CHERNE Conference 2018

Cooperation in Higher Education on Radiological and Nuclear Engineering and Radiation Protection

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Analysis of the bias induced by the voxel and unstructured mesh Monte Carlo models with the MCNP6 code

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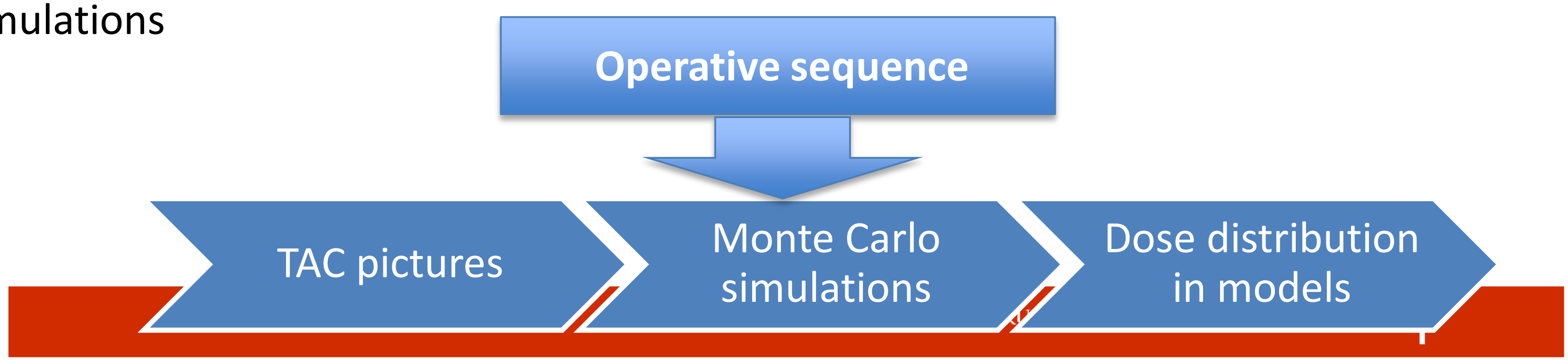
Superficial Radiotherapy with Photons
Orthovoltage treatments

- Collaboration with the Medical Physics Department IRCSS - Arcispedale S. Maria Nuova Reggio Emilia

- Superficial and Orthovoltaic Radiotherapy application areas:
  - Nonmelanoma Cutaneous Tumors
  - Cutaneous Mycosis

- Current treatment protocols
  - High rates of tumor control
  - Absence Treatment Planning System (TPS)

- Target: realization and evaluation of the benefits of a tps protocol based on Monte Carlo simulations



Issues:

- Transition from "slice" information contained in the TAC as gray scale (**Hounsfield** scale "dependent machine") to **volumetric and material information**

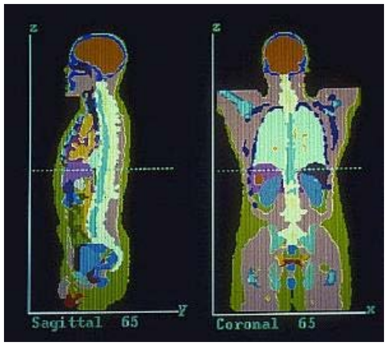
- Choice of the **most useful and fastest model geometry** from the simulation point of view to simulate the particles transport processes (photons) with a Monte Carlo code:
  - unstructured meshes (optimal option from the point of view of the **simulation of transport processes**)

- Choice of MC code: **GEANT, FLUKA, MCNP**:
  - GEANT & FLUKA procedures not yet consolidated for the transition from TAC to unstructured meshes

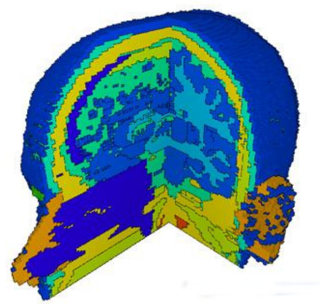
  - **Used Monte Carlo code: MCNP6.1.1**: Code **extensively tested and validated**, Integration with geometric models with non-structured meshes validated (also by manufacturers of therapy machines, eg VARIAN)

From TAC to Model for Transport processes: Anthropomorphic Computational Phantoms

Voxel Models



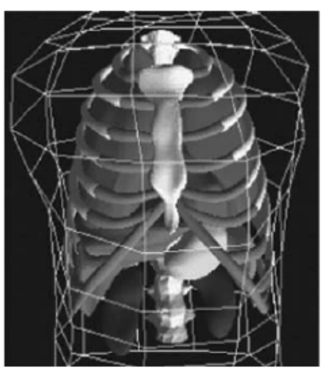
Zubal et al. 1994



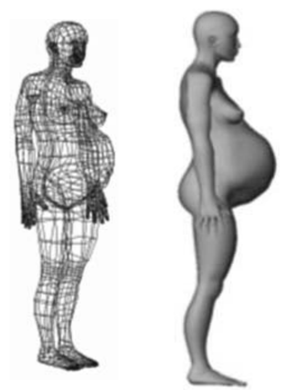
Zubal et al. 1995

- Field in great development
  - Computational power
  - Imaging techniques diffusion

Non structured mesh models (**UM NURBS type**)



Segars et al. 2001



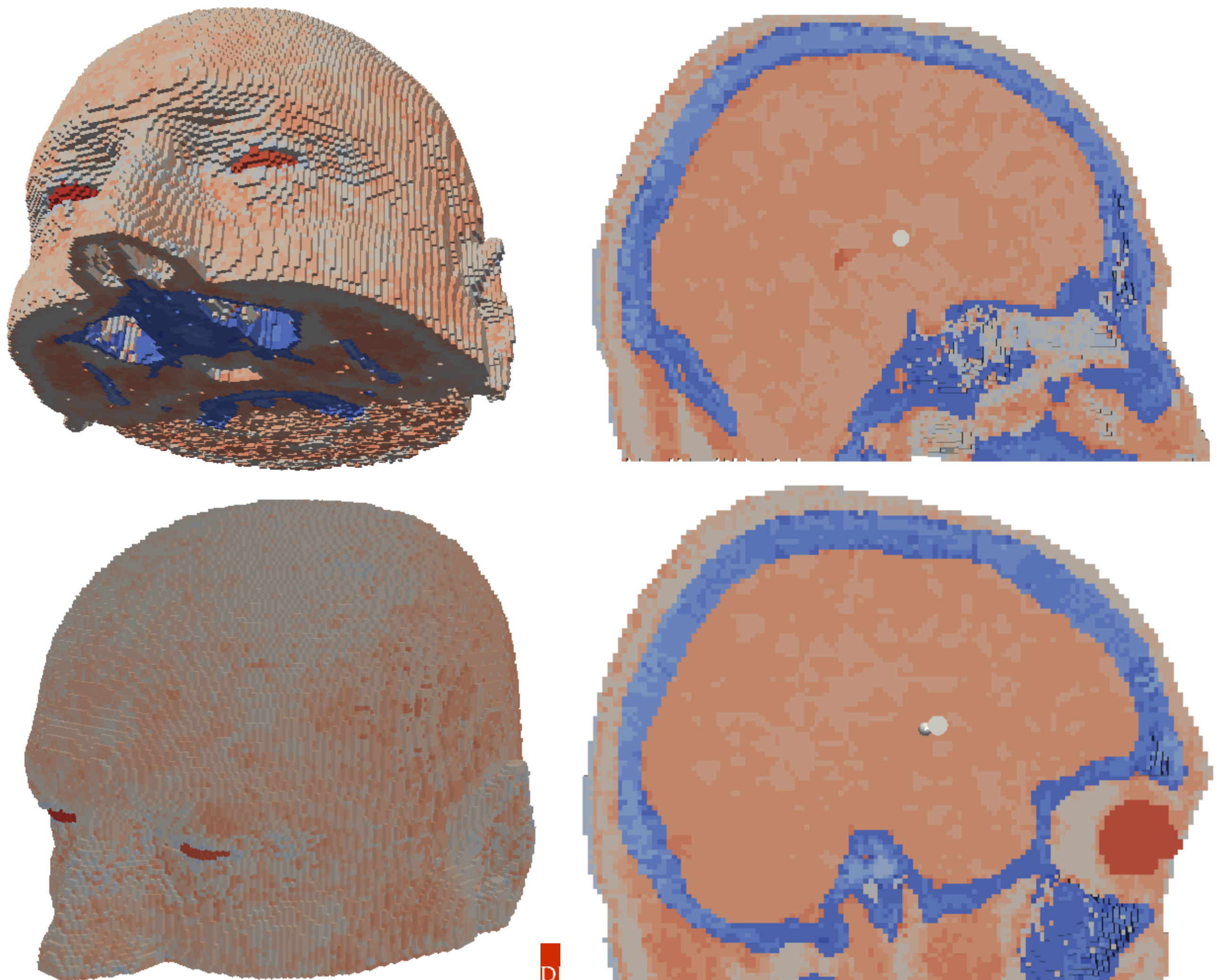
Xu et al. 2004

Benefits of the NURBS models:

