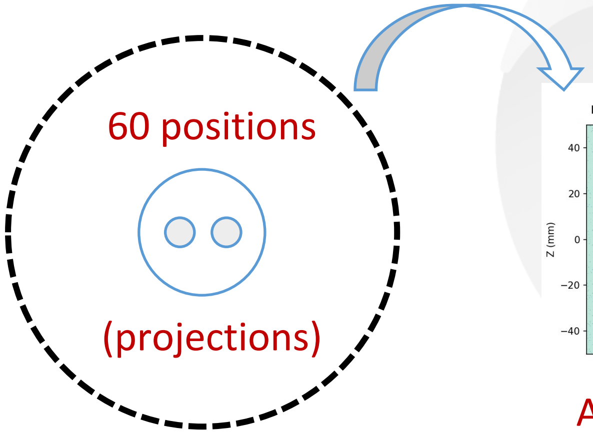
- Used actors:

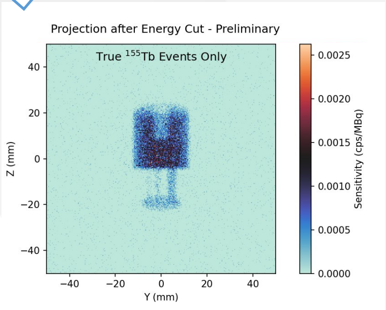


Tomographic Reconstruction

- **Tomographic SPECT reconstruction** performed using CASToR platform.[1]
- Developed a code to convert data from GATE 10 form to CASToR form.
- Ordered Subset Expectation Maximization (OSEM) algorithm, an MLEM variant.
- Camera geometry defined, correction added and parameters optimized.

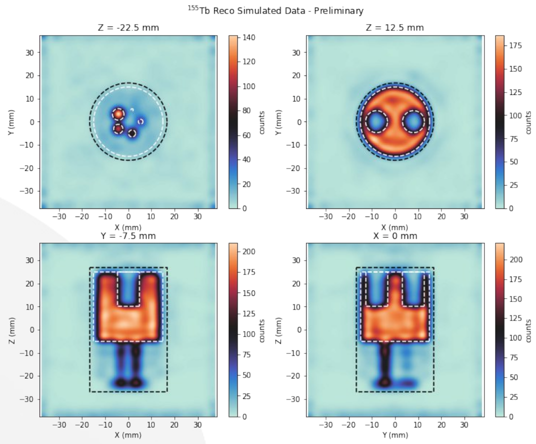






A 2D Projection

3D image reconstruction (OSEM)

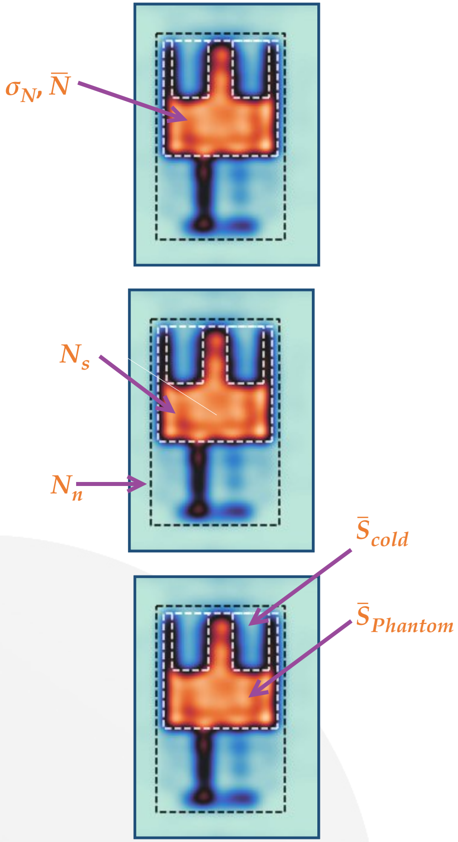


3D reconstructed image

[1] CASToR: a generic data organization and processing code framework for multi-modal and multi-dimensional tomographic reconstruction, Thibaut Merlin et al., 2018.

