Calculation of secondary organ doses in proton therapy based on whole-body pediatric and adult phantoms

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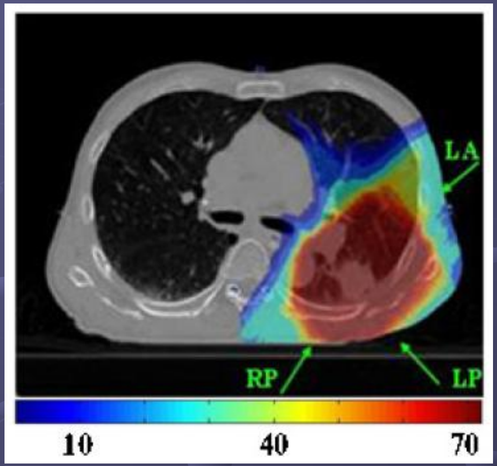
Motivation

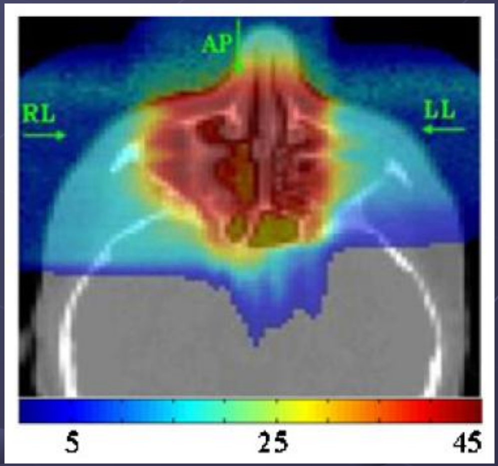
- Improved chemotherapy, surgical and radiotherapy techniques have resulted in higher cure rates of pediatric patients
- Children surviving cancer have a higher risk for developing secondary tumours (both genetic and treatment related predisposition)
- Proton beams prefered to other modalities due to optimal target conformation and significant reduction of healthy tissue irradiation
- Concern for secondary dose because of high RBE and range of neutrons produced in the treatment head and in the patient

Previous Study

H. Jiang et al., PMB 50 (2005) 4337-4353

- Effective dose calculation for two treatment plans for a whole-body adult phantom: 0.162 Sv (lung) and 0.0266 Sv (paranasal sinus) (the ICRP annual occupational limit is 0.02 Sv)
- Secondary organ dose was found to be in general three orders of magnitude lower than target dose / dependence on distance between organ and target / relates to beam range and modulation, shape of aperture and compensator





Aim of Present Study

Assess phantom (patient) age dependence of secondary organ dose calculation

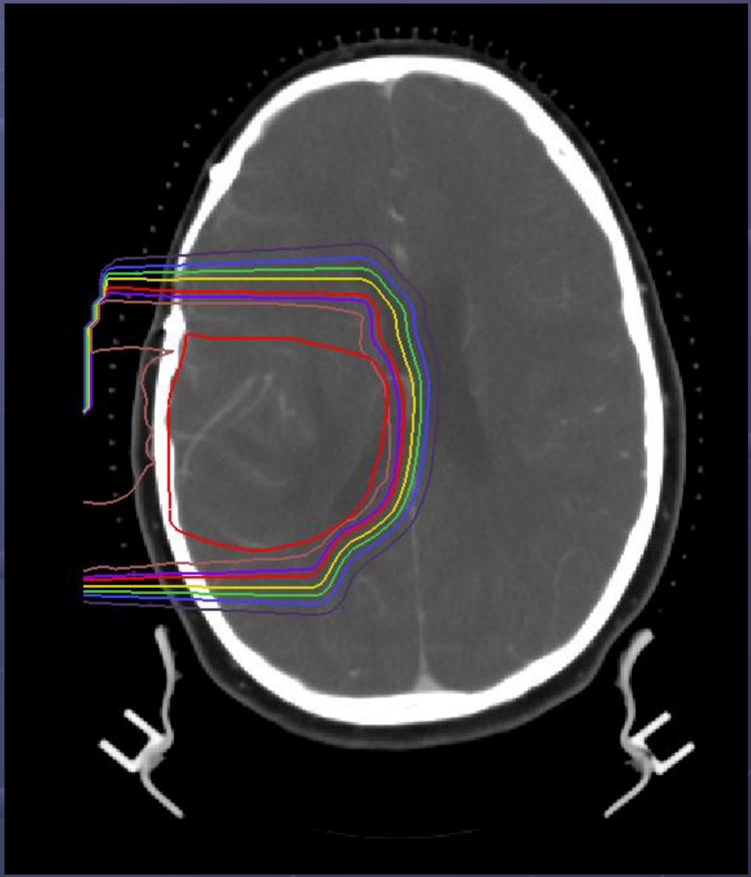
- Age-dependent tissue composition and density
- Larger part of a pediatric patient is exposed to scattered radiation from the treatment head than in the case of the adult
- Secondary dose is therefore expected to be higher for children than for adults