- Better representation of volumes and surfaces
- Deformability
- 4D models
- Removal of Voxel effects due to geometric "bias"

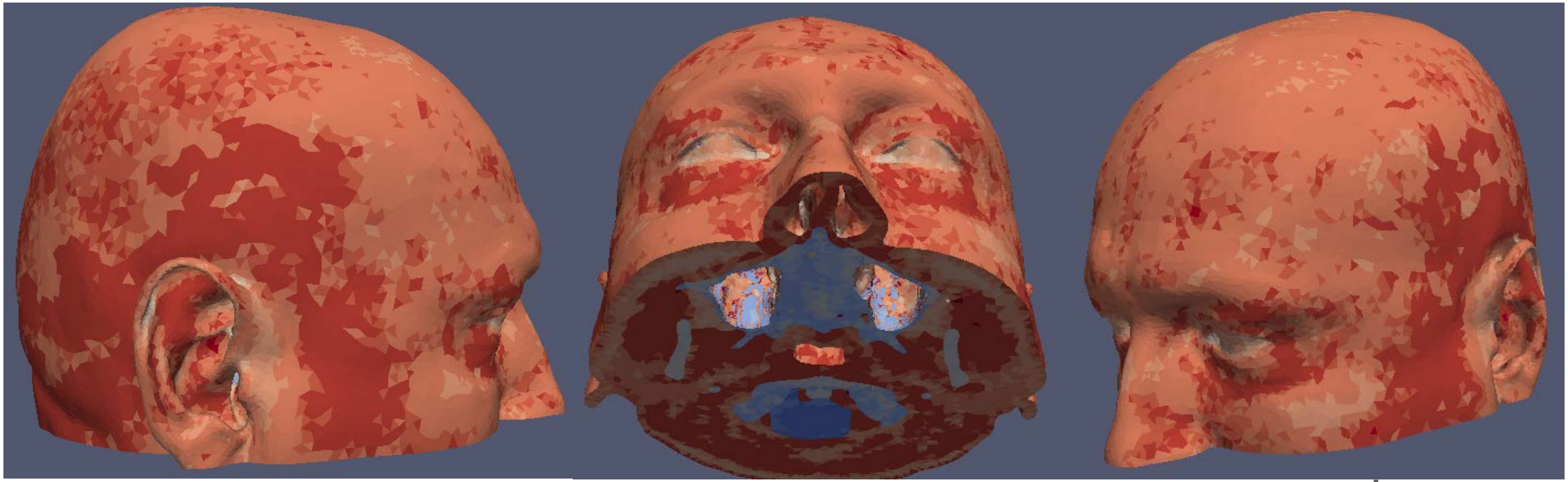
Voxel model visualization

- Cubic Voxels
- Every element has the same dimension as all the others
- The elements are parallel and simply traslated to each others



Unstructured mesh model visualization

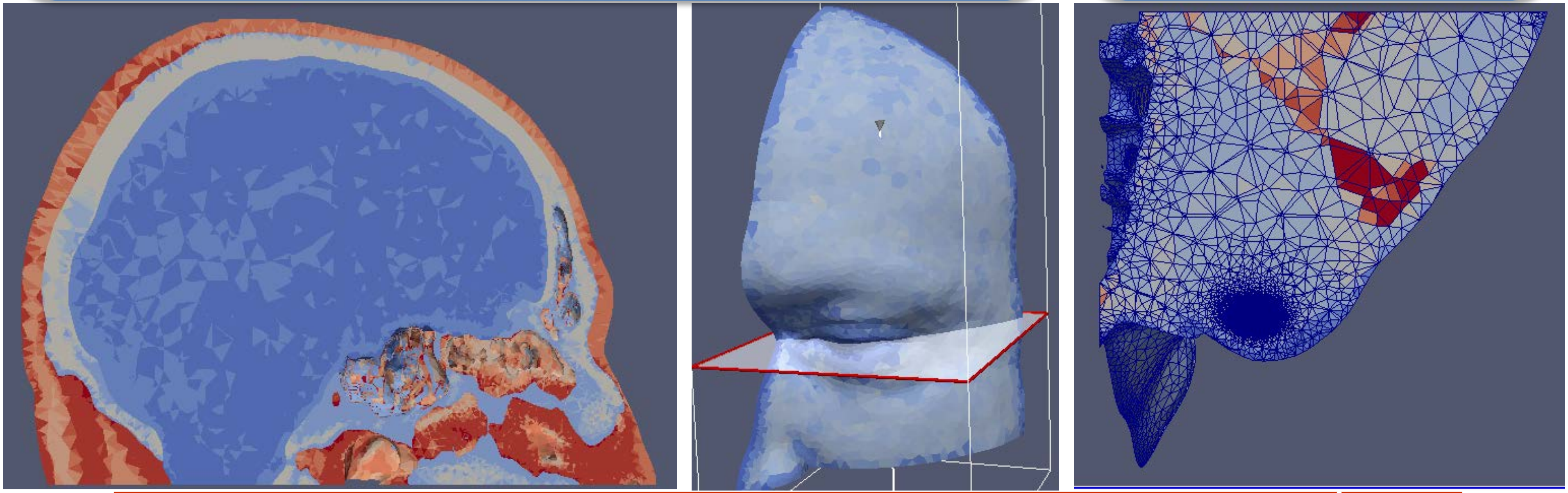
- The unstructured mesh models can be tetrahedal, exahedral,….
- The order of the mesh can be 1 or 2 (curved faces of the elements)
- The volumes are better descripted



Unstructured mesh model visualization

- The material inhomogeneities can be taken into account
- The UM is adaptatives, so, mesh refinements occurred to better descript the organ volumes
- The mesh can be refined or modified with different softwares
- The UM interfaces (between the elements) are distribuited in each direction

- Mesh refinements of size inferior to the TC resolution (1-2 mm) are admitted in homogeneous organs

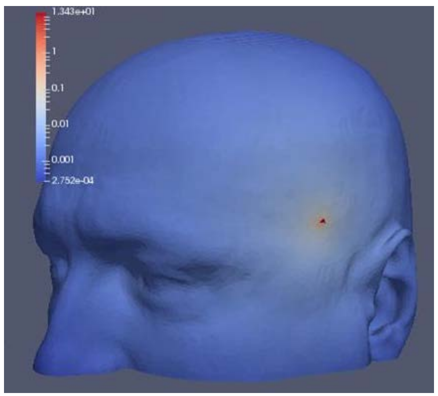


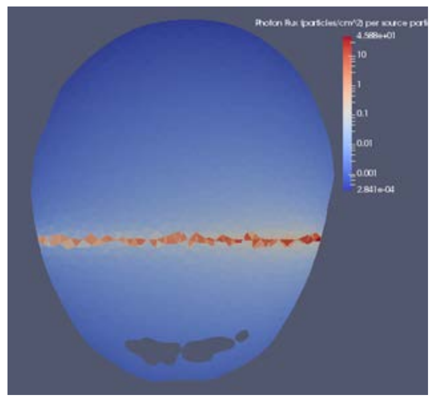
Example of Voxel effects on a TAC model

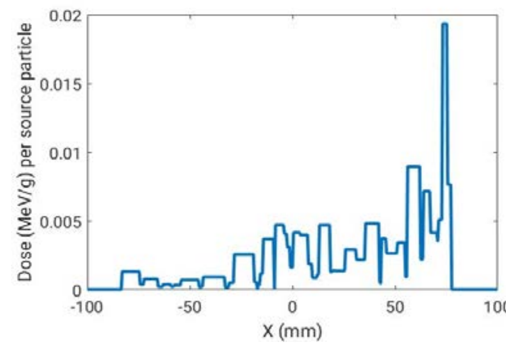
Monoenergetic point Beam Analysis in homogeneous material (water)