To quantify the reconstructed images, multiple factors were calculated:

- Integral uniformity [%]: $$IU = \frac{\sigma_N}{\bar{N}}$$
- Signal to noise ratio: $$SNR = \frac{|N_s - N_n|}{N_n}$$
- Contrast factor of the cold cylinders [%]: $$Q_{cold} = [1 - \frac{\bar{S}_{cold}}{\bar{S}_{Phantom}}]$$



σ_N: Standard deviation of voxels values in ROI.
$\bar{N}$: Sum of counts in ROI averaged by # of voxels.

N_s: # of counts considered as signal in ROI.
N_n: # of counts considered as noise in ROI.

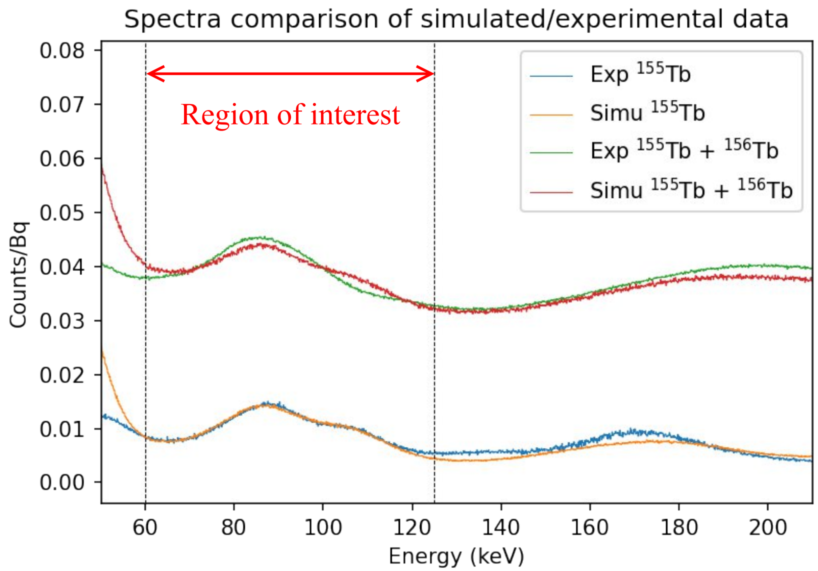
$\bar{S}_{cold}$: average counts in the cold cylinder.
$\bar{S}_{Phantom}$: average counts in the ROI of the phantom.

ALBIRA Simulation Validation

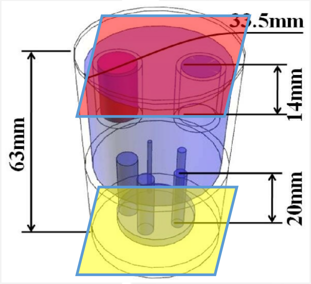
- Two measurments to validate ALBIRA simulation at CHUV :
  - Pure ^{155}Tb (6 MBq + 12 MBq ^{139}CeO).
  - Contaminated ^{155}Tb (28.7 MBq) with ^{156}Tb (2.5 MBq) (+ 1.2 MBq ^{154}Tb).
- Experimental observations :
  - 79.8% ^{156}Tb detected counts in [60, 125] keV for 8% activity contamination.

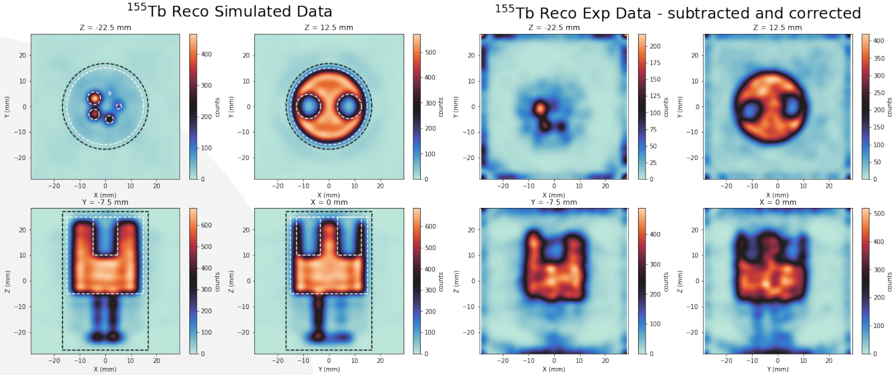
➢ Simulation validation :

- Good agreement between spectra in [60, 125] keV window.
- Some discrepancies between experiment and simulation.