Method

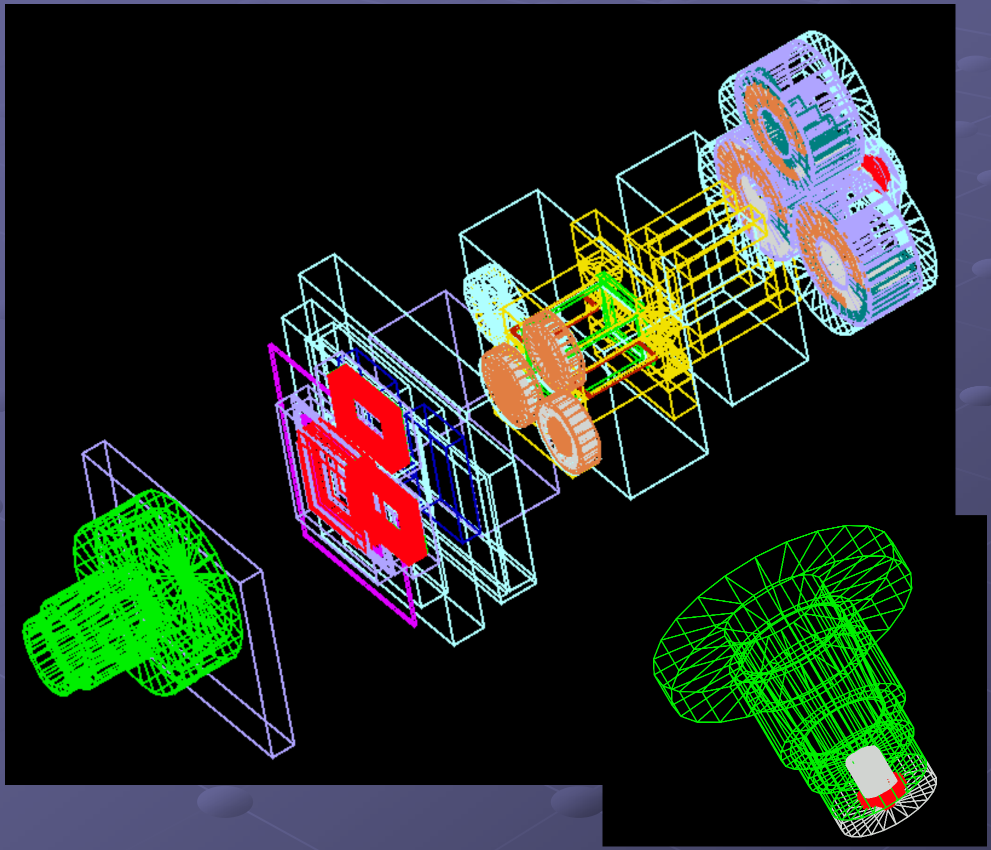
- Patient case (H&N)
- Simulation of treatment field
- Implementation of virtual patients
- Energy deposition and neutron fluence in specific organs
- Radiation factors
- Organ equivalent dose
- First part of study: Geant4 8.0 p01

H&N patient

- Case:
  - 9-year-old patient diagnosed with a left temporal tumour
  - Treated at F.H.B. Proton Therapy Center with 3 fields (LL and two oblique) for a total dose of 54 Gy in 30 fractions
  - Geant4: simulation of left lateral field (gantry angle at 90°) assuming 2 Gy target dose



Phase-space simulation



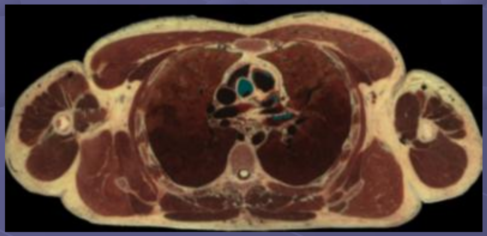
H. Paganetti et al., Med. Phys. 31 (2004) 2107-2118

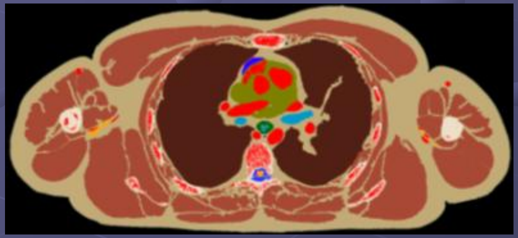
- Model of the treatment head:
  - ionization chambers
  - magnets
  - range modulation wheels
  - scatterers
  - jaws
  - snout (aperture, compensator)

- Separate phase-spaces for protons and neutrons to distringuish between external (nozzle) and internal (patient) neutron doses

Adult phantom

- VIP-Man model developed from axial cryosection photographic images of the cadaver of a 39-year-old male (Visible Human Project)





- 63 segmented organs/tissues
- Number of voxels: 147 x 86 x 470
- Resolution: 4 mm x 4 mm 4 mm

G. Xu et al., Health Phys. 78 (2000) 476-485

UF Pediatric Voxel Phantoms

- Series A:

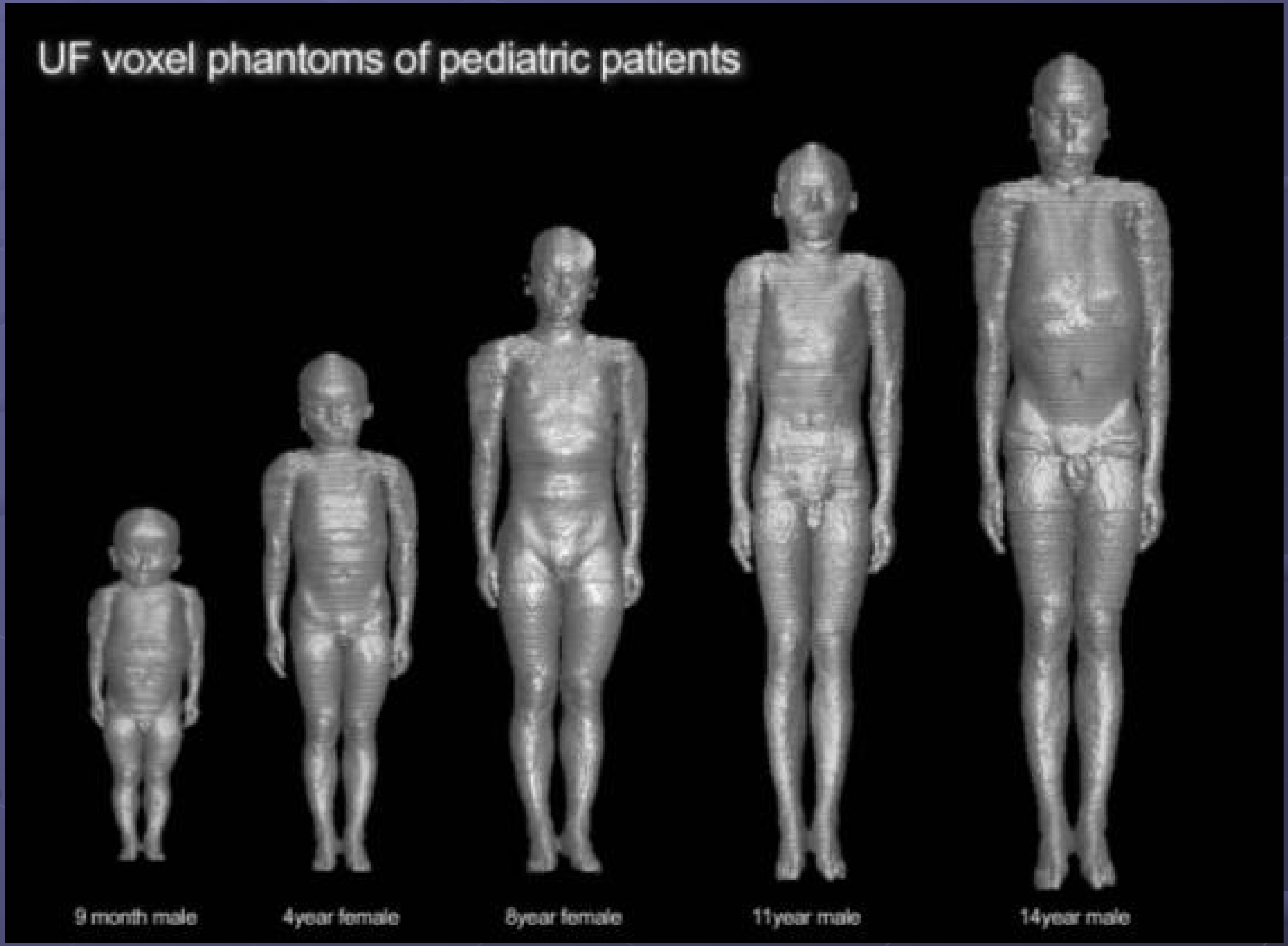
  - Reconstructed from (fused) patient CT images (head and chest-abdomen-pelvis examinations)
  - Semi-automatic organ segmentation (except for lung, bone and adipose)
  - Reference values for skin thickness (Cristy and Eckerman)
  - Age and gender specific elemental organ/tissue compositions and densities (ICRU 46)
  - Organ masses adjusted to match reference values

- Series B:

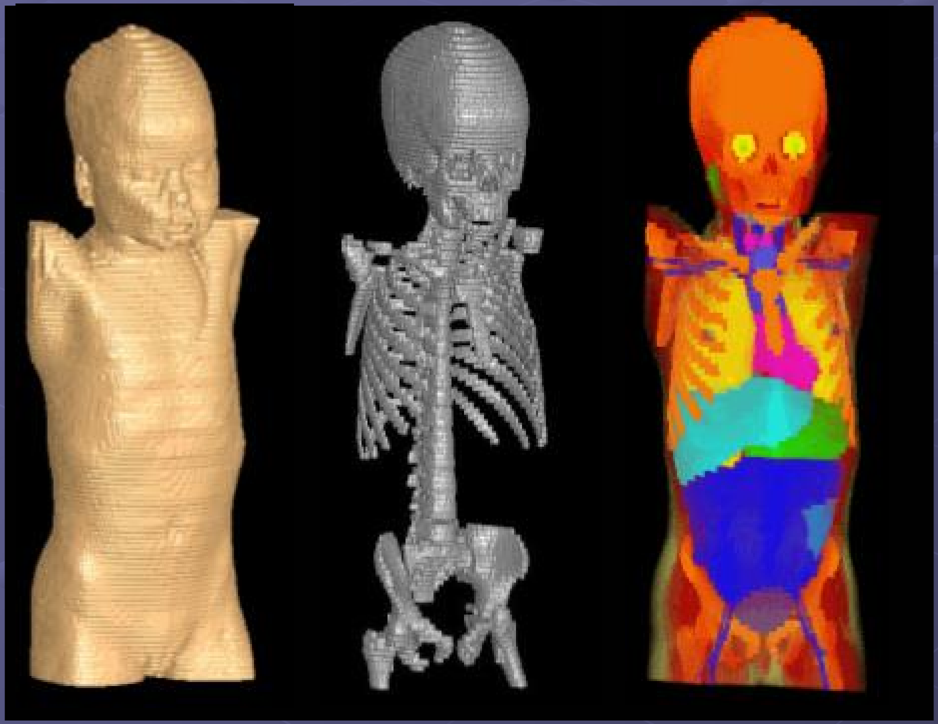
  - Images of extremities from whole-body CT scan of adult volunteer
  - Arms and legs scaled and attached to pediatric phantoms