Impact Arrangement and Size of elements in areas with high gradient

Unstructured mesh

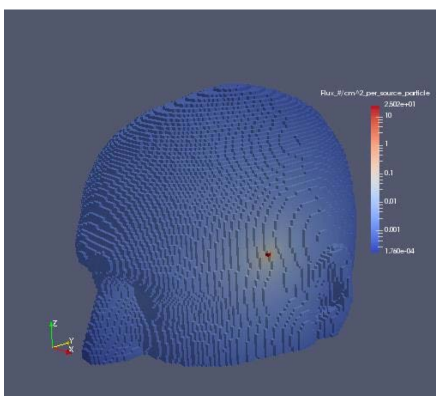


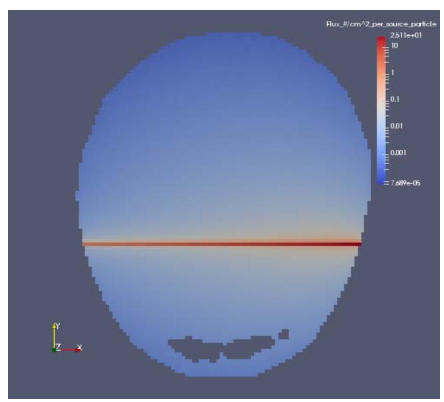


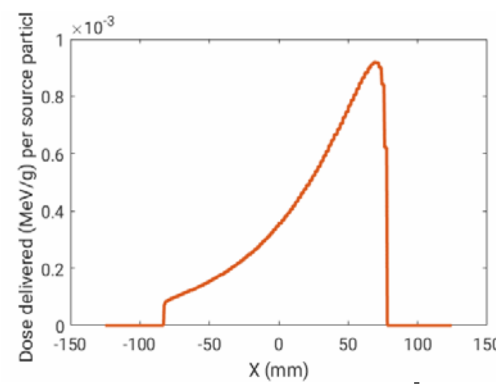


Dose profile on Unstructured meshes

Voxel 2 mm



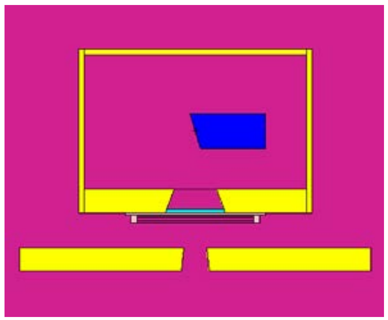


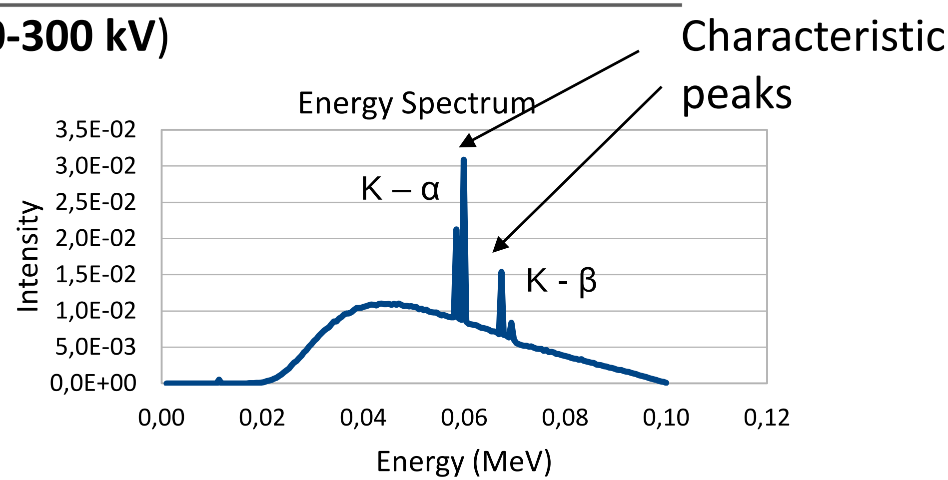


Dose profile on Voxel 2 mm

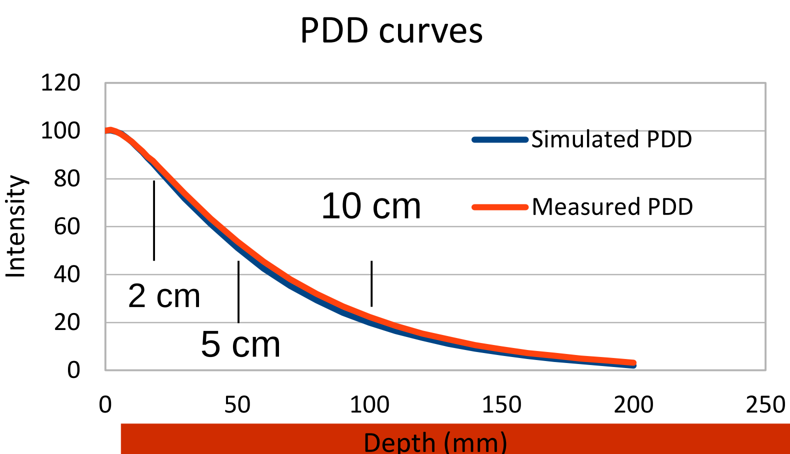
Source modeling

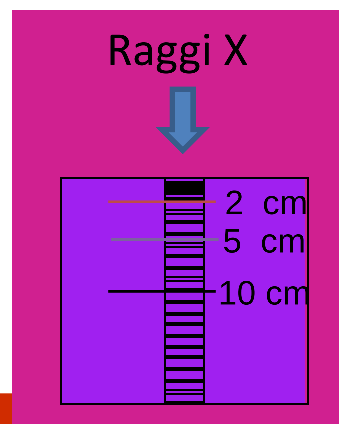
- **X-ray tube – Therapax DXT 300 (50-300 kV)**

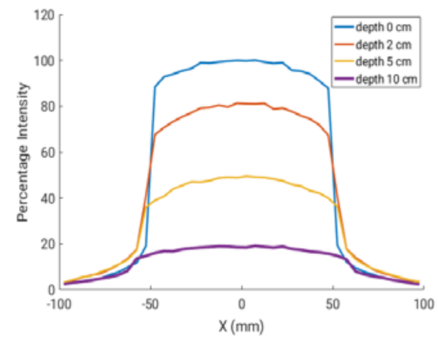




- **SEV & PDD Validation – Protocol IAEA 398**







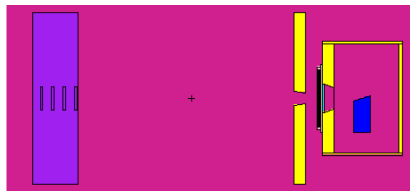
Open field 10 x 10 cm

Source validation

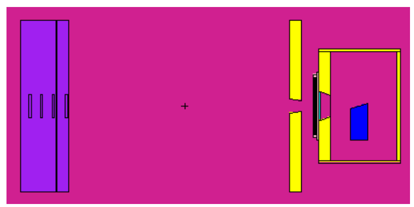
Experimental measurements on 3 instrumentated phantoms