Quantification factor	^{155}Tb exp	^{155}Tb +8% ^{156}Tb exp	^{155}Tb simu	^{155}Tb+8% ^{156}Tb simu
SNR	50.86	7.12	103.9	15.86
IU (%)	8.39	7.54	4.49	4.08
Q_{cold} (%)	84.48	63.19	89.73	83.93

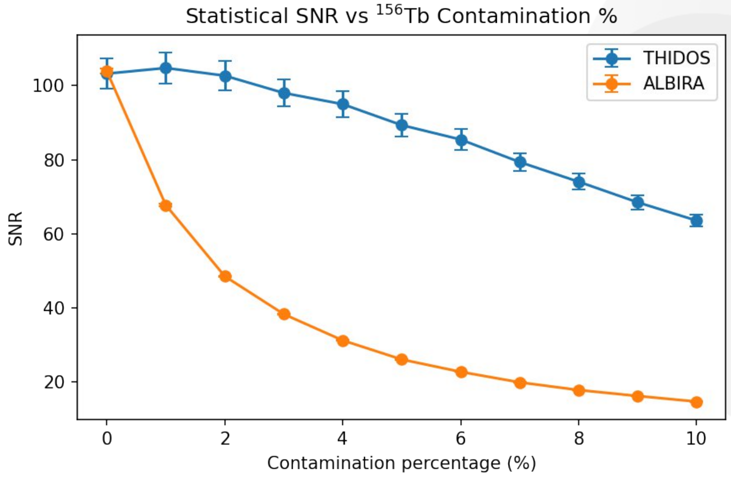


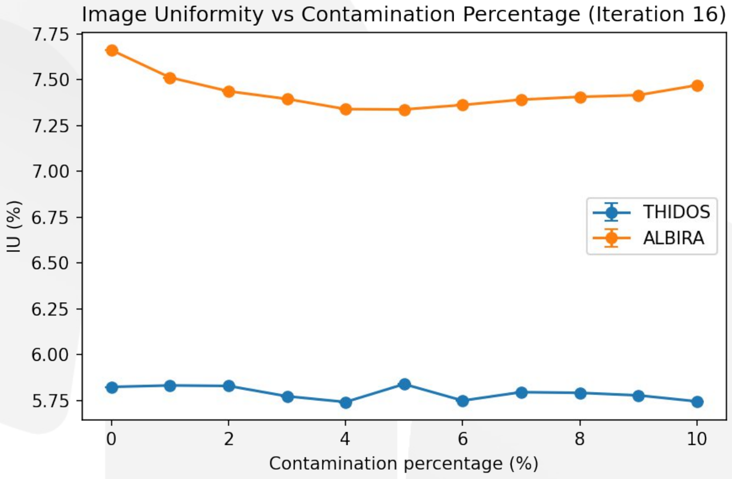


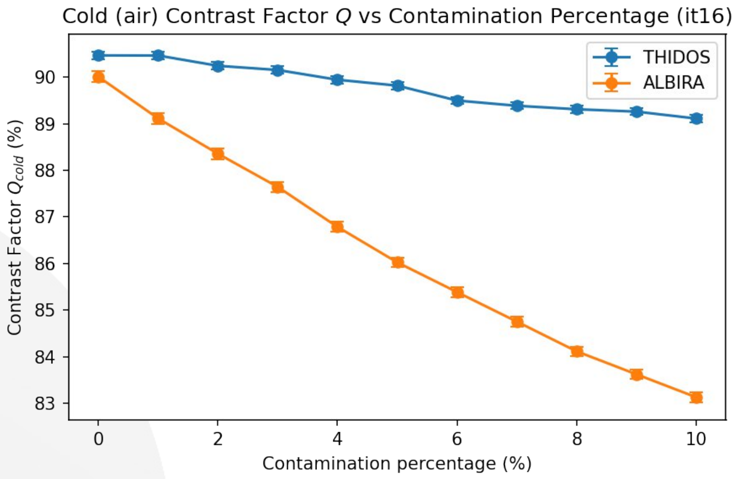
Simulation Results

Images Quantification

- At 10% contamination → SNR drops 40% for THIDOS vs >80% for ALBIRA.
  - ➢ For a low energy configuration : contamination limit must be < 2% to limit SNR reduction < 50%.
- Nearly nearly constant IU, better for THIDOS.
- Q_{cold} for ALBIRA decreases faster than THIDOS as contamination (%) increases.





