DeSyT-2025
International workshop on Detection Systems and Techniques in Nuclear and Particle Physics
24-26 February 2025, LNS Catania

Internal dosimetry for paediatric patients: a GATE Monte Carlo study on UF/NCI phantoms

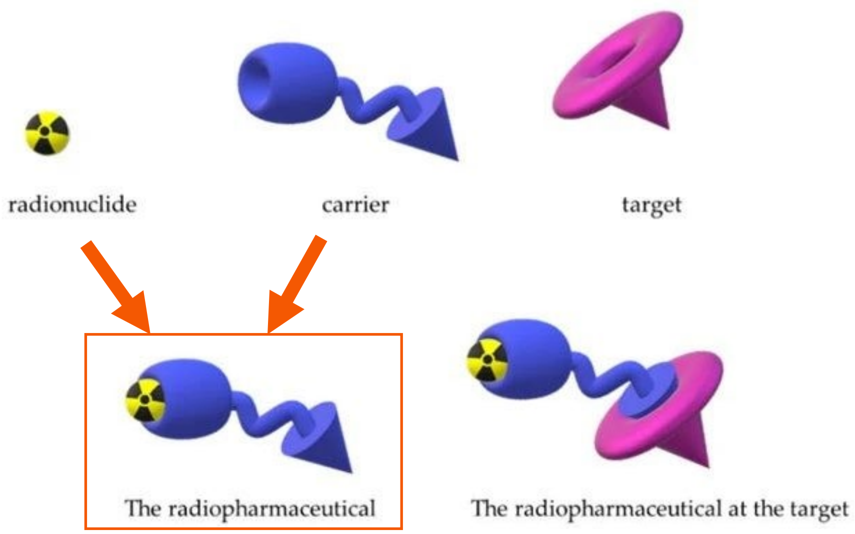
Paola Mantineo[1], Daniele Pistone[2,3], Lucrezia Auditore[4,5], Ernesto Amato[4,5,6]

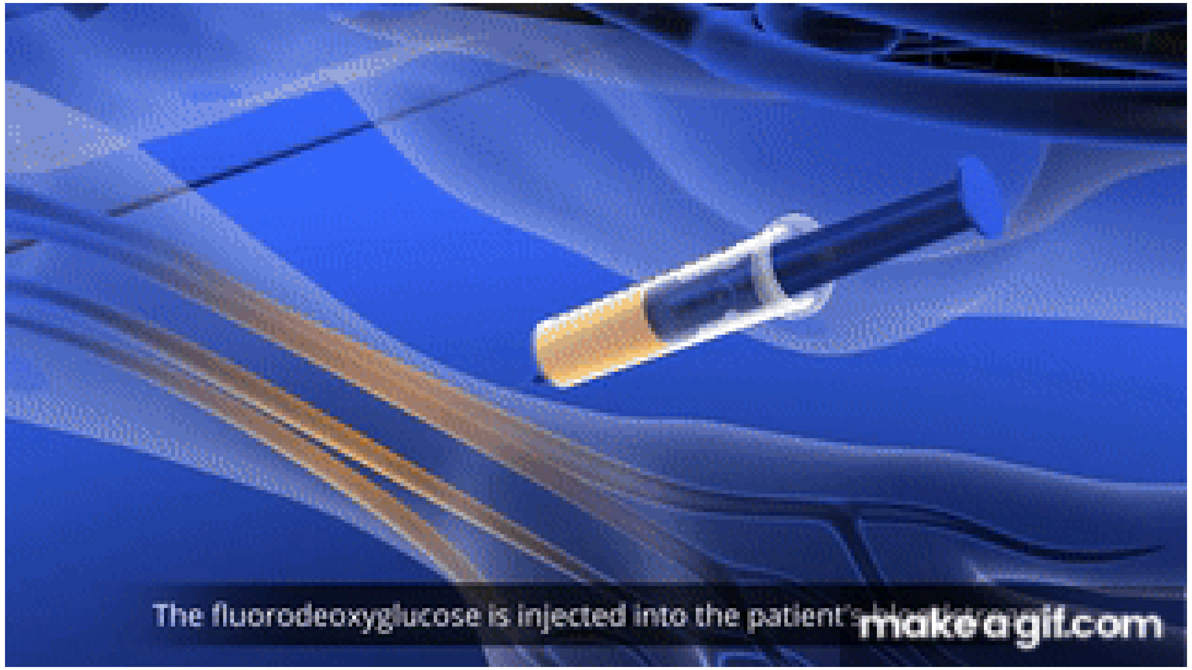
[1] Dipartimento di Scienze Matematiche e Informatiche, Scienze Fisiche e Scienze della Terra, Università degli Studi di Messina, Messina, Italy
[2] Dipartimento di Matematica e Fisica, Università degli Studi della Campania "Luigi Vanvitelli", Caserta, Italy
[3] Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Napoli, Italy
[4] Dipartimento di Scienze Biomediche, Odontoiatriche e delle Immagini Morfologiche e Funzionali, Università degli Studi di Messina, Messina, Italy
[5] Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Catania, Italy
[6] Unità di Fisica Sanitaria, Policlinico Universitario 'Gaetano Martino', Messina, Italy

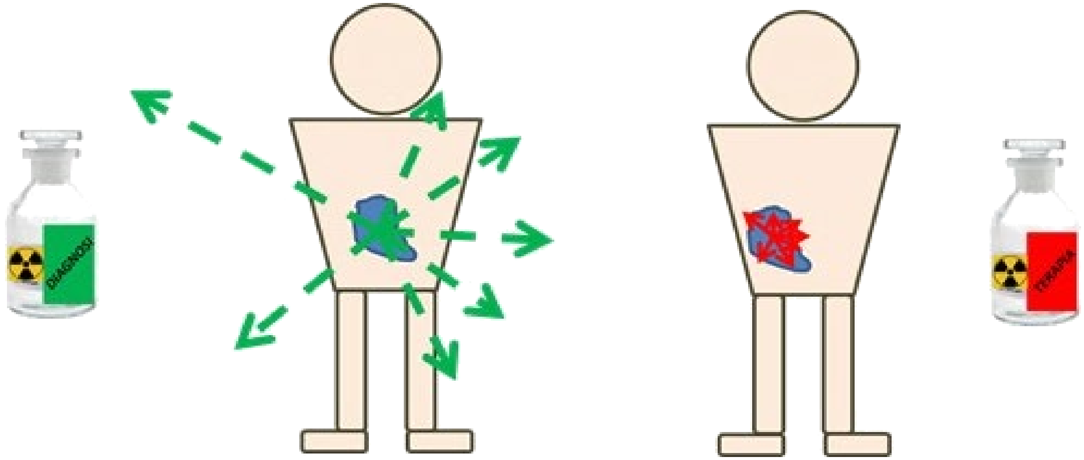
Università degli Studi della Campania Luigi Vanvitelli

INFN

Nuclear Medicine





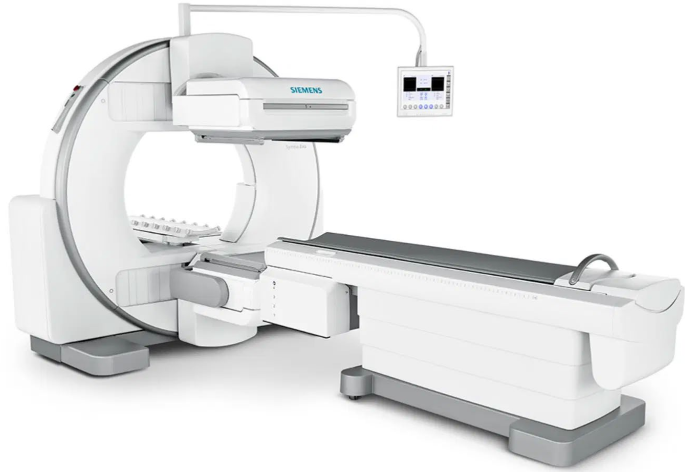


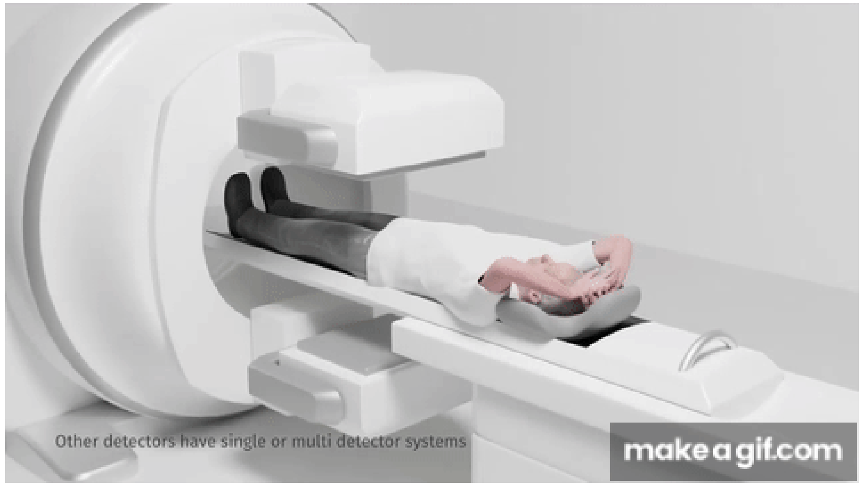
Diagnostics: γ and β+

Therapies: β- and α

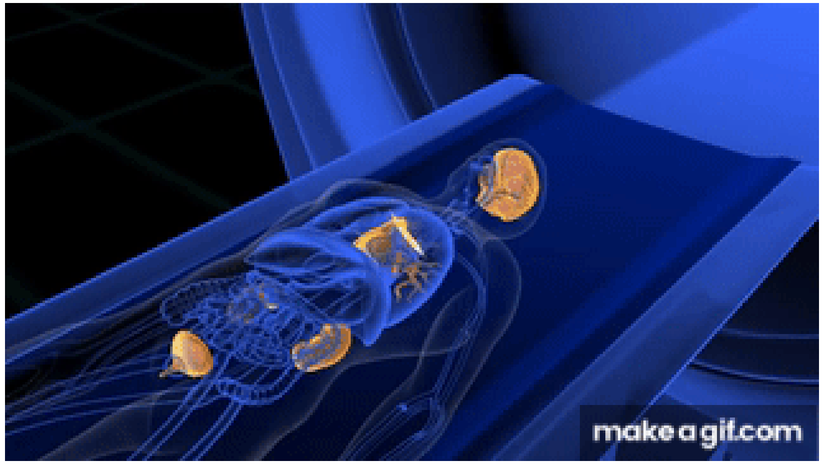
Nuclear Medicine tomographic detection systems