Phantoms setup

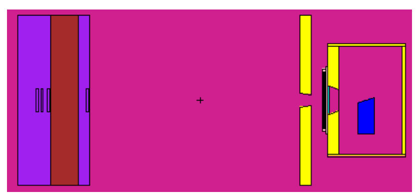
1) Homogeneous



2) 2.4 mm Al

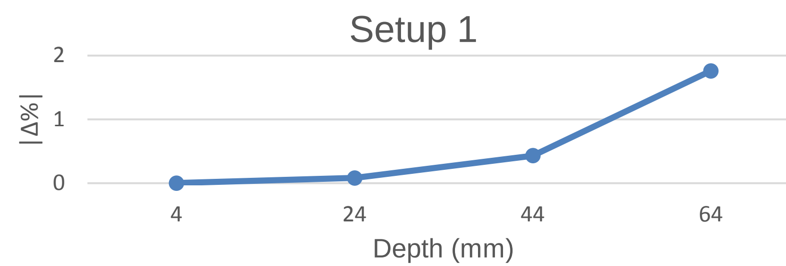


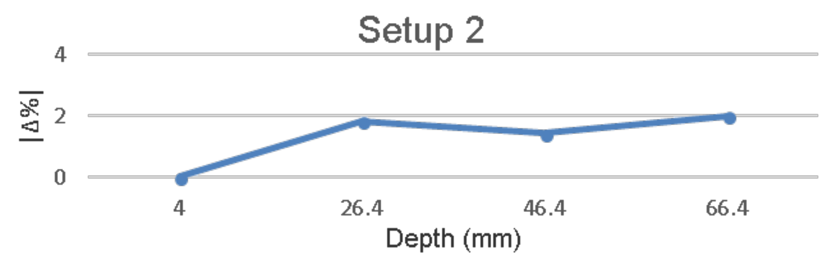
3) 5 cm XPS

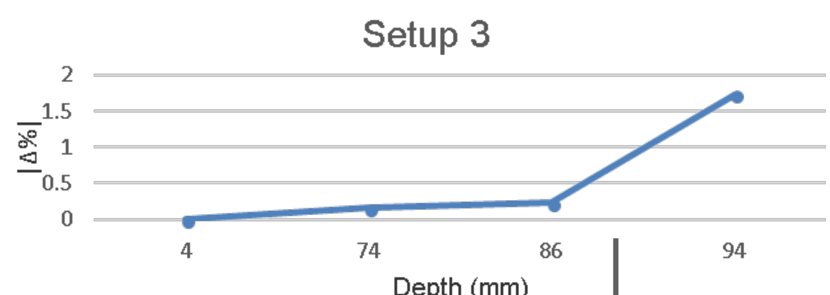


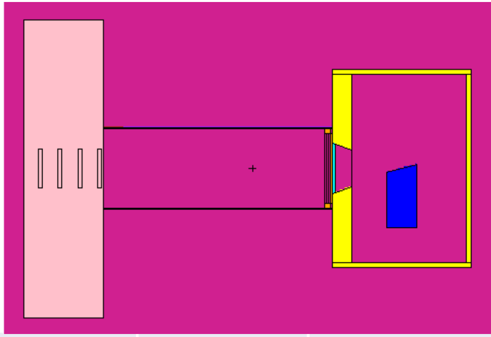
Setup	Tension (kV)	$\|\Delta\%\|_{Medio}$
1	100	0.75
2	100	1.74
3	100	0.70

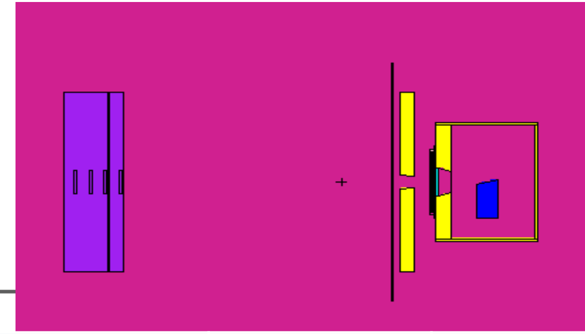
Relative differences between measurements and simulations





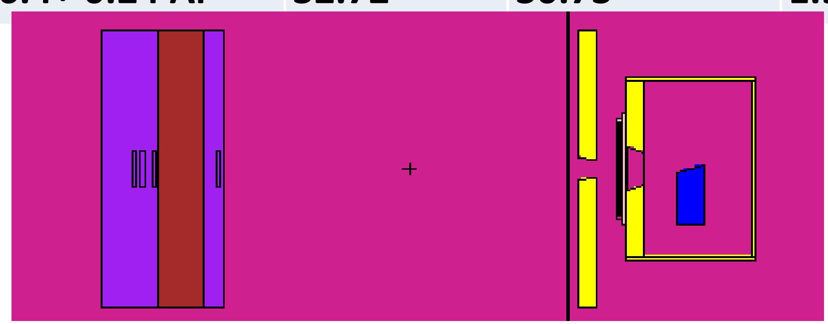






[kV]	Depth [cm]	Measure [%]	Simulation [%]	Δ%
50	0.4	100.00	100.00	0.00
50	2.4	46.67	52.54	5.87
50	4.4	22.60	27.16	4.55
75	0.4	100.00	100.00	0.00
75	2.4	62.03	60.33	1.70
75	4.4	36.37	34.96	1.41
100	0.4	100.00	100.00	0.00
100	2.4	79.78	79.70	0.08
100	4.4	57.58	57.16	0.43
100	6.4	39.04	37.28	1.76
300	0.4	100.00	100.00	0.00
300	2.4	86.29	86.03	0.26
300	4.4	68.22	67.62	0.60

[kV]	Depth [cm]	Measure [%]	Simulation [%]	Δ%
100	2.4 + 0.24 Al	65.47	63.64	1.83
100	4.4+ 0.24 Al	48.10	46.66	1.44
100	6.4+ 0.24 Al	32.72	30.73	1.99

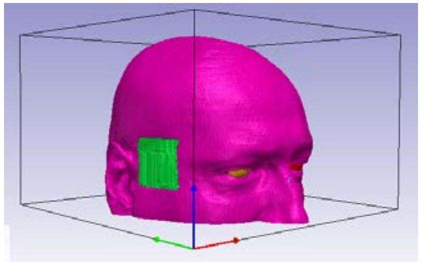


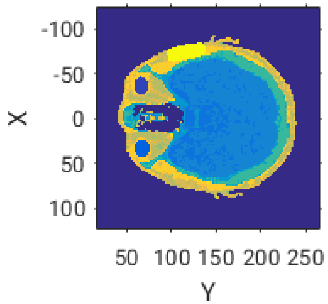
[kV]	Depth [cm]	Measure [%]	Simulation [%]	Δ%
100	2.4 +5 XPS	58.96	59.13	0.16
100	3.6 + 5 XPS	51.69	51.92	0.23
100	4.4 + 5 XPS	44.69	46.42	1.73

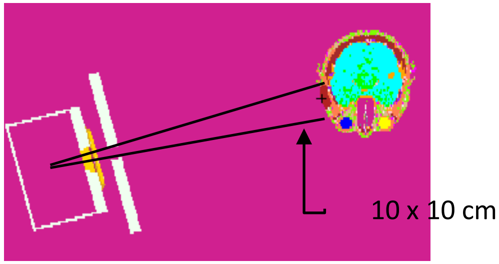
Development of a Voxel model Equivalent to the UM ones

- 2. Voxelizzation and Importation in MCNP6.1.1
- Tools: Abaqus/CAE + MATLAB Scripts

UM mesh model → Equivalent Voxel model → File Input MCNP6.1.1







- Produced by ScanIP
- Abaqus Mesh File format
- Meshing verification with Abaqus/CAE

- Voxelizzation with script MATLAB

- Realized with script MATLAB
- Choice of Voxel dimension
- Isocenter Positioning and Source Integration
- Assignment Material Properties ICRU (Composition + density)

Voxel dimension	**2 x 2 x 2 mm**
Voxel number	**1,250,000**
Simulated photons	**10E+08**
Runt time (Xeon 32 thread)	**~ 43 h**