C. Lee et al., Med. Phys. 32 (2005) 3537-3548, C. Lee et al., PMB 51 (2006) 4649-4661

UF Pediatric Voxel Phantoms

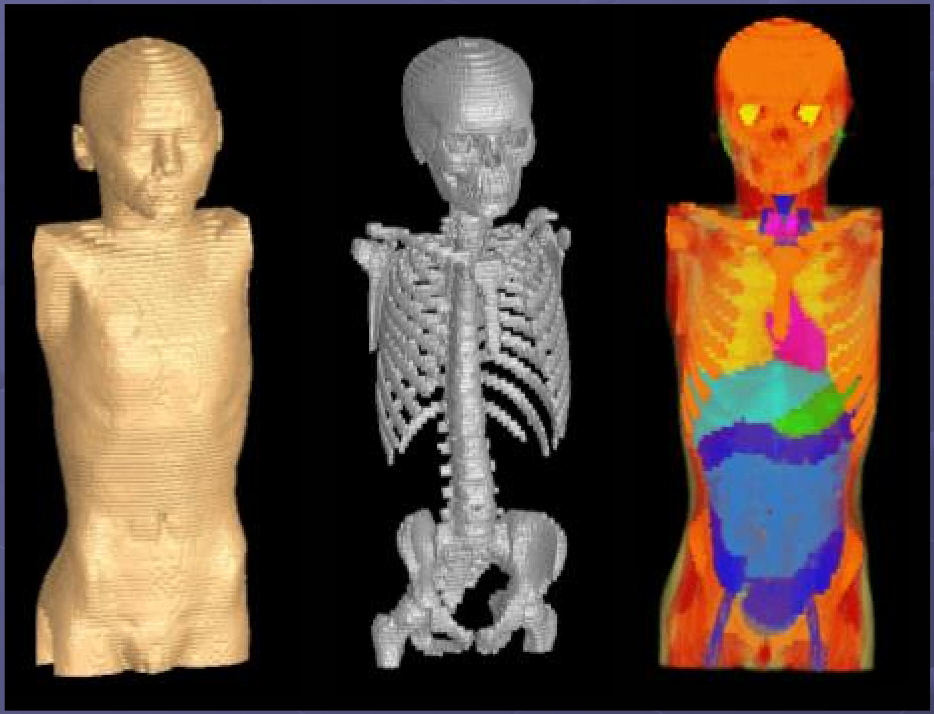


UF 4-year-old phantom



- 4-year female patient
- 64 organs/tissues
- Number of voxels:
  351 x 207 x 211
- Resolution:
  0.9 mm x 0.9 mm x 5 mm

UF 11-year-old phantom

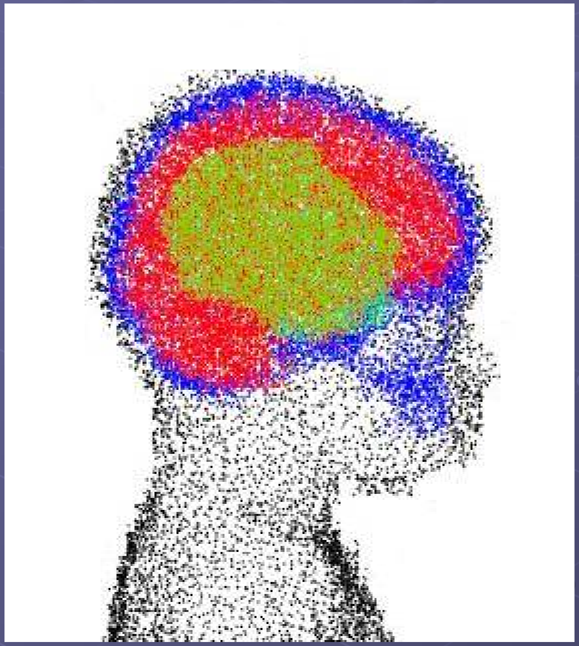


- Fused images from a head exam (12-year-old) and a CAP exam (11-year-old) of male patients
- 63 organs/tissues
- Number of voxels:

  398 x 242 x 252
- Resolution:

  0.94 mm x 0.94 mm x 6 mm

Patient Set-up



- The phantoms were positioned so that:

- The field would be centered to the sagital view of the entire brain
- The air gap between the nozzle and the phantom would be the same as during treatment

Organ equivalent dose

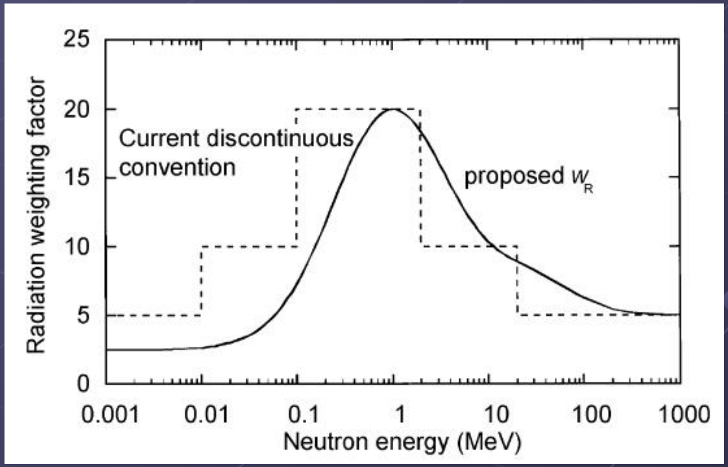
- The organ equivalent dose was calculated as

$$H_T = w_{R,T}\, D_{T,R}$$

where $D_{T,R}$ is the averaged absorbed dose to the organ T and $w_{R,T}$ is the neutron radiation factor for organ T