- SPECT (Single Photon Emission Computed Tomography)





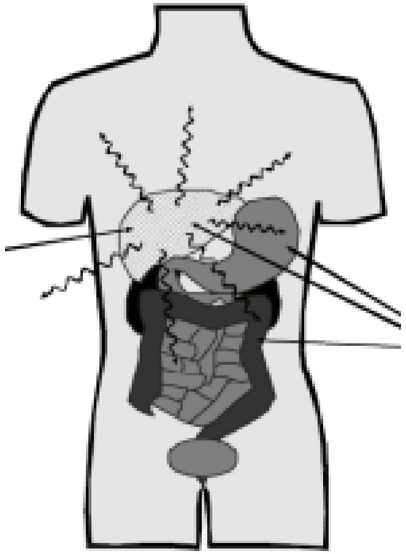
- PET (Positron Emission Tomography)

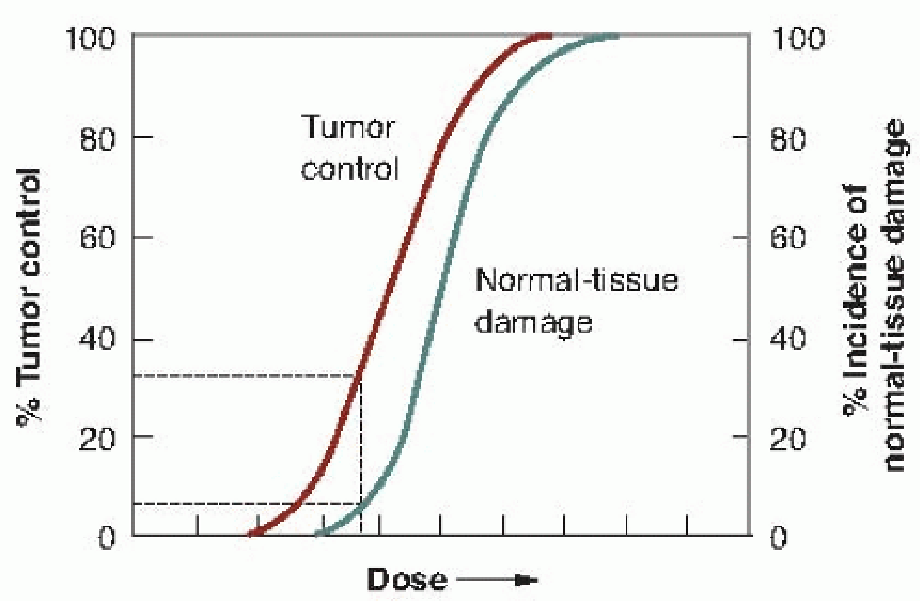


Internal Dosimetry in Nuclear Medicine

- Quantification of the Absorbed Dose to internally irradiated organs and tissues

$$D = \frac{dE_{abs}}{dm} \left[Gy = \frac{J}{kg} \right]$$





Fundamental role in assessing:

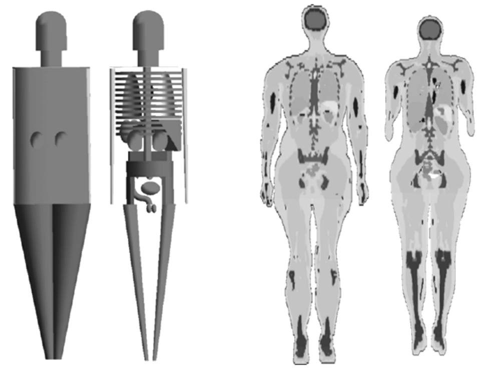
- Damage to pathologic tissues
- Risk for healthy tissues
- Deduce dose-effect correlations →
- → Optimize activity administration

Internal Dosimetry in Nuclear Medicine

- Modeling anatomy: specific organs, tissues or the whole human body
- Modeling the radionuclide distribution

Three main approaches:

- Model-based dosimetry

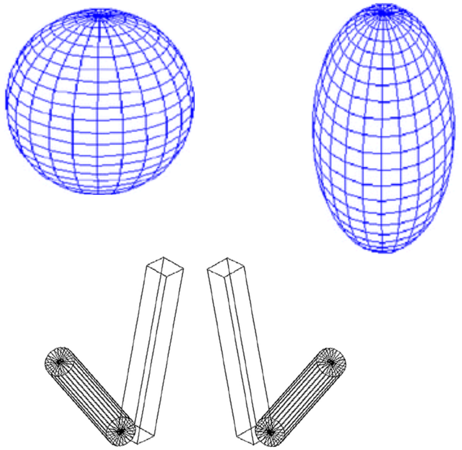


MIRD5 mathematical model

ICRP110 voxelized adult human model

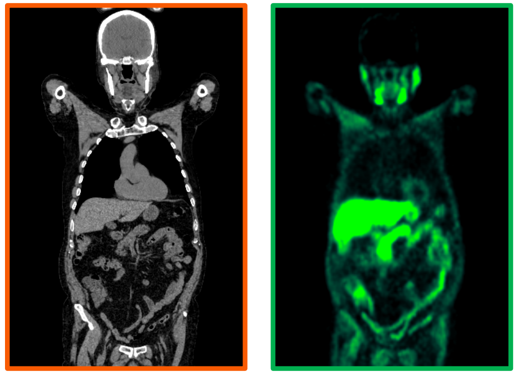
- Reference dosimetry, mainly used for diagnostics and radioprotection

- Single-organ dosimetry



- Lesions or anatomical regions absent in standardized anthropomorphic models

- Imaging-based dosimetry



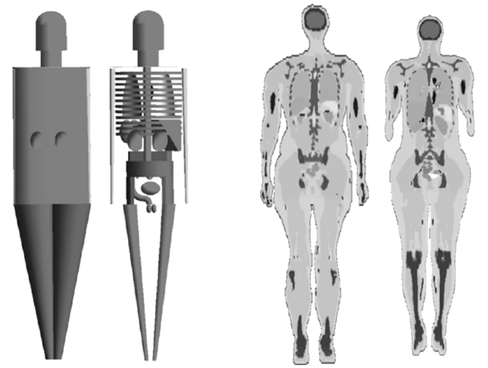
- Patient-specific dosimetry, mainly used for therapy

Internal Dosimetry in Nuclear Medicine

- Modeling anatomy: specific organs, tissues or the whole human body
- Modeling the radionuclide distribution

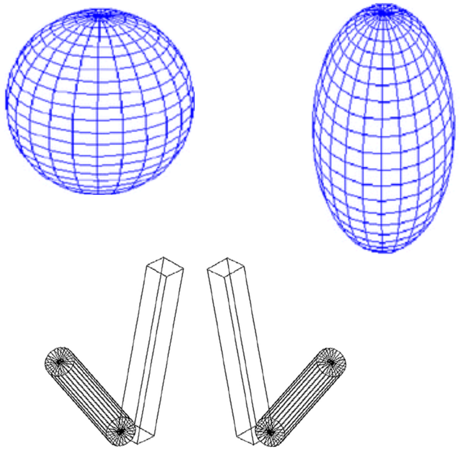
Three main approaches:

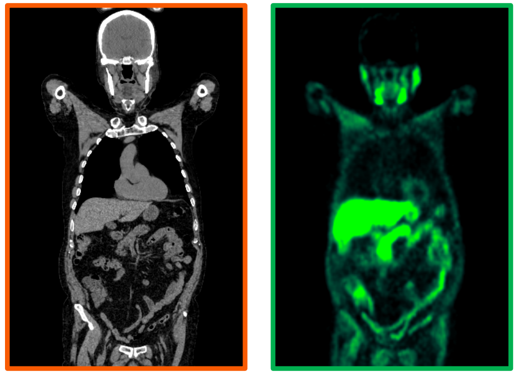
- Model-based dosimetry
- Single-organ dosimetry
- Imaging-based dosimetry



MIRD5 mathematical model

ICRP110 voxelized adult human model

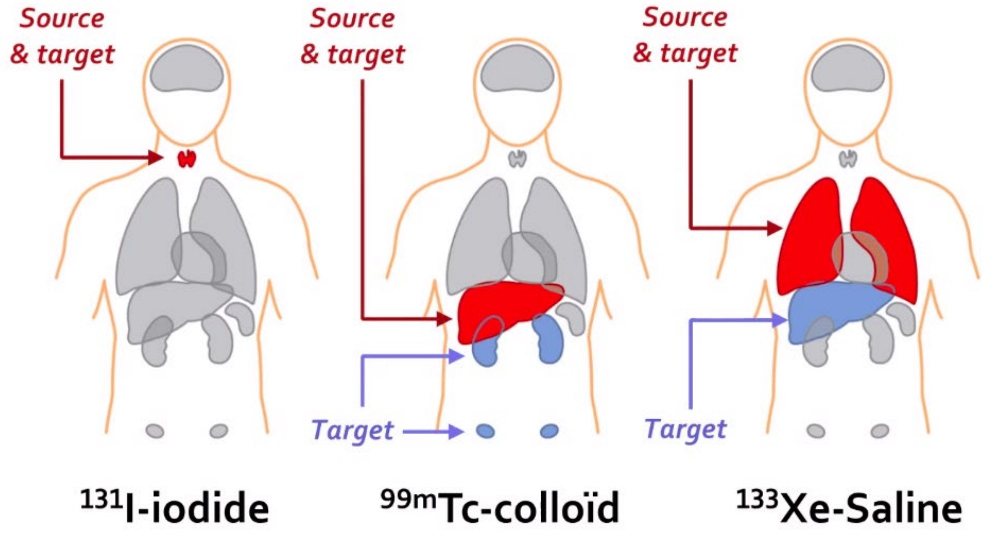




- Reference dosimetry, mainly used for diagnostics and radioprotection
- Lesions or anatomical regions absent in standardized anthropomorphic models
- Patient-specific dosimetry, mainly used for therapy

Model-based organ-level dosimetry

- MIRD (Medical Internal Radiation Dose committee) organ-level dosimetry formalism



$$D(r_T) = \sum_{r_S} \widetilde{A}_{r_S} \sum_i \Delta_i SAF_i(r_T \leftarrow r_S)$$