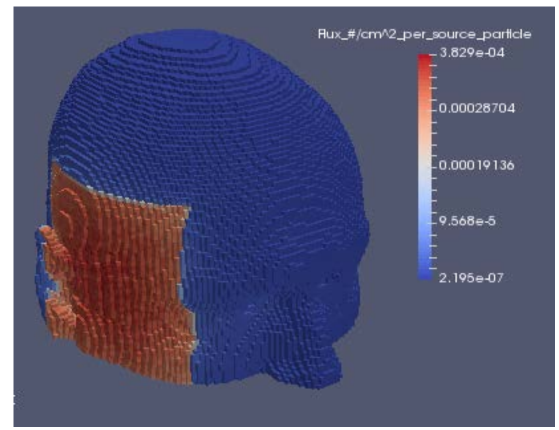
Voxel model

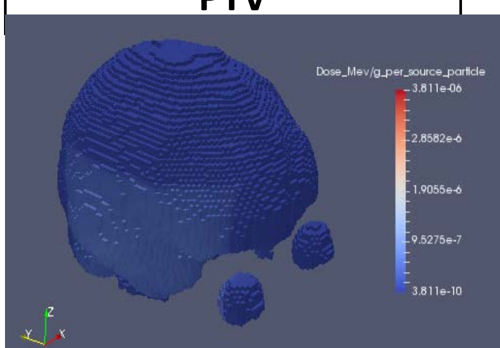
- 3. Post-Processing & analysis results.
- Tools: MATLAB Scripts + ParaView

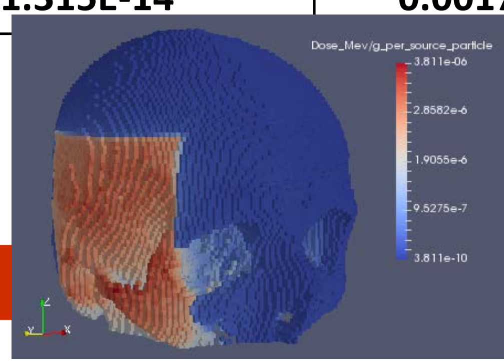
Average dose at the structures

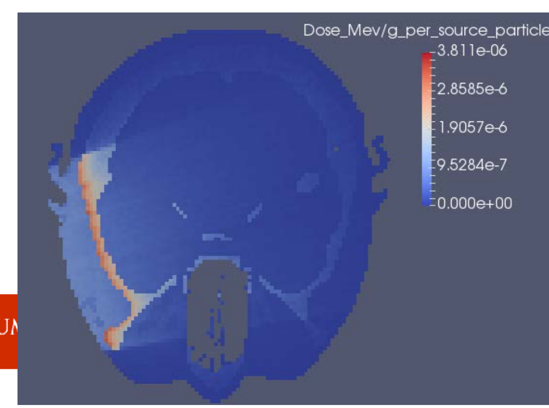
Structure	Dose (cGy) per particle source	Relative error
Left eye	4.714E-16	0.0154
Right eye	2.436E-15	0.0069
Central nervous system	2.011E-15	0.0013
Bones	6.087E-15	0.0009
Soft tissues	2.148E-15	0.0009
PTV	1.315E-14	0.0017

Spatial dose distribution









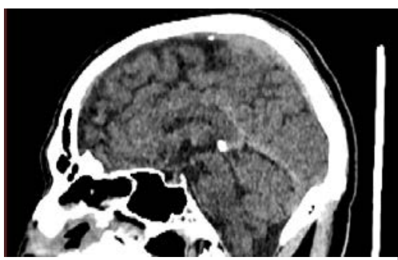
Unstructured Mesh Model Development

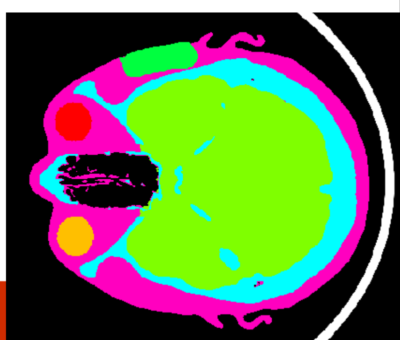
- 1. Meshing segmented model. Tool: ScanIP
- 2. Import in MCNP6.1.1. with the pre-processing tool

TAC pictures → Unstructured segmented mesh model → File Input MCNP6.1.1

- ScanIP
- Mesh verification with Abaqus/CAE

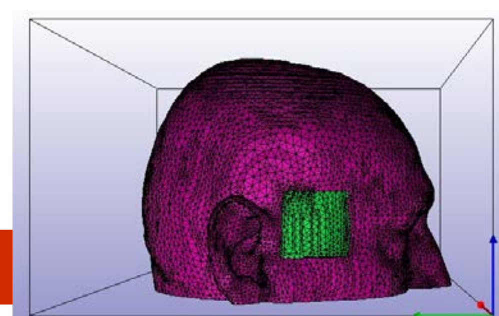
- Um_pre_op611

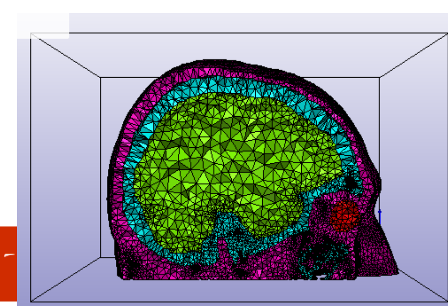




Downsample factor	0.65
Target minimum side	3 mm
Target maximum side	7.5 mm
Number of elements	740996
Number of nodes	161486

Number of structures	6
Number of material	14
Simulated photons	10E+08
Run time (Xeon 32 thread)	~ 8 h





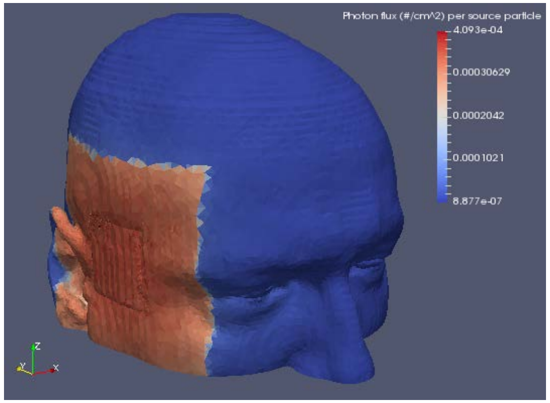
Unstructured Mesh Model Development

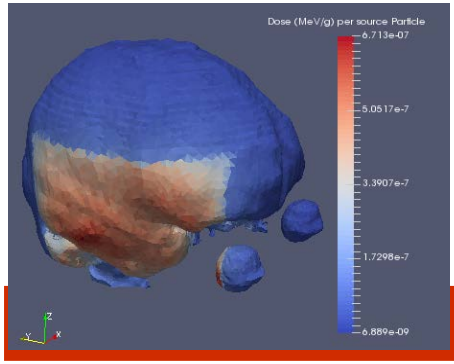
3. Post-Processing & Analisys Risults.Tools: MATLAB Scripts + ParaView

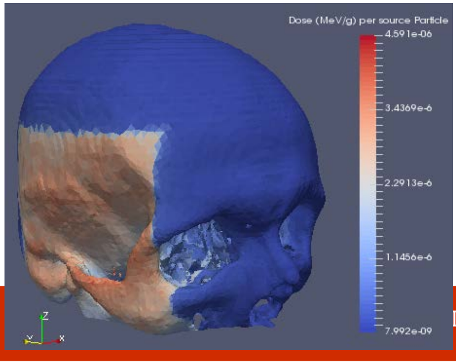
Average dose to structures

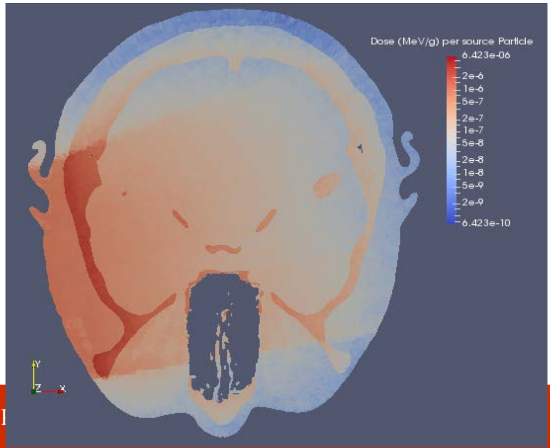
Structure	Dose (cGy) per Particle Source	Relative error
Left eye	4.821E-16	0.0107
Right eye	2.473E-15	0.0048
Central nervous system	1.987E-15	0.0019
Bones	6.125E-15	0.0032
Soft tissues	2.119E-15	0.0016
PTV	1.317E-14	0.0012