- H_T was normalized to target Gy

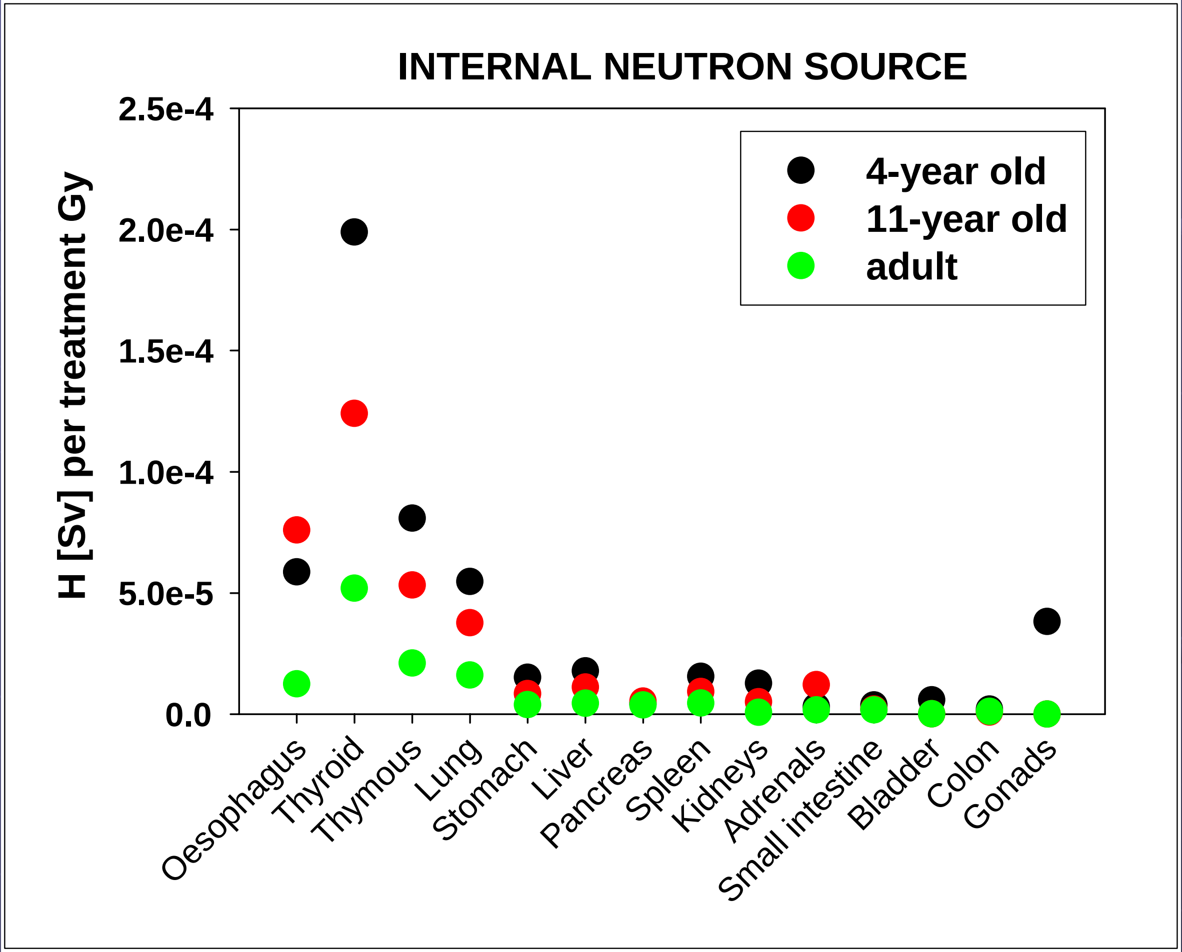
- The neutron radiation factors were calculated as weighted averages of the ICRU 60 definition and the energy distributions of neutrons entering an organ