Δ_i = average energy emitted per decay due to i-th radiation type

$$\widetilde{A}_{r_S} = \int_0^\infty A(r_S, t)dt$$

TIA (Time-Integrated Activity) in the source organ r_S

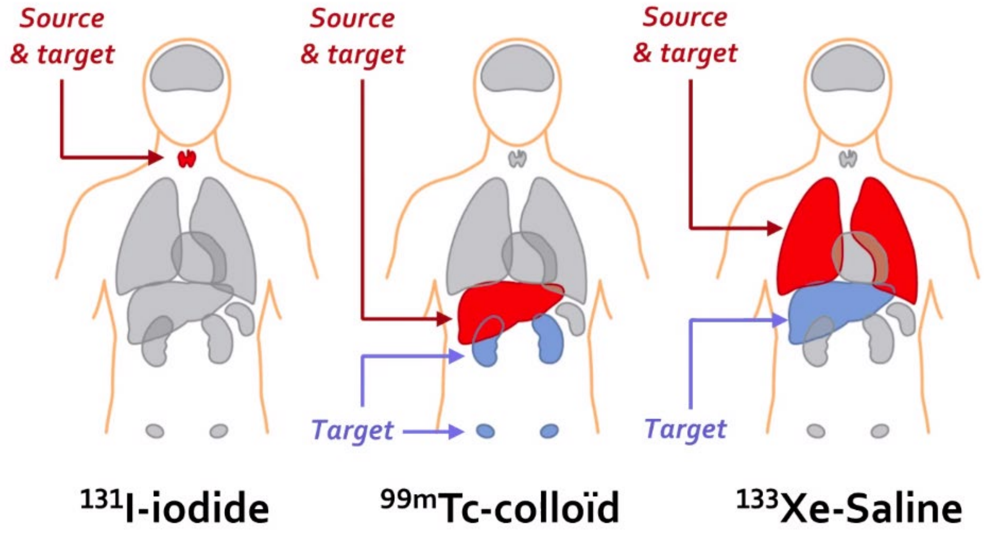
$$SAF_i(r_T \leftarrow r_S) = \frac{\phi_i(r_T \leftarrow r_S)}{M(r_T)}$$

SAF (Specific Absorbed Fraction) = fraction (ϕ_i) of the energy E_i emitted in the source organ r_S and absorbed in the target organ r_T per unit mass $M(r_T)$ of the target

Model-based organ-level dosimetry

- MIRD (Medical Internal Radiation Dose committee) organ-level dosimetry formalism

$$D(r_T) = \sum_{r_S} \tilde{A}_{r_S} \sum_i \Delta_i SAF_i(r_T \leftarrow r_S)$$



Δ_i = average energy emitted per decay due to i-th radiation type

$$\tilde{A}_{r_S} = \int_0^\infty A(r_S, t)dt$$

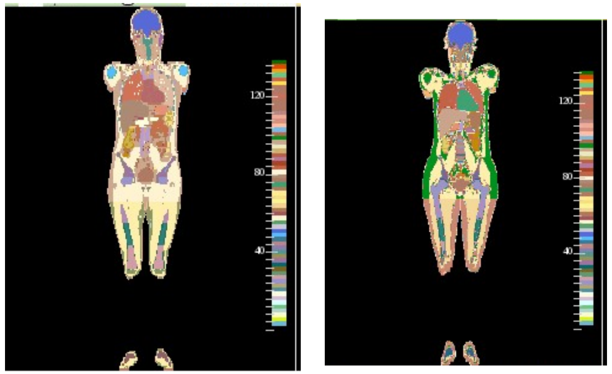
TIA (Time-Integrated Activity) in the source organ r_S

$$SAF_i(r_T \leftarrow r_S) = \frac{\phi_i(r_T \leftarrow r_S)}{M(r_T)}$$

SAF (Specific Absorbed Fraction) = fraction (ϕ_i) of the energy E_i emitted in the source organ r_S and absorbed in the target organ r_T per unit mass $M(r_T)$ of the target

SAFs and antropomorphic models

- SAFs can be calculated via Monte Carlo (MC) simulations on anthropomorphic computational models
- SAFs databases available for adult human computational models (e.g., ICRP 110), calculated with different MC codes



OpenDose Beta version Newsletter Contact

ISOTOPES
MODELS
SIMULATIONS
SAFs
S VALUES
DOSIMETRY

Selection

Model Se

Submit

Specific Absorbed Fractions

To display SAFs, first select a model from the left panel, then select a source, target and a particle type.

Specific Absorbed Fractions (SAFs) are calculated from the Monte Carlo simulations. Absorbed doses to targets are converted to SAFs by dividing by the initial particle energy (J) and by the number of simulated particles.

SAFs are uploaded in the OpenDose relational database as a function of the model source and target, the particle type and energy, and the number of simulated particles. The source, target and the particle type are identified with an ID linking them to other database tables with their description (model, name, volume, mass). Every SAF is also associated with an ID that identifies its provenance (provider, code, version, email, date):

provenance_id	source_id	target_id	particle_id	energy_MeV	saf	saf_std	nb_primaries
48	95	104	2	2	5.05828e-05	2.860568e-06	100000000
48	95	105	2	2	8.85874e-07	3.166879e-07	100000000
48	95	106	2	2	4.34269e-06	9.282826e-08	100000000
48	95	107	2	2	0.082379406	7.93368e-07	100000000
48	95	108	2	2	2.19283e-05	9.66317e-08	100000000
48	95	109	2	2	2.92716e-07	6.04694e-09	100000000
48	95	110	2	2	0.0106176	2.584169e-05	100000000
48	95	111	2	2	2.25291e-06	3.475611e-07	100000000
48	95	112	2	2	3.9635e-06	6.80921e-07	100000000
48	95	113	2	2	0.085079158	9.621008e-06	100000000

This section allows to query SAFs from the OpenDose database and to display them. An interactive chart shows SAFs from the different Monte Carlo codes and

JNM The Journal of NUCLEAR MEDICINE

J Nucl Med. 2020 Oct;61(10):1514–1519. doi: 10.2967/jnumed.119.240366

OpenDose: Open-Access Resource for Nuclear Medicine Dosimetry

Maxime Chauvin [1], Damian Borys [2], Francesca Botta [3], Pawel Bzowski [2], Jérémie Dabin [4], Ana M Denis-Bacelar [5], Aurélie Desbrée [6], Nadia Falzone [7,8], Boon Quan Lee [7,8], Andrea Mairani [9,10], Alessandra Malaroda [11,12], Gilles Mathieu [13], Erin McKay [14], Erick Mora-Ramirez [1,15], Andrew P Robinson [5,16,17], David Sarrut, Lara Struelens [4], Alex Vergara Gil [1], Manuel Bardiès [1]

ICRP ABOUT ICRP WHO WE ARE WHAT WE DO EVENTS ICRPAEDIA DONATE

ICRP Publication 110

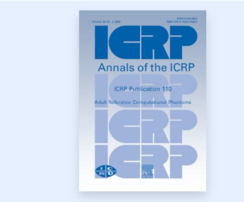
Adult Reference Computational Phantoms

Prepared jointly with ICRU

Recommended citation

ICRP, 2009. Adult Reference Computational Phantoms. ICRP Publication 110. Ann. ICRP 39 (2).

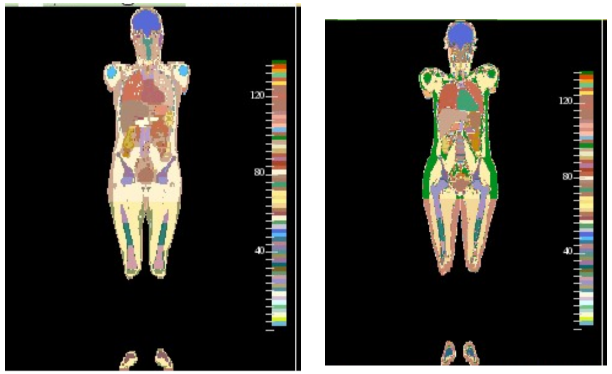
Abstract - This report describes the development and intended use of the computational phantoms of the Reference Male and Reference Female. In its 2007 Recommendations, ICRP adopted these computational phantoms for forthcoming updates of organ dose coefficients for both internal and external radiation sources (ICRP, 2007). The phantoms are based on medical image data of real people, yet are consistent with the data given in Publication 89 (ICRP, 2002) on the reference anatomical and physiological parameters for both male and female subjects. The reference phantoms are constructed after modifying the voxel models (Golem and Laura) of two individuals whose body height and mass resembled the reference data. The organ masses of both models were adjusted to the ICRP data on the adult Reference Male and Reference Female, without compromising their anatomic realism. This report describes the methods used for this process and the characteristics of the resulting computational phantoms.



- Lack of SAFs on paediatric data

SAFs and antropomorphic models

- SAFs can be calculated via Monte Carlo (MC) simulations on anthropomorphic computational models
- SAFs databases available for adult human computational models (e.g., ICRP 110), calculated with different MC codes



OpenDose Beta version Newsletter Contact

ISOTOPES
MODELS
SIMULATIONS
SAFs
S VALUES
DOSIMETRY

Selection

Model Se

Submit

Specific Absorbed Fractions

To display SAFs, first select a model from the left panel, then select a source, target and a particle type.

Specific Absorbed Fractions (SAFs) are calculated from the Monte Carlo simulations. Absorbed doses to targets are converted to SAFs by dividing by the initial particle energy (J) and by the number of simulated particles.