Spatial dose distribution







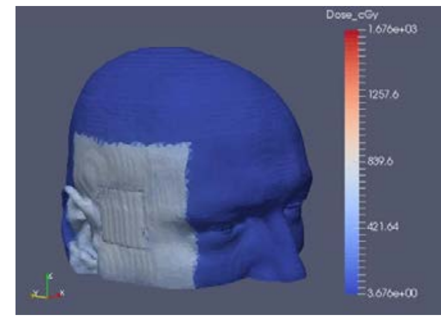


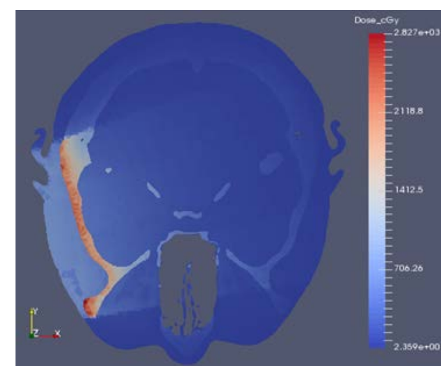
Results exportation

TAC pictures → Monte Carlo simulation → DICOM – RT Dose

3. Exportation DICOM – RT Dose

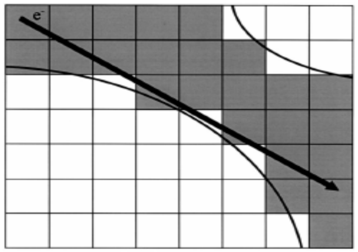
- Format to export Spatial Distribution Dose Absorbed in the model
- DICOM format extension (TAC images). Standard for Data Integration Radiotherapy with Patient Information
- Essential for the implementation of the Treatment Planning System (TPS) based on Monte Carlo
- Used in all Commercial Calculation codes for Patient Data Management and TPS
- Made using MATLAB scripts for Voxel and Non-Structured Mesh results



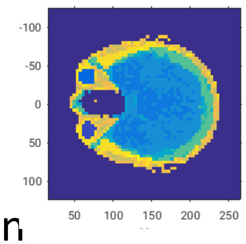


Voxel effects on big application field

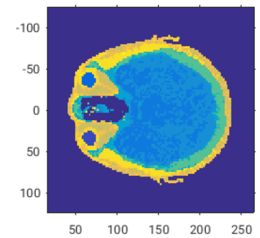
Abnormalities related to the Voxel model description



Voxel 4 mm

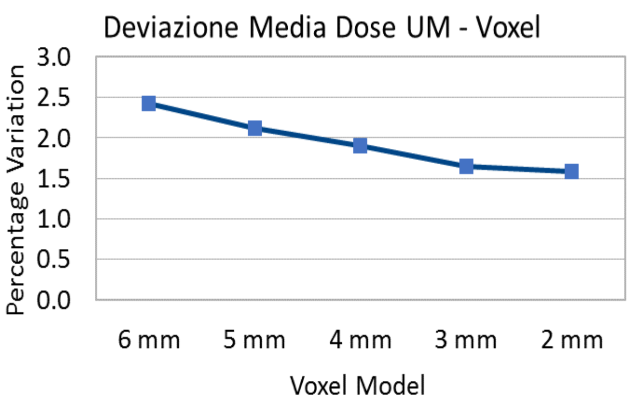


Voxel 2 mm

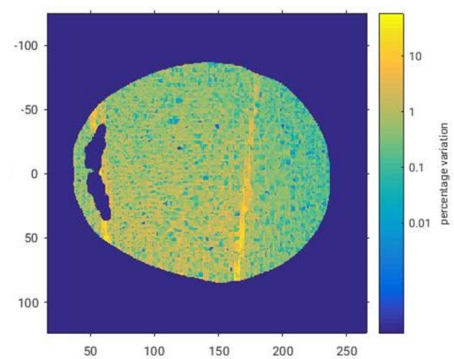


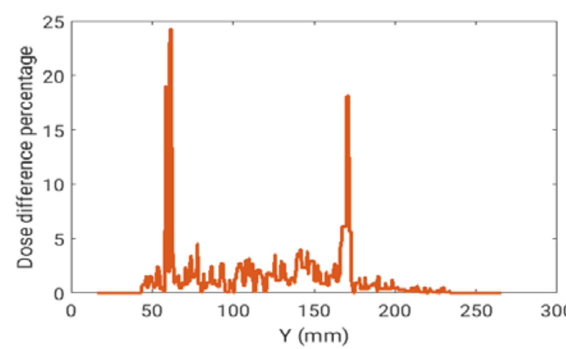
- Simulations with increasing voxel resolution
- 10 x 10 field – monoenergetic beam
- Homogeneous material (water)

- Wrong volume reproduction
- Impact on particle transport simulations



Local dose deviation





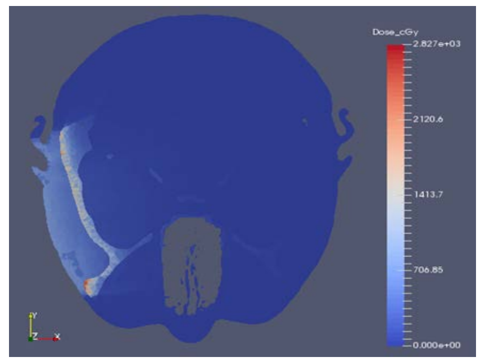
- Partial Convergence for increasing resolution
- Deviations localized in regions with a high dose gradient

X-ray tube voltage evaluation

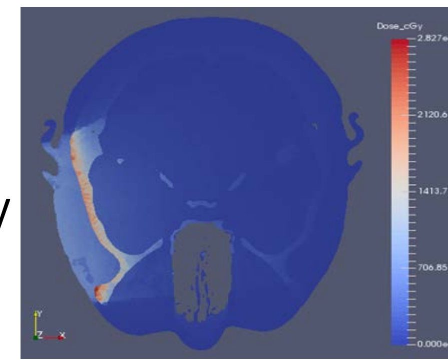
N. Setup	SSD (cm)	Applicator	Filter	**(kV)**
1	30	8 cm – Cylindrical	F1	**50**
2	30	8 cm – Cylindrical	F3	**75**
3	50	Open field – 10 cm square	F4	**100**
4	50	Open field – 10 cm square	F8	**300**

Filter	Materials	Thickness (mm)
F1	Aluminum	1.65
F3	Aluminum	3.10
F4	Aluminum Copper	2.5 0.1
F8	Aluminum Copper Tin	1.5 0.25 0.8