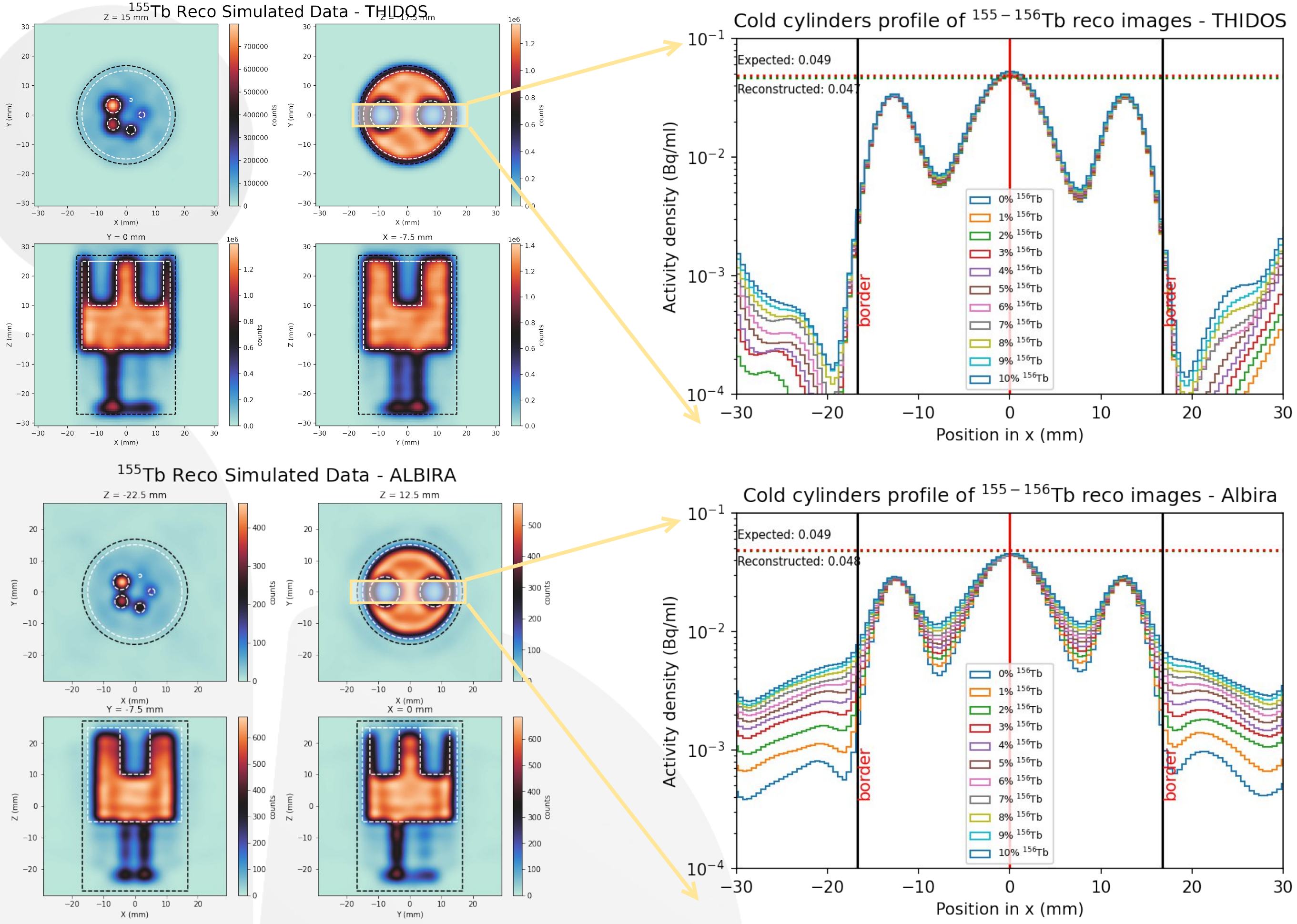


- Strong contamination effect on images.

➢ At 8% ^{156}Tb: ALBIRA = 72%, THIDOS = 30% of detected counts from ^{156}Tb.

➡ However, contamination limit strongly depends on collimator/shielding.