SAFs are uploaded in the OpenDose relational database as a function of the model source and target, the particle type and energy, and the number of simulated particles. The source, target and the particle type are identified with an ID linking them to other database tables with their description (model, name, volume, mass). Every SAF is also associated with an ID that identifies its provenance (provider, code, version, email, date):

provenance_id	source_id	target_id	particle_id	energy_MeV	saf	saf_std	nb_primaries
48	95	104	2	2	5.05828e-05	2.860568e-06	100000000
48	95	105	2	2	8.85874e-07	3.166879e-07	100000000
48	95	106	2	2	4.34269e-06	9.282826e-08	100000000
48	95	107	2	2	0.002379406	7.93368e-07	100000000
48	95	108	2	2	2.19283e-05	9.66317e-08	100000000
48	95	109	2	2	2.92716e-07	6.04694e-09	100000000
48	95	110	2	2	0.0106176	2.584169e-05	100000000
48	95	111	2	2	2.25291e-06	3.475611e-07	100000000
48	95	112	2	2	3.9635e-06	6.80921e-07	100000000
48	95	113	2	2	0.085079158	9.621008e-06	100000000

This section allows to query SAFs from the OpenDose database and to display them. An interactive chart shows SAFs from the different Monte Carlo codes and

ICRP ABOUT ICRP WHO WE ARE WHAT WE DO EVENTS ICRPAEDIA DONATE

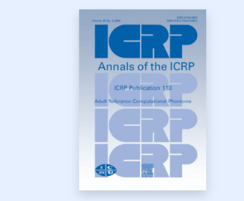
ICRP Publication 110

Adult Reference Computational Phantoms

Prepared jointly with ICRU

Recommended citation
ICRP, 2009. Adult Reference Computational Phantoms. ICRP Publication 110. Ann. ICRP 39 (2).

Abstract - This report describes the development and intended use of the computational phantoms of the Reference Male and Reference Female. In its 2007 Recommendations, ICRP adopted these computational phantoms for forthcoming updates of organ dose coefficients for both internal and external radiation sources (ICRP, 2007). The phantoms are based on medical image data of real people, yet are consistent with the data given in Publication 89 (ICRP, 2002) on the reference anatomical and physiological parameters for both male and female subjects. The reference phantoms are constructed after modifying the voxel models (Golem and Laura) of two individuals whose body height and mass resembled the reference data. The organ masses of both models were adjusted to the ICRP data on the adult Reference Male and Reference Female, without compromising their anatomic realism. This report describes the methods used for this process and the characteristics of the resulting computational phantoms.



JNM The Journal of NUCLEAR MEDICINE

J Nucl Med. 2020 Oct;61(10):1514–1519. doi: 10.2967/jnumed.119.240366

OpenDose: Open-Access Resource for Nuclear Medicine Dosimetry

Maxime Chauvin [1], Damian Borys [2], Francesca Botta [3], Pawel Bzowski [2], Jérémie Dabin [4], Ana M Denis-Bacelar [5], Aurélie Desbrée [6], Nadia Falzone [7,8], Boon Quan Lee [7,8], Andrea Mairani [9,10], Alessandra Malaroda [11,12], Gilles Mathieu [13], Erin McKay [14], Erick Mora-Ramirez [1,15], Andrew P Robinson [5,16,17], David Sarrut, Lara Struelens [4], Alex Vergara Gil [1], Manuel Bardiès [1,✉]

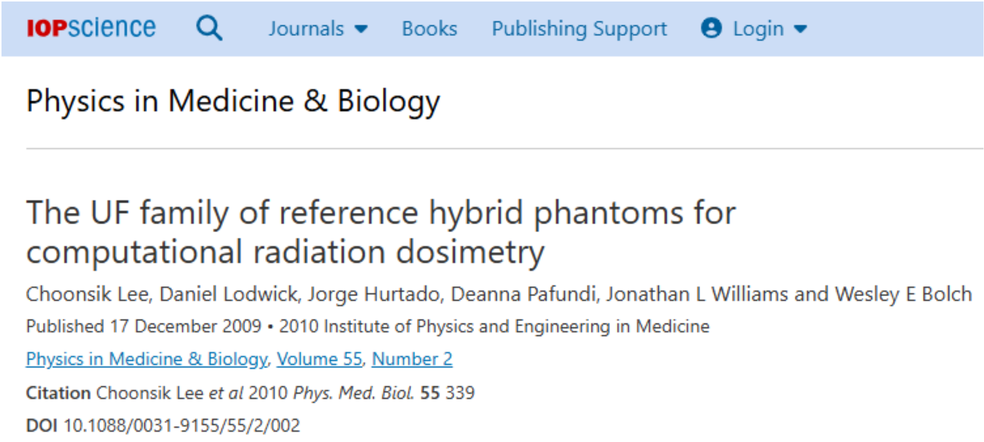
- Lack of SAFs on paediatric data

Aims

- Implementing MC simulations for dosimetry on paediatric computational models
- Estimating SAFs for electrons and photons for couples of organs of interest

UF/NCI voxelized paediatric models

- University of Florida / National Cancer Institute family of hybrid computational models
- Among them, male and female series of voxelized peadiatric, adolescent and adult models, ages: newborn (0 yrs), 1, 5, 10, 15, 35 yrs


IOPscience Journals Books Publishing Support Login

Physics in Medicine & Biology

The UF family of reference hybrid phantoms for computational radiation dosimetry

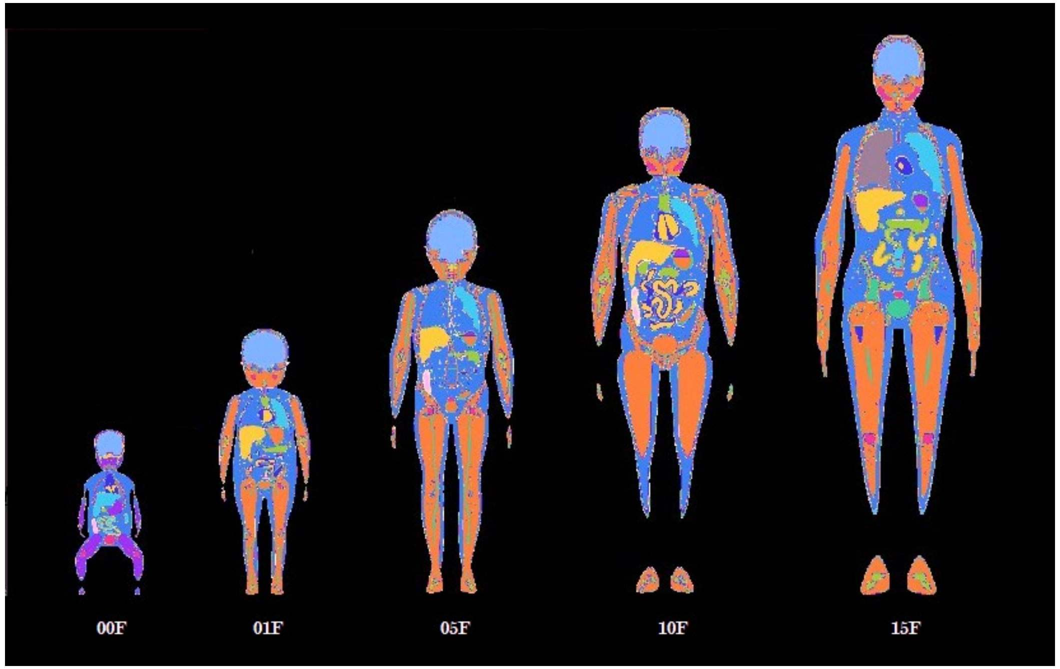
Choonsik Lee, Daniel Lodwick, Jorge Hurtado, Deanna Pafundi, Jonathan L Williams and Wesley E Bolch

Published 17 December 2009 • 2010 Institute of Physics and Engineering in Medicine

Physics in Medicine & Biology, Volume 55, Number 2

Citation Choonsik Lee *et al* 2010 *Phys. Med. Biol.* **55** 339

DOI 10.1088/0031-9155/55/2/002



Female

Male

GATE/GEANT4 MC simulations setup

Geometry settings

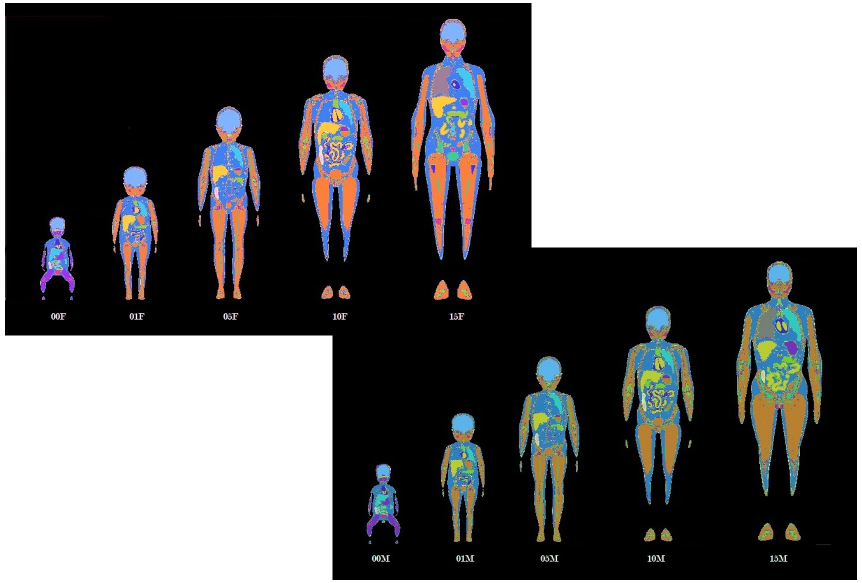
- .mhd + .raw files for each model as voxelized volumes
- Material and density associated to each organ according to Lee et al. 2010

Source settings

- 16 organs acting as homogeneous source: brain, kidneys (3 separate regions), liver, lungs (2 different organs), pancreas, salivary glands (3 regions each, 6 total), spleen, thyroid
- Photons and electrons, 91 energy values each: from 5 keV to 10 MeV
- Physics: emstandard_opt4, range cut for secondaries: 0.1 mm

Scoring settings

- Average energy deposited in all the organs
- 1e7 primary events for each combination of: model, particle, energy, source organ



$$SAF(r_S \rightarrow r_T)[kg^{-1}] = \frac{E_{dep}^{(r_S \rightarrow r_T)}}{E_{part} \cdot n_{evts} \cdot m_{r_T}}$$

Simulation runs: CINECA HPC Marconi-100

- Simulations were run on the Marconi-100 supercomputer of CINECA (Consorzio Interuniversitario del Nord-Est per il Calcolo Automatico)
- Within the CINECA ISCRA Class B "Project Medical physIcs and RAdiation in Crystals simuLation with gEant4" (IsB24_MIRACLE, October 25, 2021 – January 25, 2023, PI: Alexei Sytov)
- Using Marconi-100 enabled parallelization into 62 runs per node, thus strongly reducing the overall simulation time