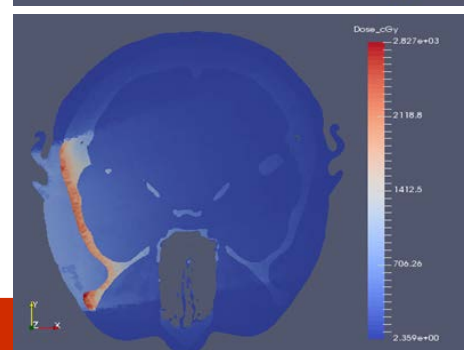
50 kV



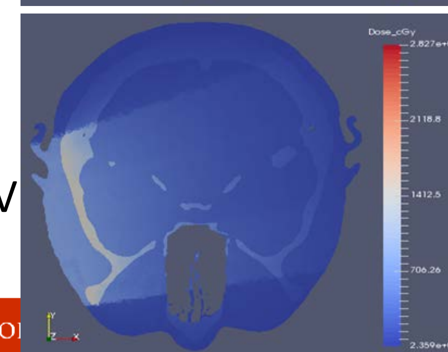
75 kV



100 kV



300kV

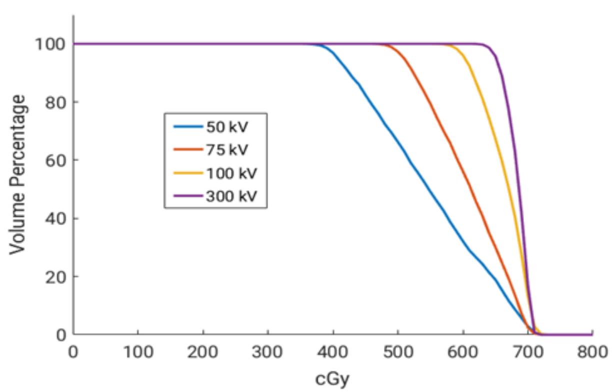


X-ray tube voltage evaluation

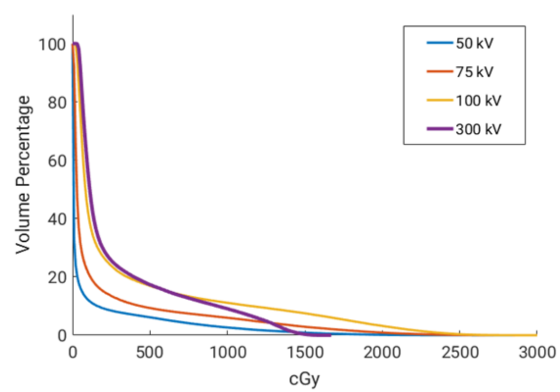
- **4. Average dose to structures analysis**
- **5. Histograms Dose-Volume**

Tension	100 kV	50 kV		75 kV		300 kV	
Structure	Dose (cGy)	Dose (cGy)	Δ%	Dose (cGy)	Δ%	Dose (cGy)	Δ%
PTV	**664.1**	**549.0**	**-17.3**	**608.2**	**-8.4**	**683.3**	**2.9**
Left eye	24.2	2.7	-88.9	9.8	-59.4	41.0	69.5
Right eye	125.1	27.5	-78.1	58.6	-53.2	157.4	25.8
CNS	100.3	13.4	-86.6	41.2	-58.9	171.2	70.7
Bones	**230.2**	**84.2**	**-63.4**	**161.6**	**-29.8**	**278.2**	**20.8**
Soft tissues	107.9	47.8	-55.7	64.0	-40.6	143.7	33.2
Head (total)	179.3	50.7	-71.7	93.2	-48.0	201.2	12.2

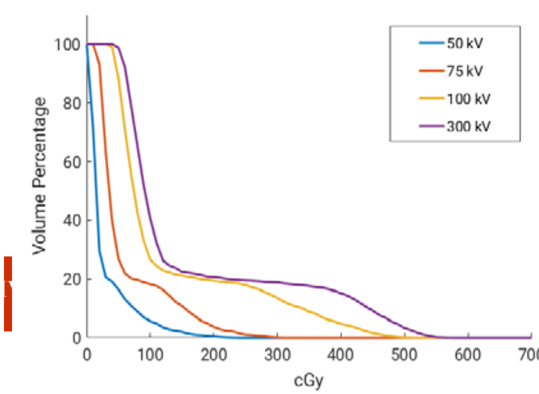
DVH – PTV



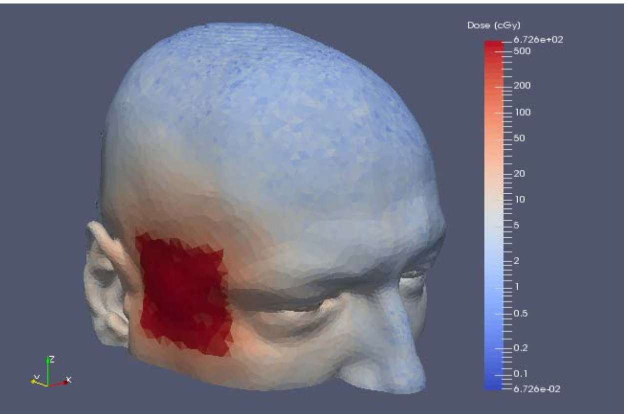
DVH – Bone tissue

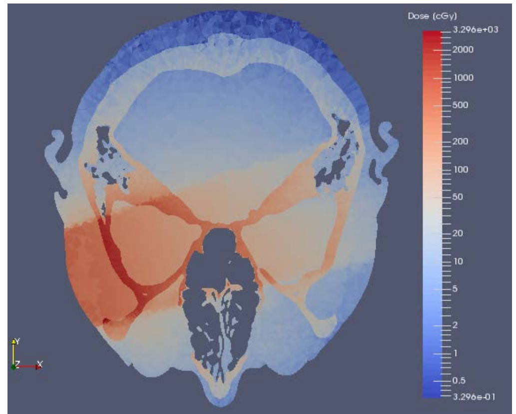


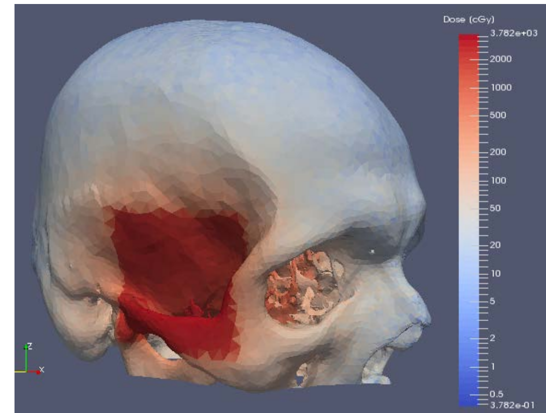
DVH – Right Eye (OAR)

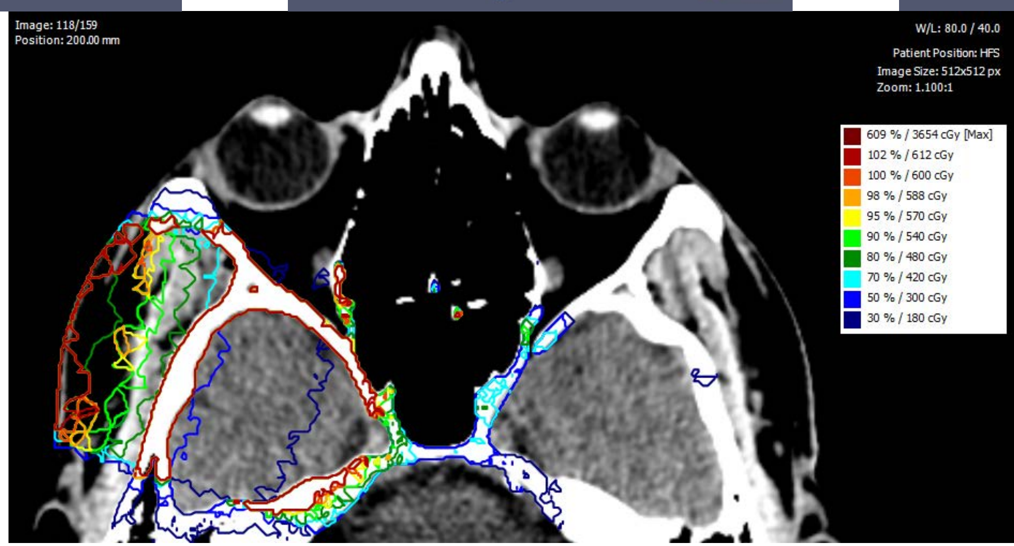


Contouring on Dicom Files (smaller field)