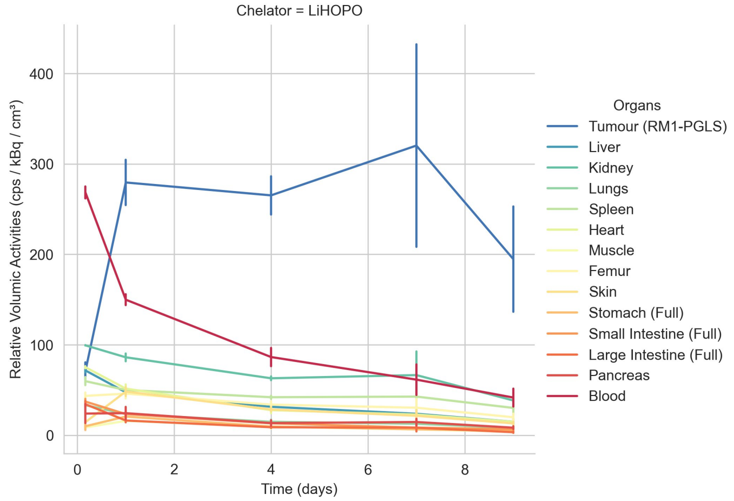
➡ Better collimation improves image quality but it is a trade-off with sensitivity.

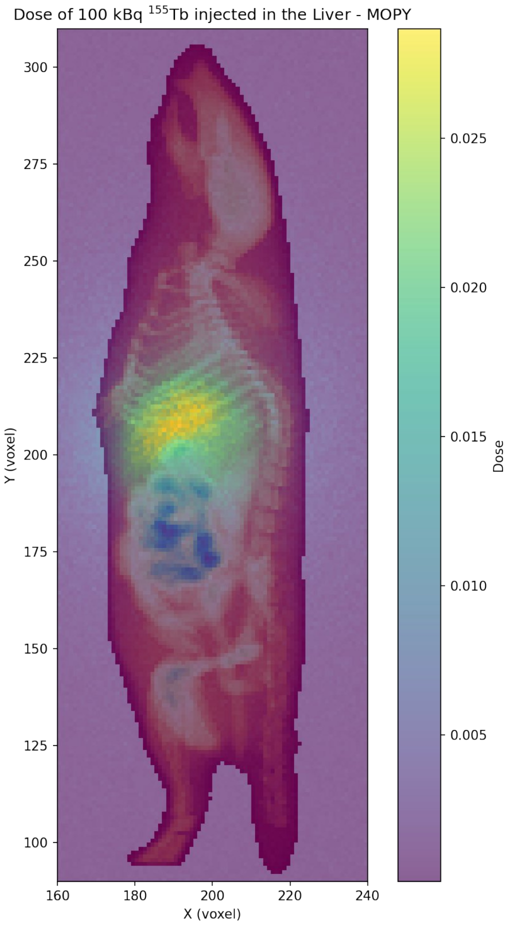


Part 2: Dosimetric Study

Dosimetry (Preliminary)

- Simulated to compute dosimetric effect of:
  - ^{161}Tb (β-).
  - ^{155}Tb + ^{156}Tb contamination (γ).
- Dosimetry studied using a voxelized GATE 10 simulated mouse phantom (MOBY):
  - 0.5^3 mm^3 voxel dimensions.
  - 140 x 140 x 400 voxels
- Simulation combined with experimental biokinetic data taken place at CHUV, Lausanne.
  - PSMA vector with 2 different chelators: LiHOPO and TPACY
  - Extract dose/(vol.Bq) & use it to evaluate time activity curves (TACs) for each organ.





Summary and Perspectives

- Simulations of the ALBIRA and THIDOS cameras were performed.
  - ALBIRA Simulation was validated with two experimentally.
- Contamination acceptable limit depends on instrumentation, not only isotope ratio.
  - For a low energy configuration : contamination limit must be < 2% to limit SNR reduction < 50%.
- THIDOS significantly reduced contamination with dedicated collimation and shielding.
- ^{156}Tb contamination importance in ^{155}Tb SPECT imaging for sources produced out of ^{nat}Gd.

- Next steps :
  - Complete dosimetric study of ^{161}Tb, and ^{155}Tb + ^{156}Tb contamination.
  - Optimize THIDOS collimation for ^{155}Tb imaging contaminated with ^{156}Tb.