CINECA

CLUSTER HPC MARCONI-100:
Nodes: 980
Processors: 2 16-cores IBM POWER9 AC922 at 2.6(3.1) GHz
Cores: 32 cores/node, 128 logical cores/nodes, **125440 cores** in total
Accelerators: 4 x NVIDIA Volta V100 GPUs/node
RAM: 256 GB/node
Internal Network: Mellanox IB EDR DragonFly++
Disk Space: 8 PB of local scratch
Peak Performance: 29 PFlop/s
10^5-10^6 times faster than a personal computer

SAF analysis for this study

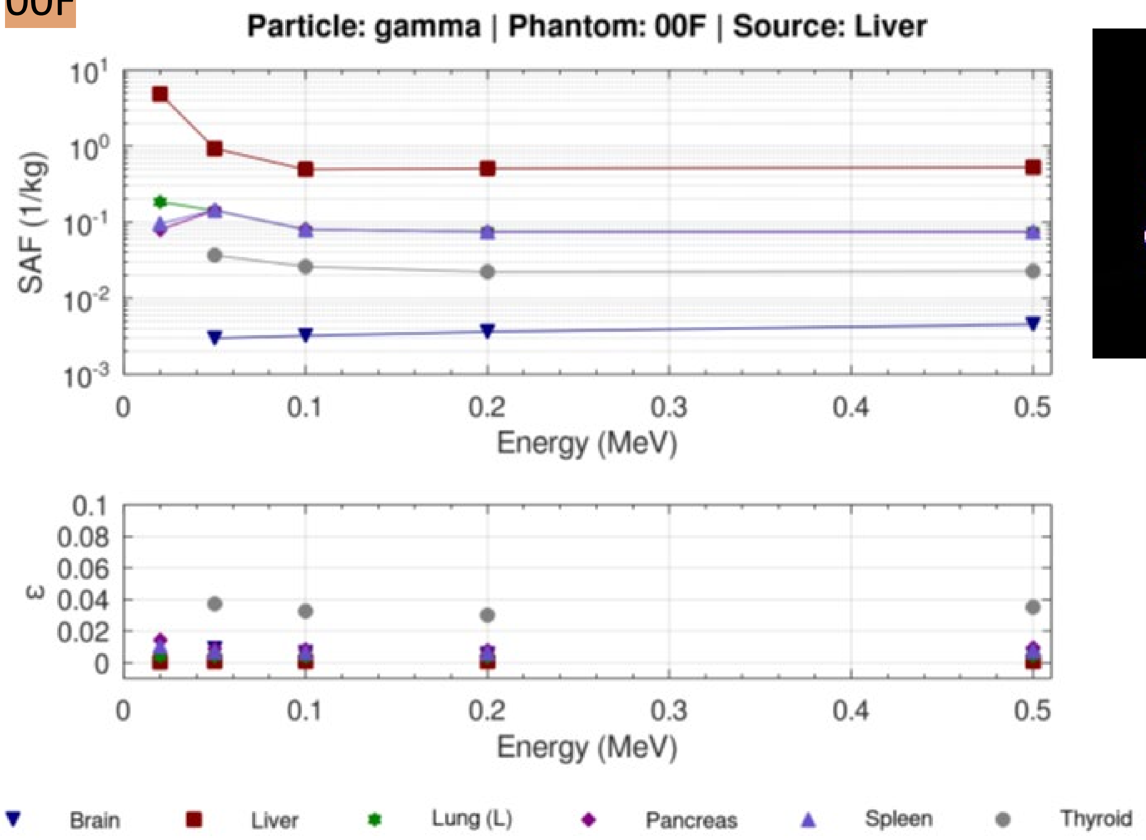
Focus on:

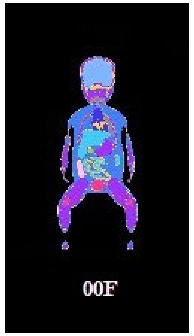
- Energies from 0.01 MeV to 0.5 MeV.
- Paediatric models: 0, 1, 5, 10, 15 yrs
- 2 Source organs: Liver, Thyroid
- 6 Target organs: Liver, Thyroid, Brain, Spleen, Pancreas, Left Lung

SAF results: photons, source: liver

➢ Running 1e7 events guaranteed the selection of photon SAFs with statistical uncertainties below 5% for most of the organ pairs examined. SAFs with uncertainty > 10% were excluded.

00F





SAF (1/kg)	0.02 MeV	0.05 MeV	0.10 MeV	0.20 MeV	0.50 MeV
Brain		2.97E-03	3.21E-03	3.61E-03	4.53E-03
Liver	4.85E+00	9.29E-01	4.94E-01	5.10E-01	5.30E-01
Lung (L)	1.84E-01	1.42E-01	7.94E-02	7.56E-02	7.54E-02
Pancreas	7.98E-02	1.43E-01	8.05E-02	7.44E-02	7.40E-02
Spleen	9.61E-02	1.44E-01	7.98E-02	7.50E-02	7.51E-02
Thyroid		3.68E-02	2.60E-02	2.23E-02	2.27E-02

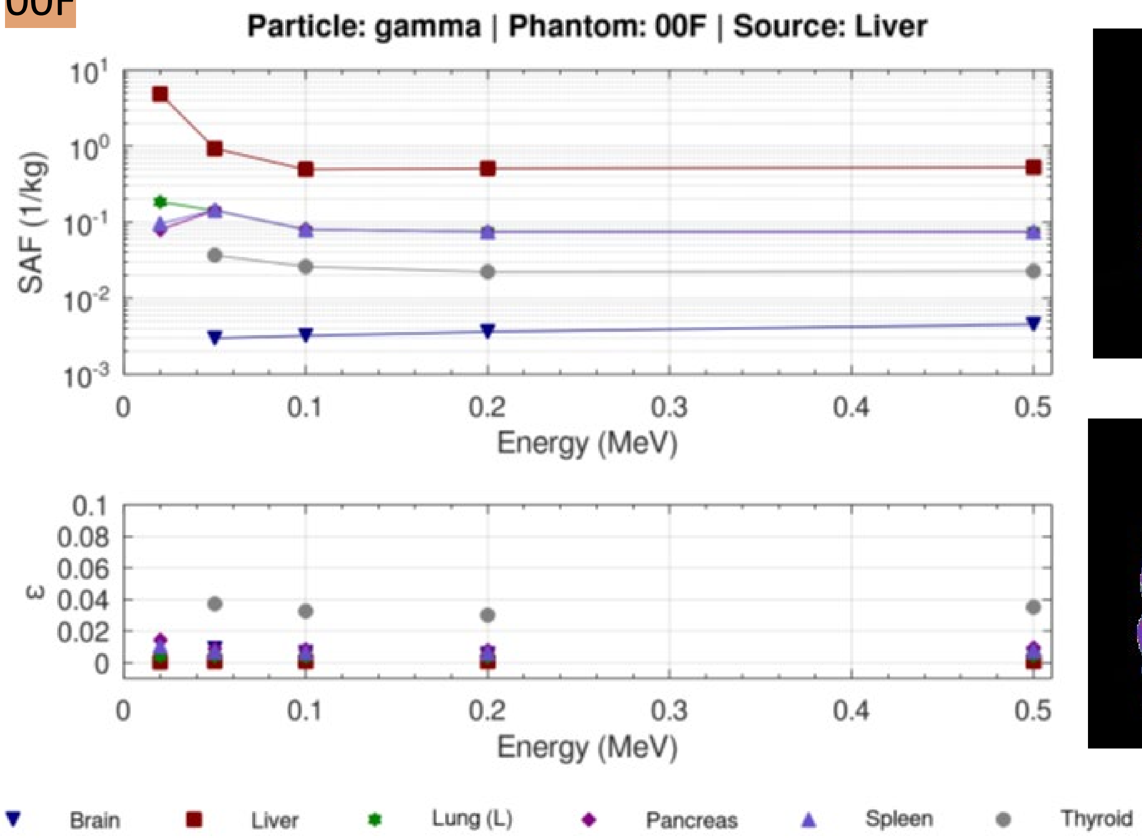
ε	0.02 MeV	0.05 MeV	0.10 MeV	0.20 MeV	0.50 MeV
Brain		9.02E-03	6.41E-03	5.46E-03	5.57E-03
Liver	2.41E-04	7.36E-04	7.18E-04	6.83E-04	7.96E-04
Lung (L)	4.33E-03	4.17E-03	3.83E-03	3.69E-03	4.42E-03
Pancreas	1.43E-02	8.91E-03	8.10E-03	7.84E-03	9.51E-03
Spleen	1.03E-02	7.14E-03	6.57E-03	6.31E-03	7.60E-03
Thyroid		3.72E-02	3.27E-02	3.00E-02	3.52E-02

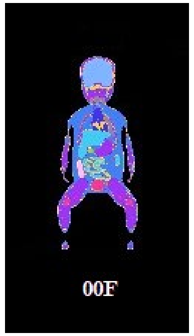
➢ Photon SAFs tend to decrease with energy except for Brain (increase)

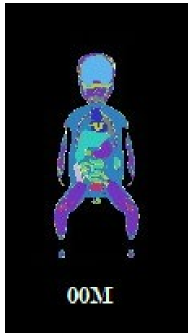
SAF results: photons, source: liver

- Running 1e7 events guaranteed the selection of photon SAFs with statistical uncertainties below 5% for most of the organ pairs examined. SAFs with uncertainty > 10% were excluded.