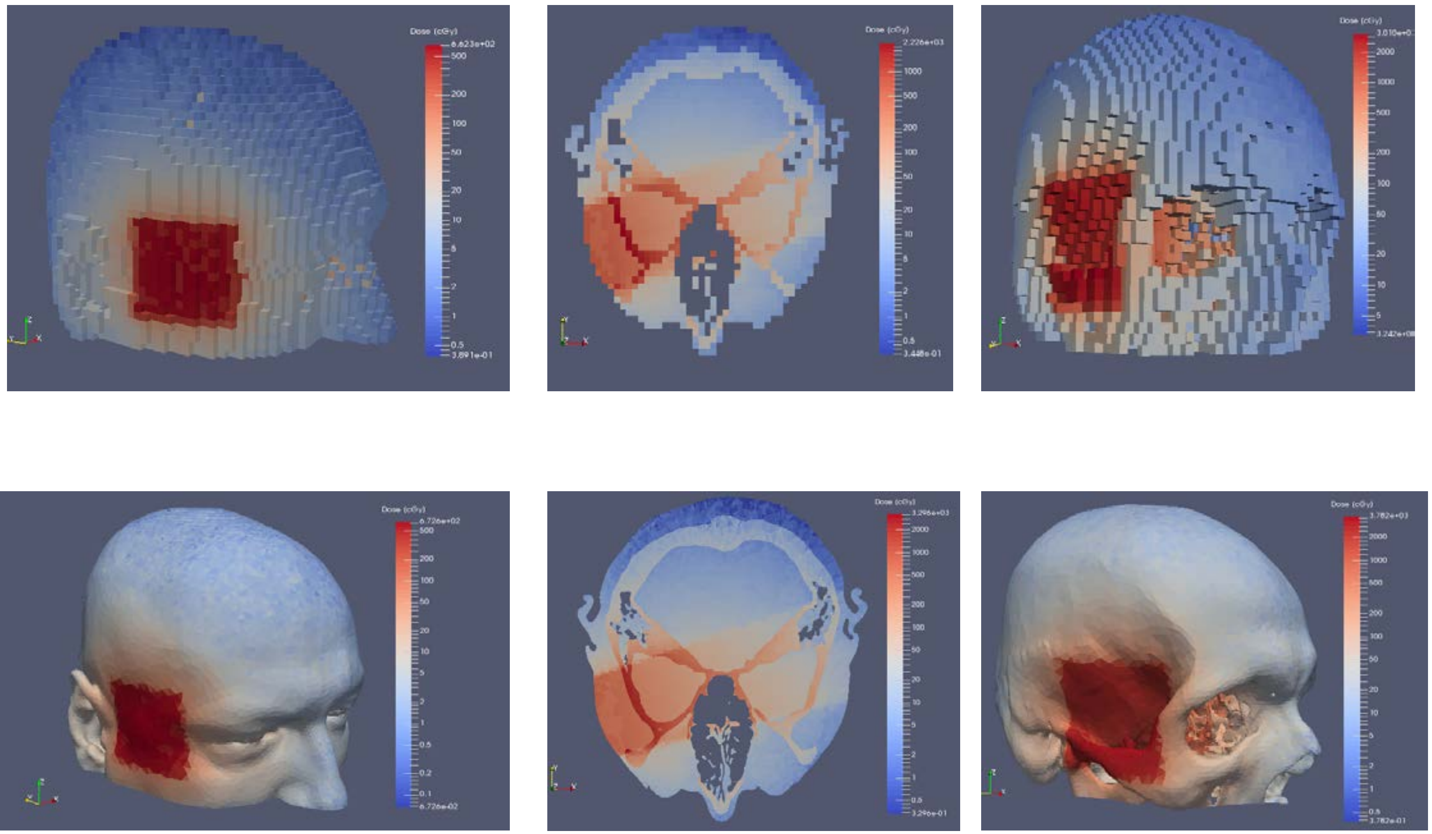




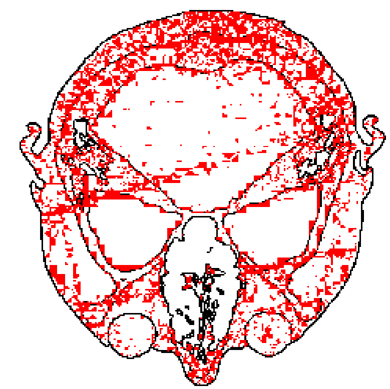




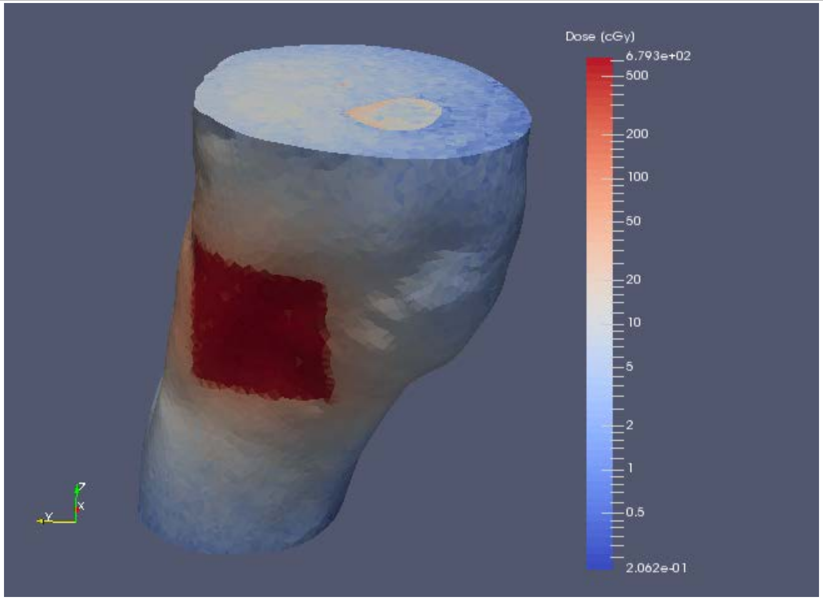
Differences between the two techniques with a smaller field

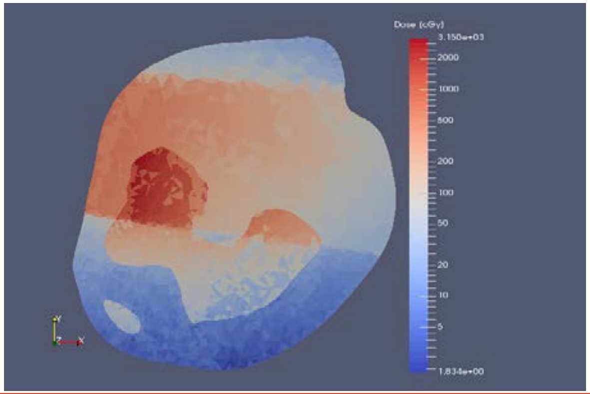


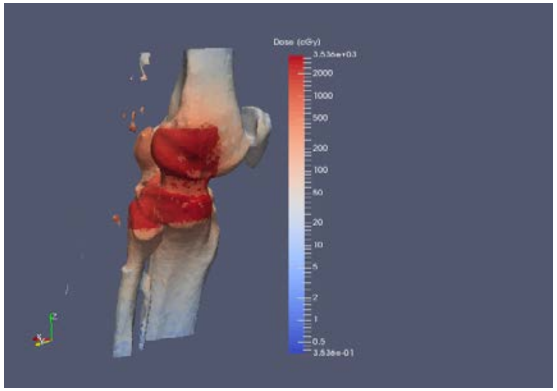
Deviation > 0.2



Example of knee treatment







Conclusions

- MC methods can now be applied with great accuracy to structures coming from CT-SCAN, in particular thanks to the UMs and therefore provide additional information in the choice of treatment parameters and avoiding geometrical bias as in classical voxel models
- Benefits: Integration of Existing Protocols with Monte Carlo-based TPS

The application of UM models in Monte Carlo methods can provide models accurately reproducing the complex surfaces of human structures, with significant benefits over voxel models. Furthermore, it has been shown that MC methods can be used effectively to evaluate the impact of Radiotherapy parameters in Orthovoltage treatments. This can produce better results in skin lesion control and an overall benefit in the patient quality life.

Future developments

- **Simplification of the creation of models from TAC pictures**
- **Developments of parameters for the reduction of the variance and of the simulation time**
- **Collaboration with IRCSS – ASMN Reggio Emilia for passage from Prototype to TPS integrated in the Treatment Protocol**

THANK YOU