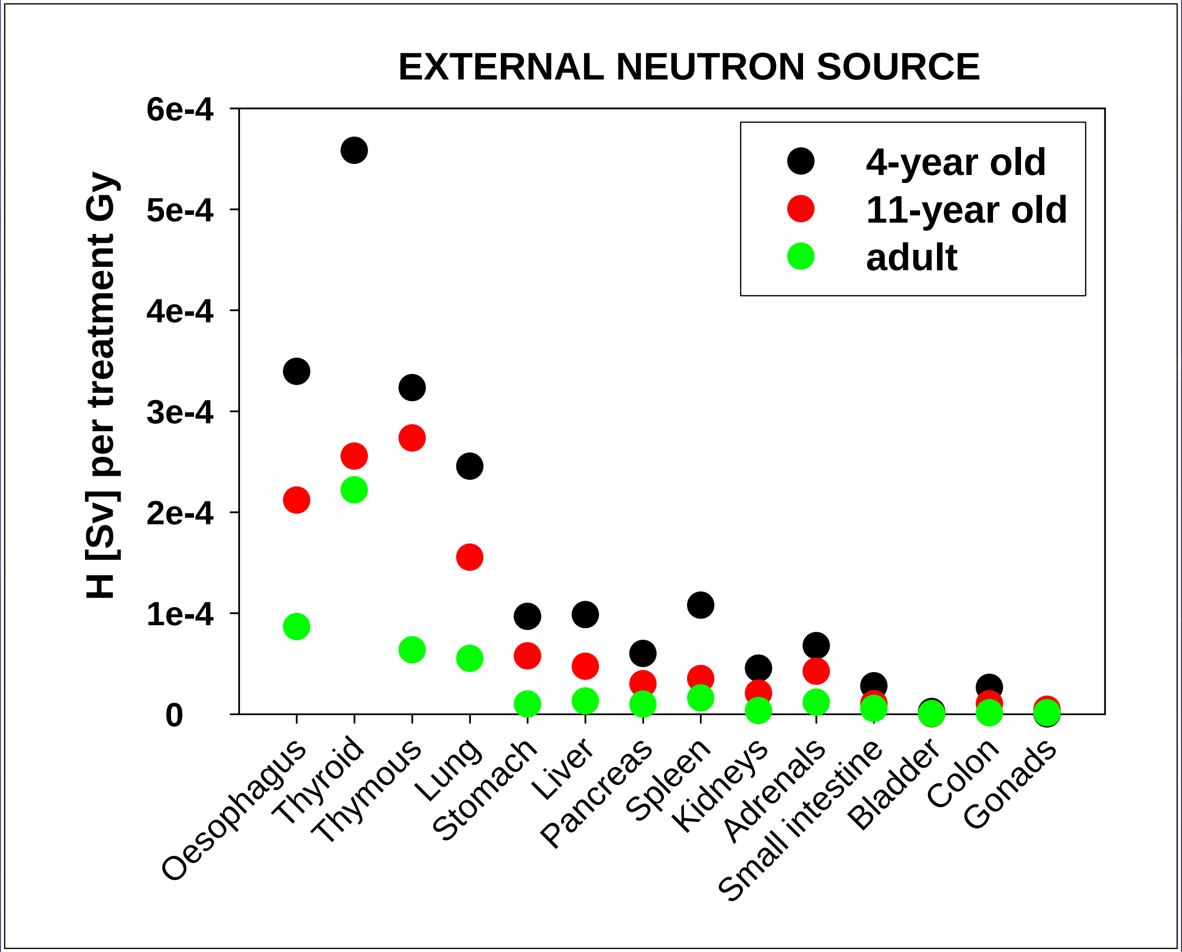
Results - Organ equivalent dose (Sv/Gy)

	4-year-old		11-year-old		adult	
Organ	H internal	H external	H internal	H external	H internal	H external
Gonads	3.81E-05	2.35E-08	0	4.55E-06	0	1.03E-06
Colon	1.95E-06	2.63E-05	7.72E-07	1.02E-05	1.03E-06	1.15E-06
Lung	5.47E-05	2.45E-04	3.76E-05	1.55E-04	1.60E-05	5.50E-05
Stomach	1.51E-05	9.67E-05	8.42E-06	5.75E-05	3.82E-06	9.93E-06
Bladder	5.82E-06	2.33E-06	1.53E-10	1.40E-09	3.76E-10	2.39E-07
Liver	1.77E-05	9.83E-05	1.11E-05	4.72E-05	4.37E-06	1.28E-05
Oesophagus	5.86E-05	3.39E-04	7.59E-05	2.12E-04	1.24E-05	8.64E-05
Thyroid	1.99E-04	5.58E-04	1.24E-04	2.55E-04	5.19E-05	2.22E-04
Adrenals	3.04E-06	6.76E-05	1.21E-05	4.23E-05	1.70E-06	1.16E-05
Kidneys	1.27E-05	4.54E-05	5.06E-06	2.06E-05	6.57E-07	3.37E-06
Pancreas	4.22E-06	5.99E-05	5.22E-06	2.99E-05	3.69E-06	9.67E-06
Small intestine	3.68E-06	2.78E-05	2.00E-06	1.02E-05	1.69E-06	5.33E-06
Spleen	1.55E-05	1.08E-04	9.28E-06	3.50E-05	4.48E-06	1.58E-05
Thymus	8.08E-05	3.23E-04	5.32E-05	2.73E-04	2.09E-05	6.36E-05