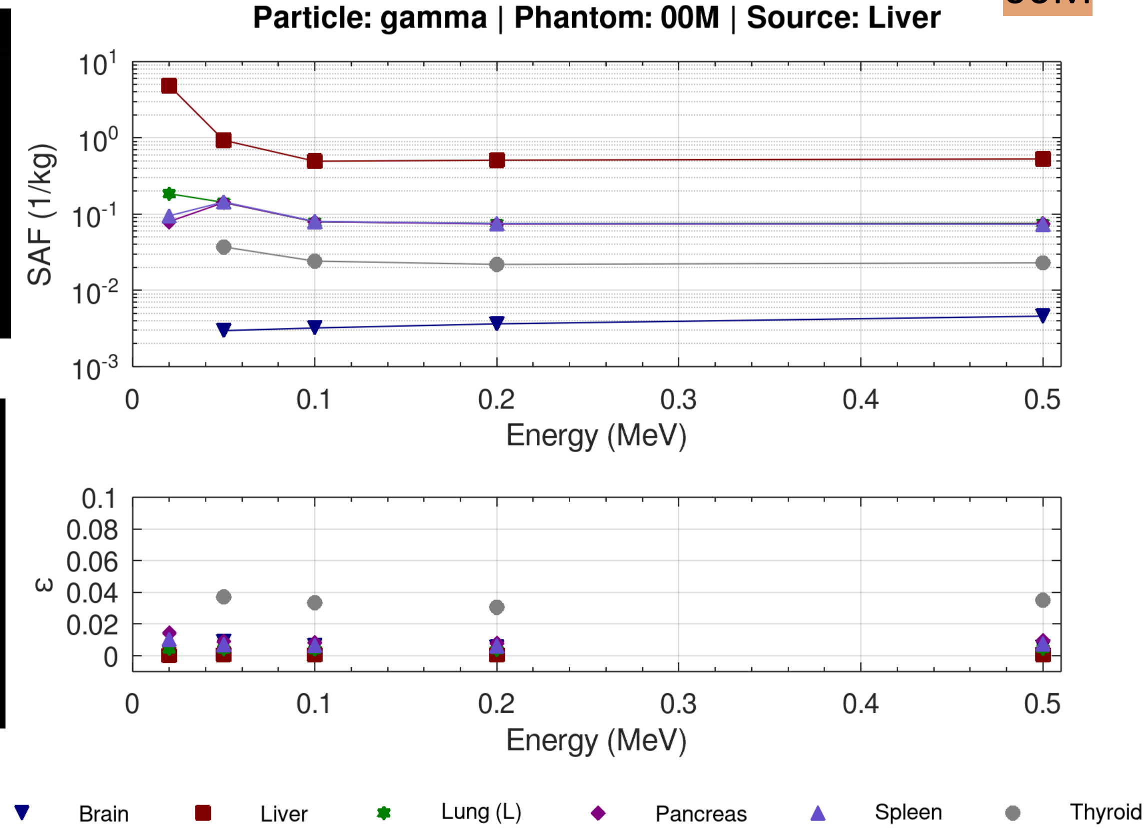
00F





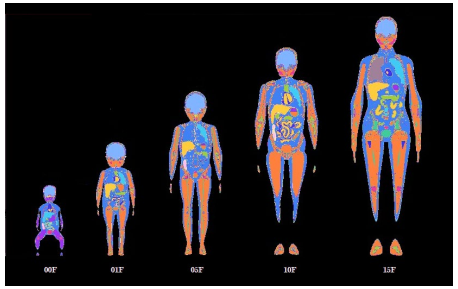


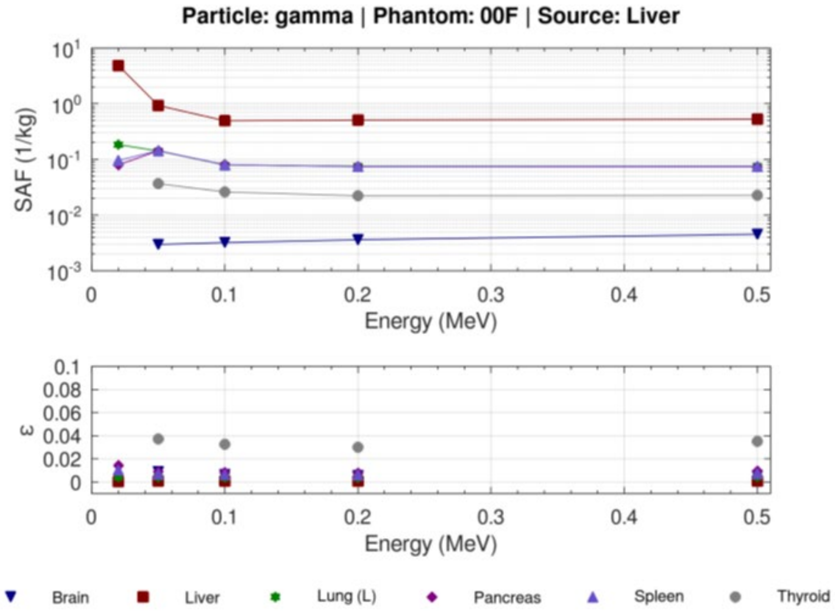
00M

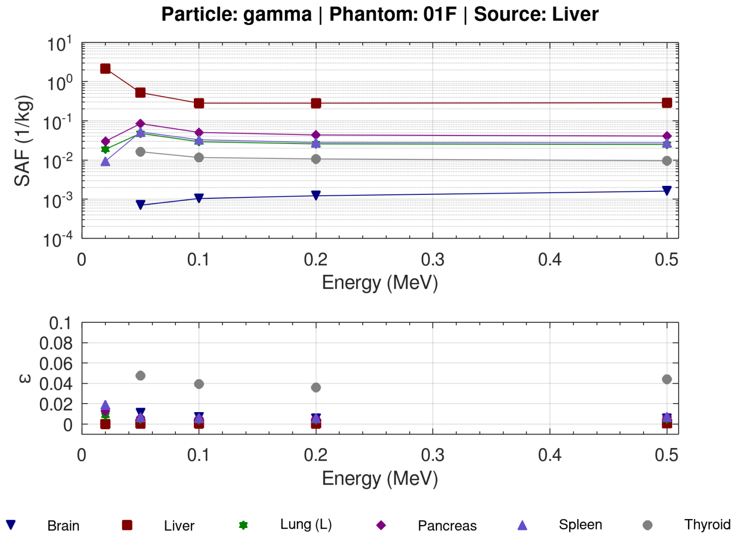


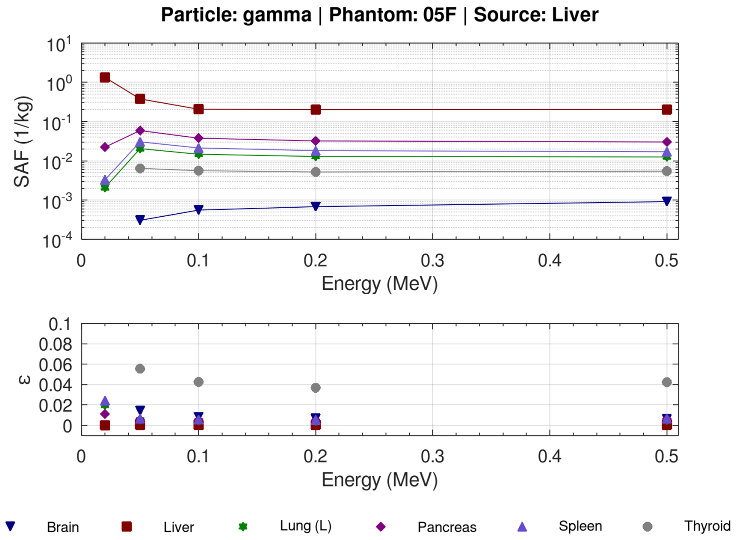
- No significant differences between F and M results for newborn and child models, slight differ. increase for adolescent (for adult models higher differences, e.g. ICRP 110)