Thank You

Irène Joliot-Curie – Laboratoire de Physique des 2 Infinis	CERN	CHUV	PSI	Institut de Chimie Moléculaire – Université de Bourgogne	Institut de Chimie de Strasbourg UMR 7177
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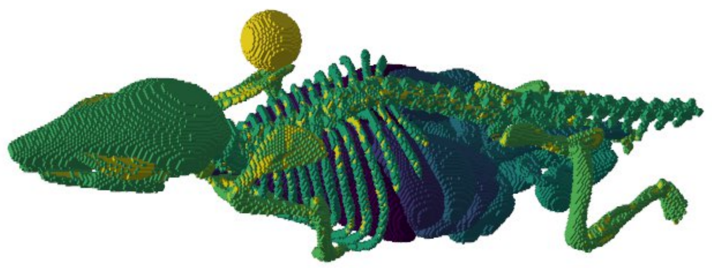
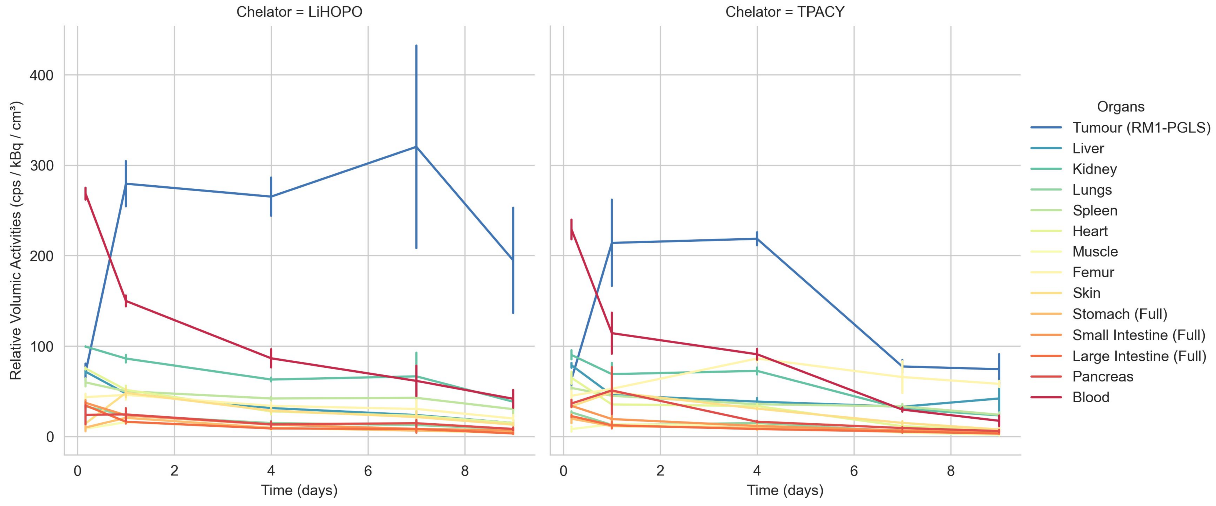
3D scheme of MOBY phantom





Dosimetry (ongoing)

- Different mouse organs simulated using biokinetic information for TACs, to evaluate the effect of contamination on dosimetry for different contamination levels.
- Most of the dose is distributed globally as it is only for gammas.
- Large organs → Bigger total dose.
- Close organs → Bigger volumic dose.

Measured Dose in Organs per Injected Organ		Injected Organs			
		Liver	Kidney	Pancreas	Heart
Total Dose (Gy)	Body	82.37 ± 0.21	55.55 ± 0.17	7.45 ± 0.06	6.35 ± 0.06
	Tumor				
	Liver	63.99 ± 0.18	8.94 ± 0.07	2.04 ± 0.03	1.65 ± 0.03
	Skin	10.60 ± 0.07	6.19 ± 0.06	0.91 ± 0.02	0.68 ± 0.02
	Heart	2.75 ± 0.04	0.37 ± 0.01	0.07 ± 0.01	2.23 ± 0.03
	Lungs	6.53 ± 0.06	1.69 ± 0.03	0.18 ± 0.01	1.24 ± 0.03
	Kidney	2.84 ± 0.04	10.59 ± 0.07	0.65 ± 0.02	0.07 ± 0.01
	Pancreas	4.41 ± 0.05	3.07 ± 0.04	2.65 ± 0.04	0.09 ± 0.01