Results - Organ equivalent dose



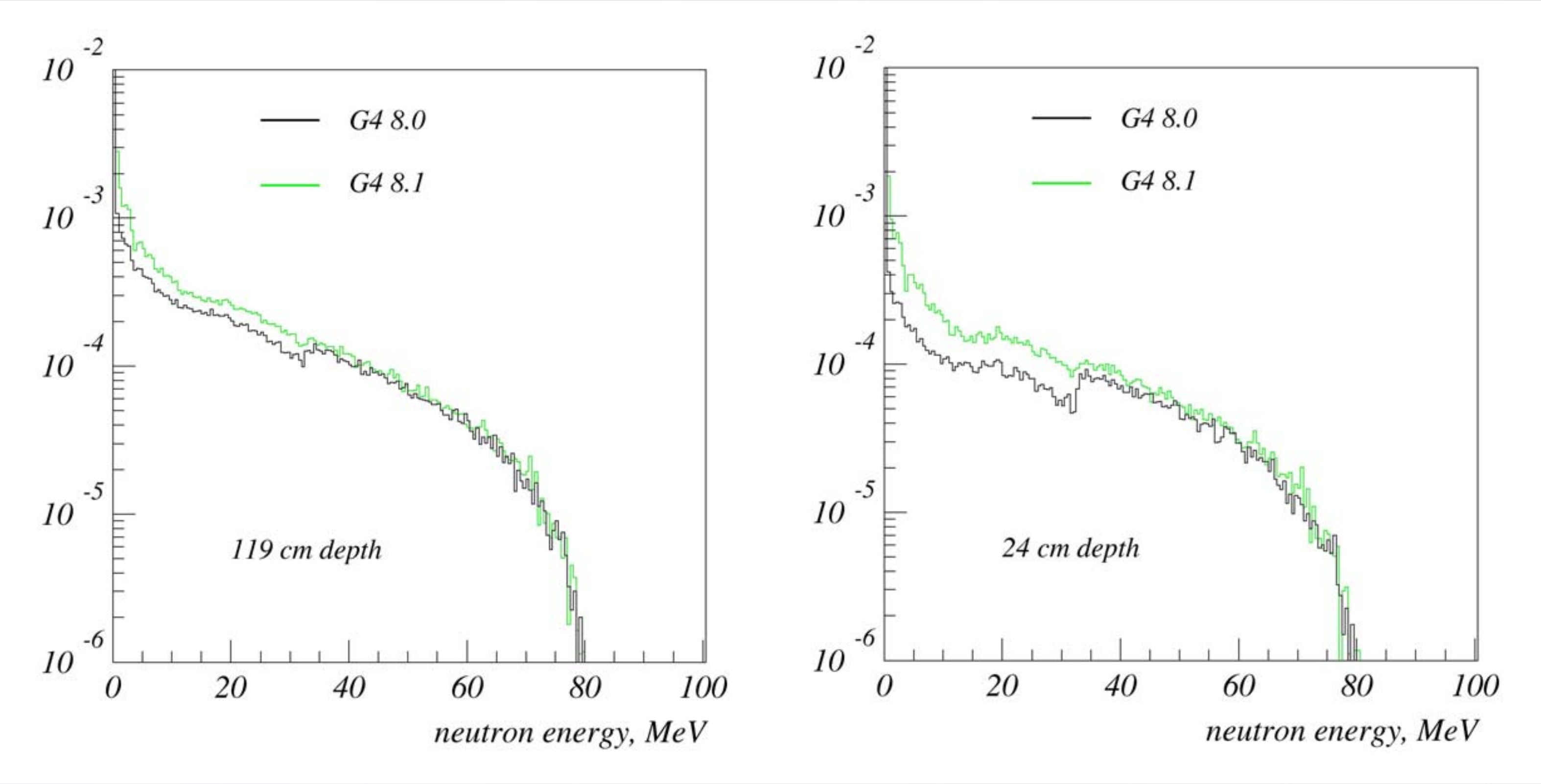
Results - Organ equivalent dose



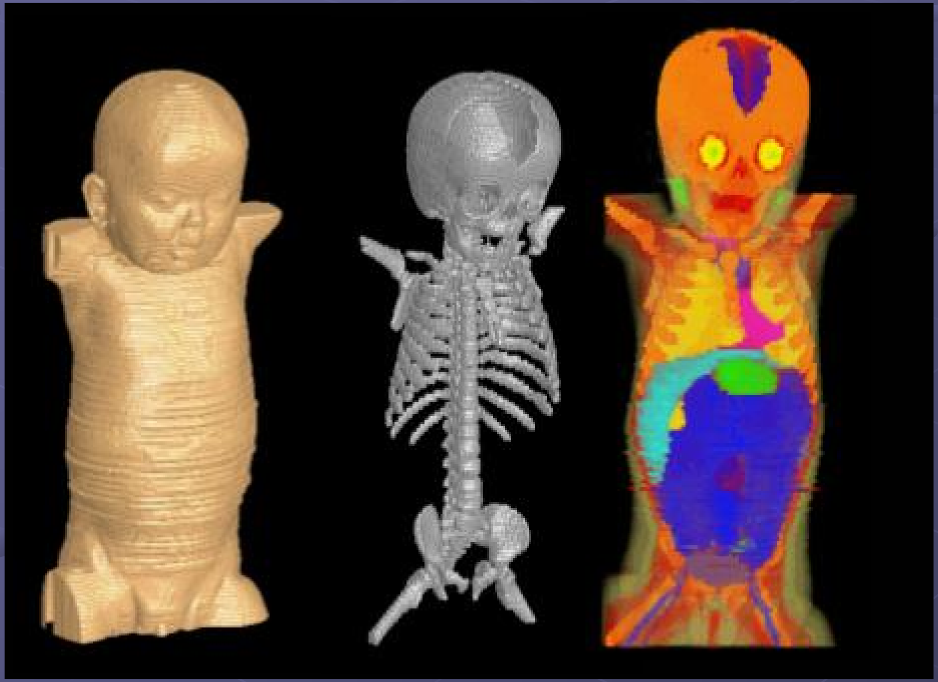
Current developments

- Improved neutron physics (Geant4 v. 8.1 p01)
- Complete UF phantom library

Neutron physics 8.0 vs 8.1



UF 9-month-old phantom

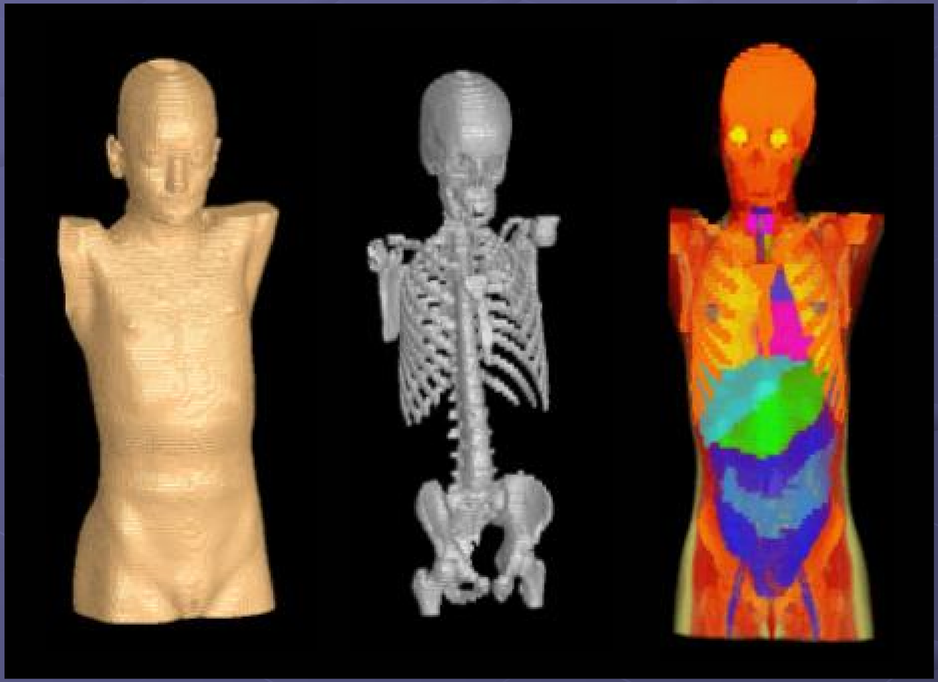


- 9-month male patient
- 63 organs/tissues
- Number of voxels:

  289 x 180 x 241
- Resolution:

  0.86 mm x 0.86 mm x 5 mm

UF 8-year-old phantom

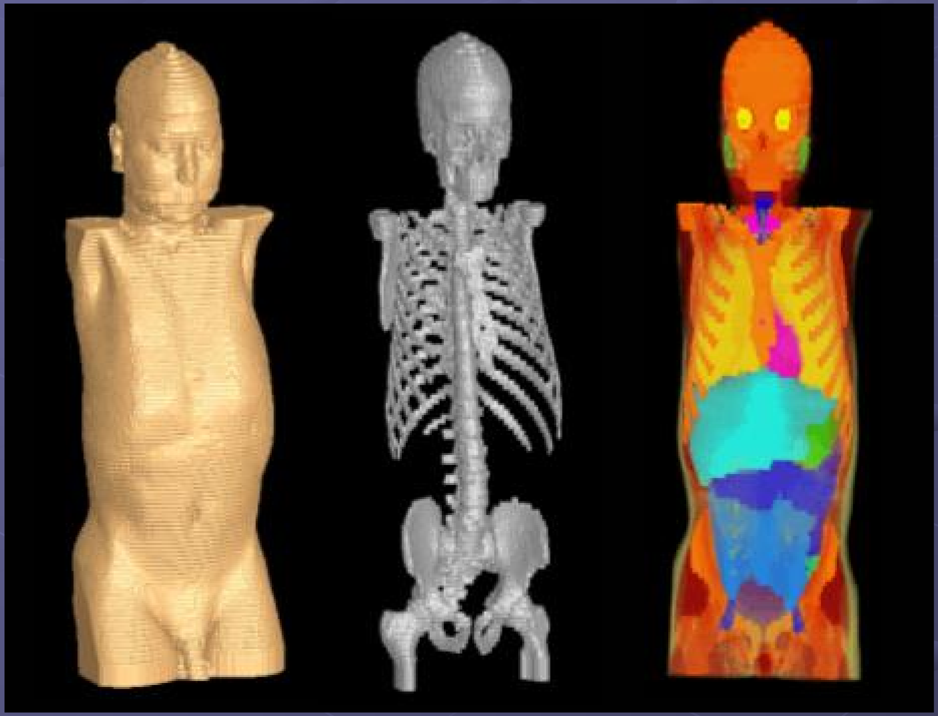


- Fused images from a head exam and a CAP exam of two female patients
- 64 organs/tissues
- Number of voxels:

  322 x 171 x 220
- Resolution:

  1.2 mm x 1.2 mm x 6 mm

UF 14-year-old phantom



- Fused images from a head exam and a CAP exam of two male patients
- 63 organs/tissues
- Number of voxels:

  349 x 193 x 252
- Resolution:

  1.2 mm x 1.2 mm x 7 mm

Conclusion

- Organ equivalent neutron doses have been calculated for a pediatric H&N case (left-lateral brain proton field) and three virtual patients (adult, 4-year-old, 11-year-old)
- The neutron dose depends on the distance between the organ and the target volume (both for external and internal neutrons)
- The pediatric phantoms received higher organ equivalent doses than the adult phantom
- Ongoing:
  - three additional phantoms (9-m, 8-y, 14-y)
  - calculation of dose to red bone marrow
  - investigation of more clinical cases

Acknowledgements

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