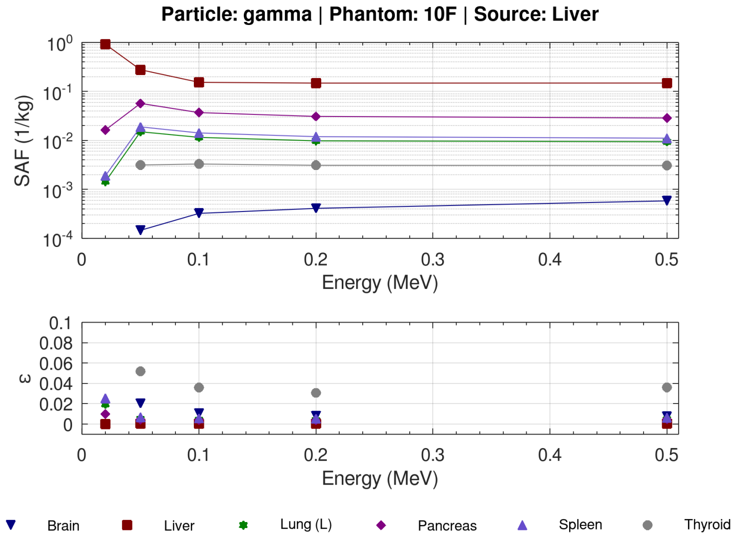
SAF results: photons, source: liver

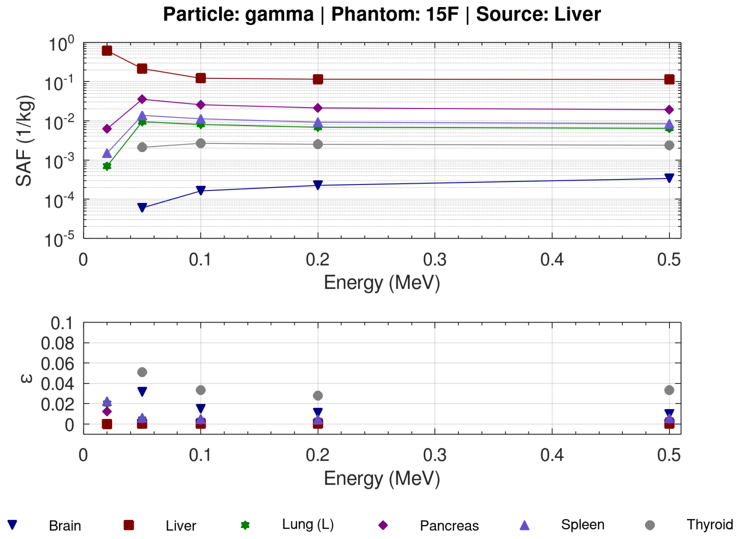








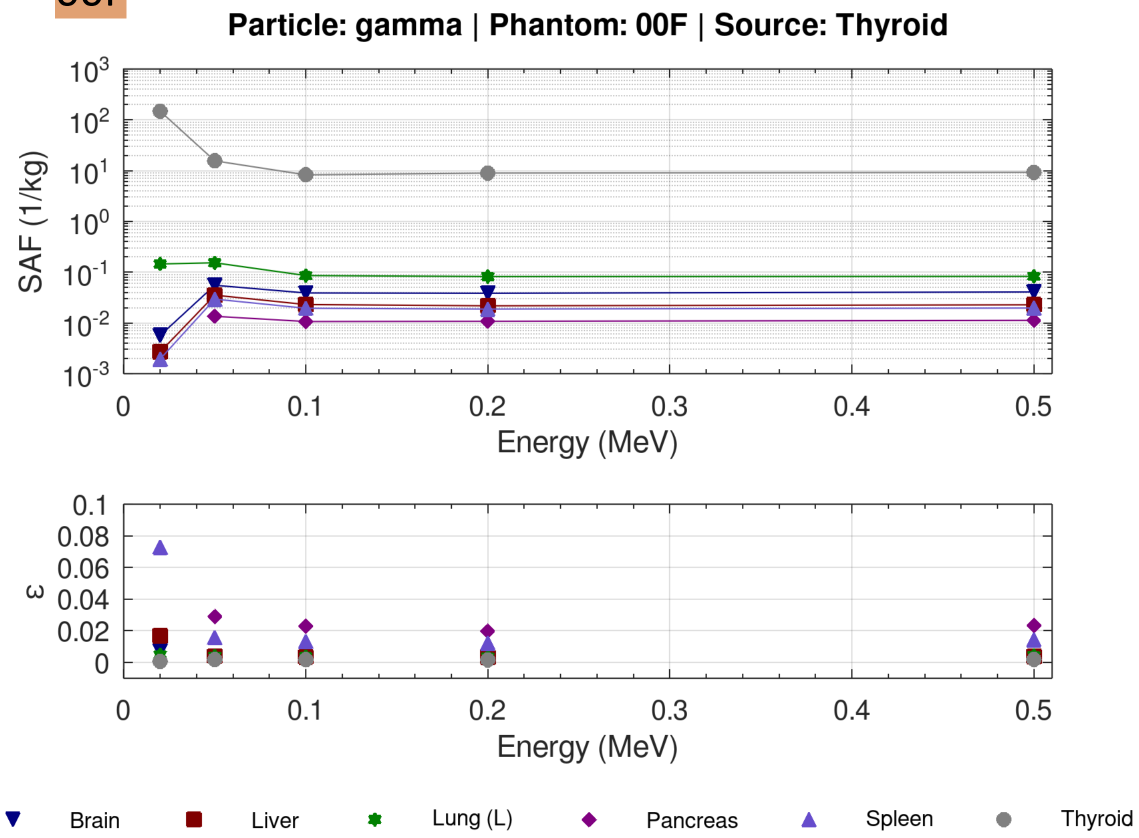




- Photon SAFs decrease as model age increases → larger organ volumes and organ – organ distances

SAF results: photons, source: thyroid

00F

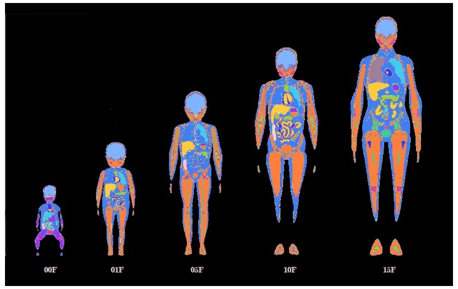


SAF (1/kg)	0.02 MeV	0.05 MeV	0.10 MeV	0.20 MeV	0.50 MeV
Brain		2.47E-03	3.56E-03	3.94E-03	4.62E-03
Liver	1.39E-05	2.25E-03	2.57E-03	2.43E-03	2.46E-03
Lung (L)	1.40E-02	2.80E-02	1.80E-02	1.64E-02	1.61E-02
Pancreas		5.04E-04	9.52E-04	9.37E-04	1.06E-03
Spleen		1.29E-03	1.66E-03	1.61E-03	1.68E-03
Thyroid	2.83E+01	3.66E+00	1.90E+00	2.01E+00	2.10E+00

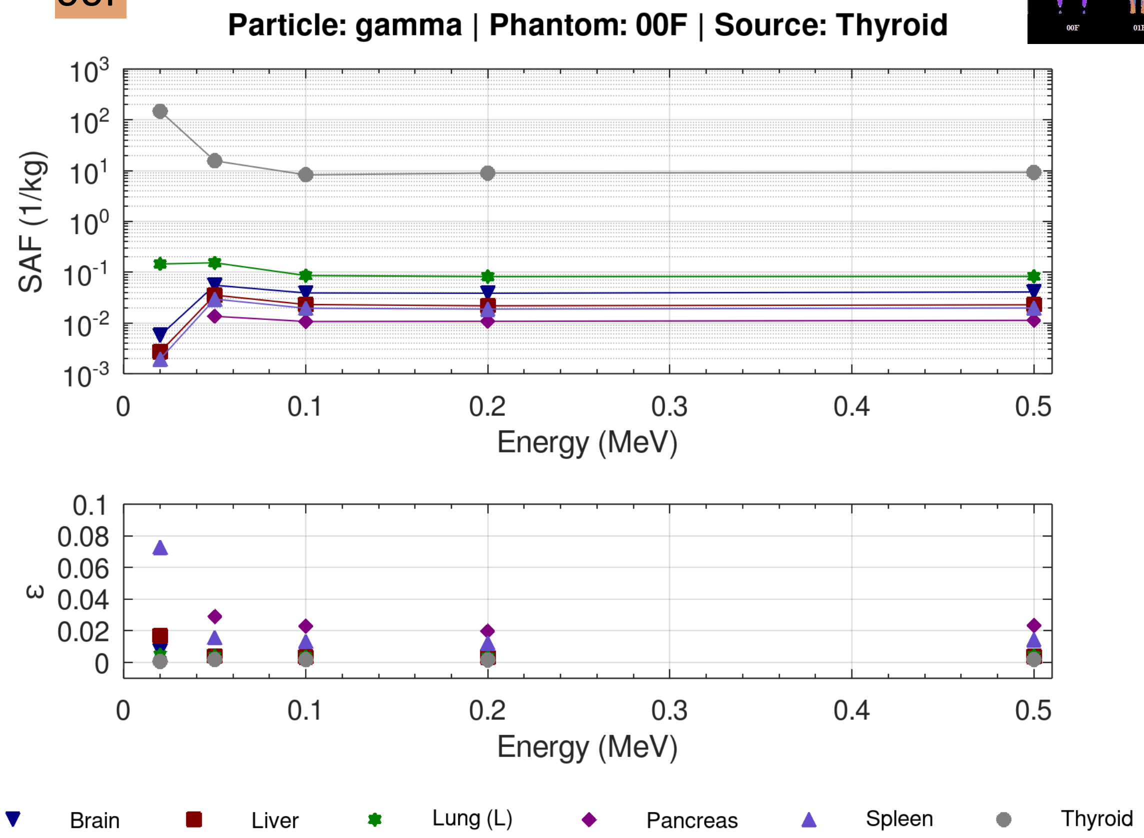
ε	0.02 MeV	0.05 MeV	0.10 MeV	0.20 MeV	0.50 MeV
Brain		4.97E-03	3.22E-03	2.72E-03	2.77E-03
Liver	7.39E-02	5.09E-03	3.69E-03	3.28E-03	3.57E-03
Lung (L)	4.53E-03	2.72E-03	2.41E-03	2.25E-03	2.70E-03
Pancreas		3.63E-02	1.94E-02	1.56E-02	1.66E-02
Spleen		2.04E-02	1.33E-02	1.11E-02	1.24E-02
Thyroid	4.37E-04	1.24E-03	1.19E-03	1.14E-03	1.33E-03

➢ Changing the source changes relative SAF importance in the other organs

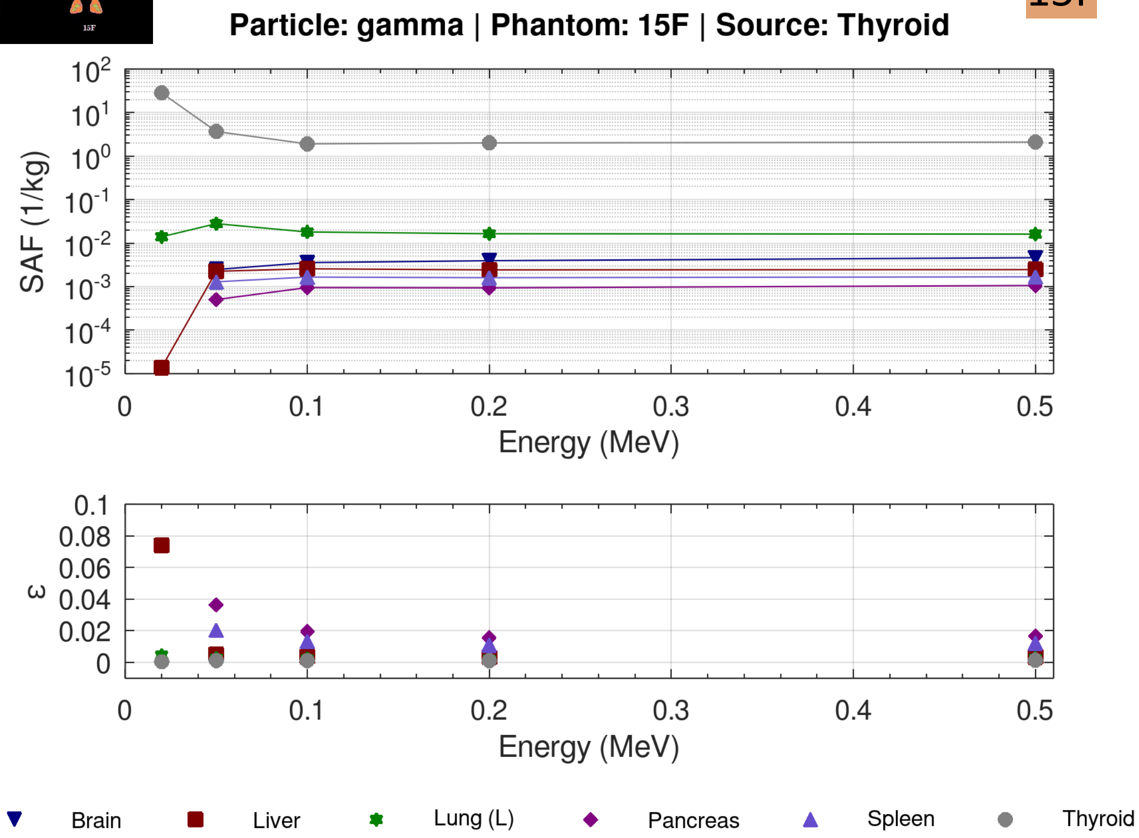
SAF results: photons, source: thyroid



00F



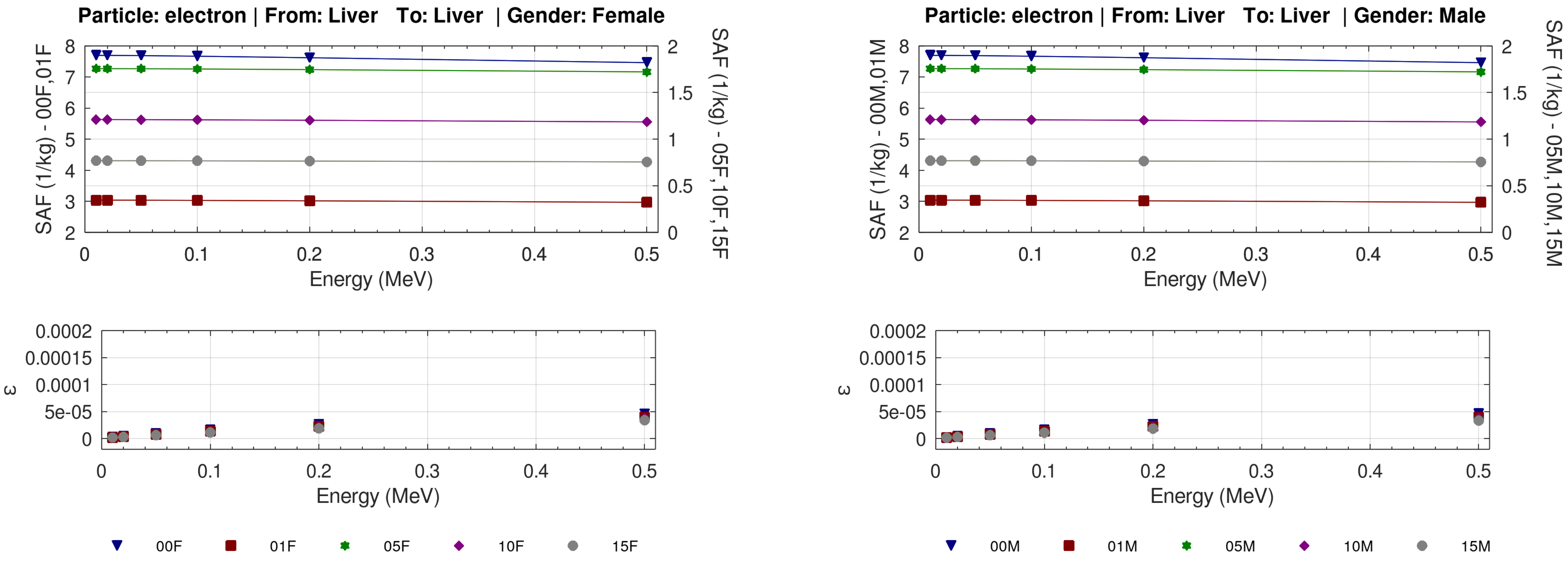
15F



- Decreasing photon SAF trend with increasing age also in this case

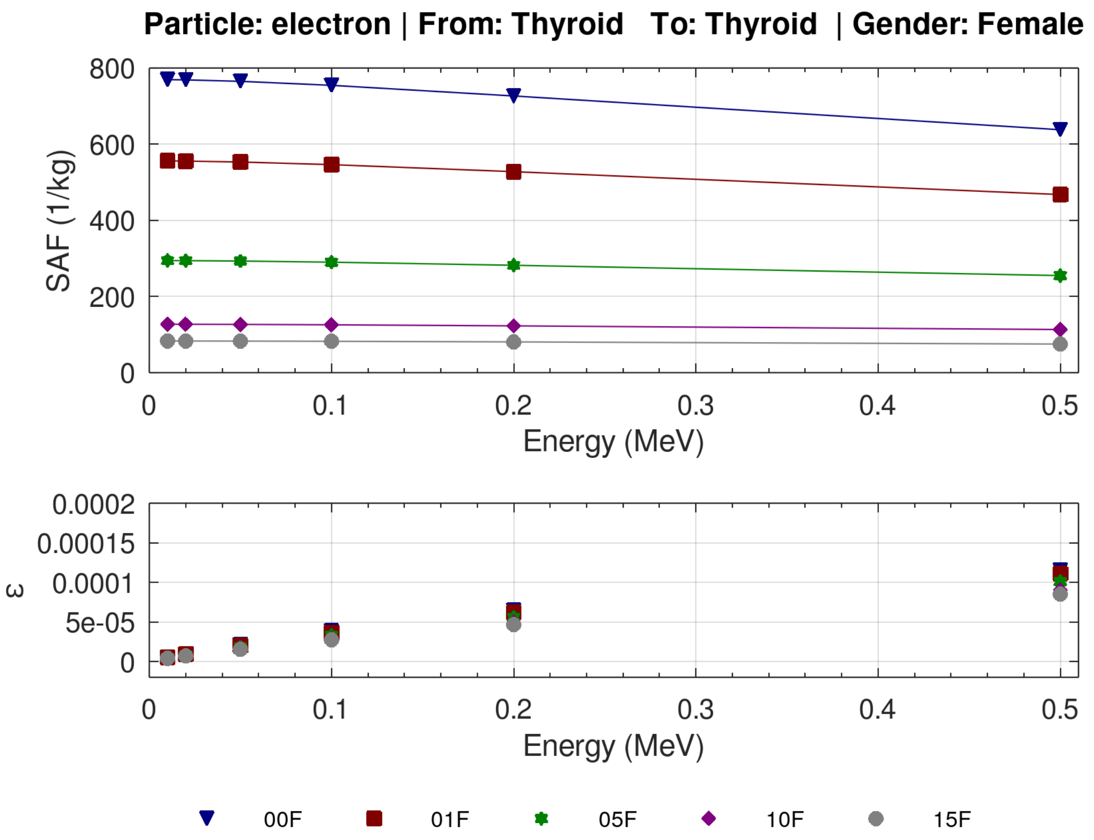
SAF results: electrons, source: liver

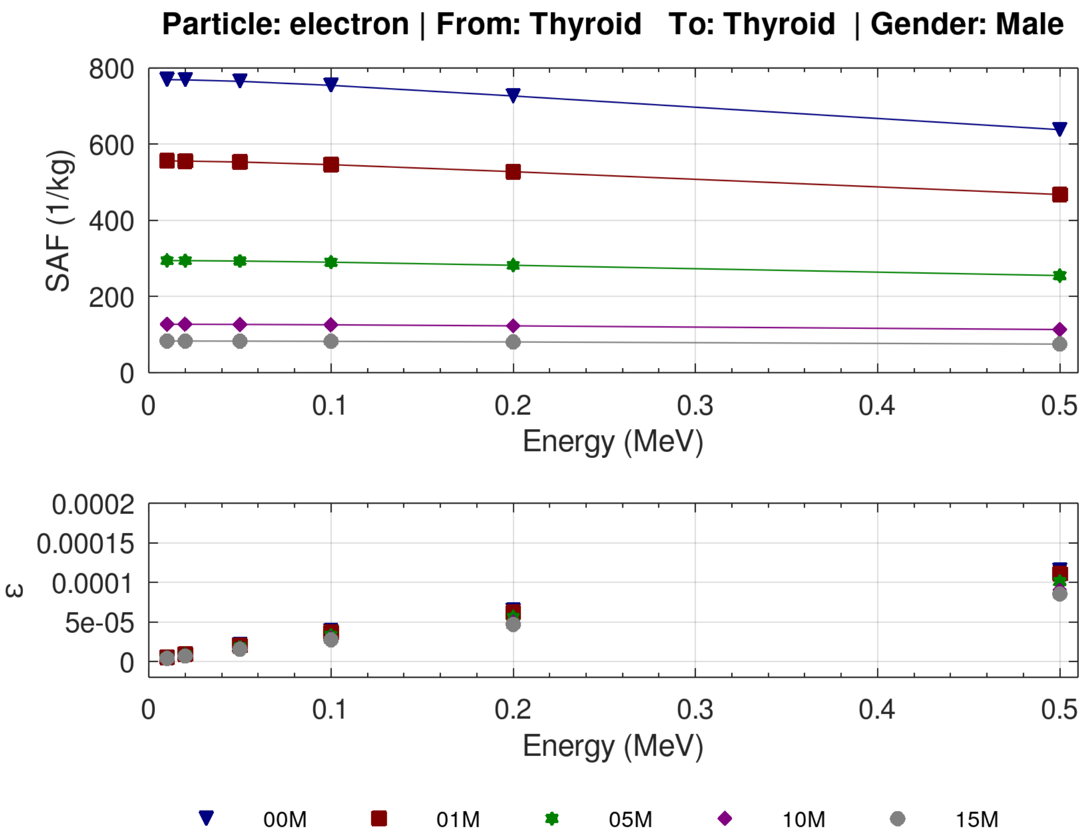
➢ Running 1e7 events guaranteed electron auto-SAFs (i.e., source = target) with statistical uncertainties well below 1%, but, as expected, uncertainties on average > 10 % for most of other target organs → focus on auto-SAFs only



➢ Decreasing electron auto-SAF trend with increasing energy and increasing age → increasing organ sizes and surfaces → e- release more energy outside

SAF results: electrons, source: thyroid





- Decreasing electron auto-SAF trend with increasing age more pronounced → thyroid smaller size and different shape w.r.t. liver

Conclusion and perspectives

Summary

- First GATE/GEANT4 SAF data on UF/NCI paediatric models
- Current status of analysis: SAFs for photons and electrons, 10 paediatric phantoms, 2 source organs, 6 target organs,

Near future

- Extend the analysis to more source and target organs
- Compare SAF results with the only other existing data on UF/NCI paediatric phantoms (done with MCNPX)

Long term

- Create a database for paediatric SAFs

Thank you for your attention!

And special thanks the colleagues from University of Messina collaborating on this research work:

Paola Mantineo (this work was a huge part of her Thesis for her Master's Degree in Physics discussed on December 2024)
Lucrezia Auditore
Ernesto Amato

Daniele Pistone, PhD
Dipartimento di Matematica e Fisica, Università degli Studi della Campania "Luigi Vanvitelli", Caserta & INFN, Sezione di Napoli

daniele.pistone@unicampania.it

Slide

- Content