Future developments

What do we need for our applications?

Virtual Training Course on Mathematical Modelling for Radiation Processing

IAEA
International Atomic Energy Agency
Atoms for Peace and Development

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Industrial needs for MC simulation

- Irradiation installation shielding
- Beam qualification
  - shape, energy, uniformity,…
- OQ
- …

Feasible with currently existing tools

- PQ → a tool which helps to map dose inside the product
  - product the most realistic possible
  - taking into account its variability
  - cold and hot spots in a reasonable time (for dosimeters placement)

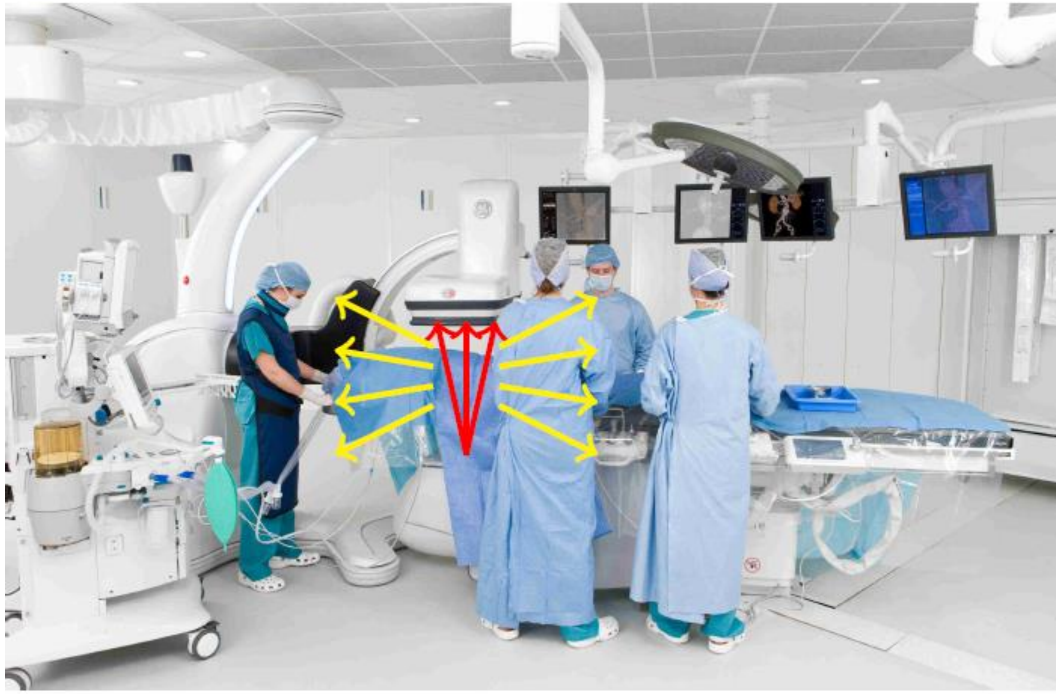
→What can we learn from medical use of Monte Carlo simulations?

Medical Imaging - Problematics

- PhD thesis work.
- **Interventional radiology:** X-Ray imaging during medical procedures.
- Radioprotection problematics for patient and staff.
- **Patient problematic:** when deterministic effects thresholds are exceeded

  → Estimation of patient exposure
- **Staff problematic:** optimization of exposure linked to the scattered beam

  → Pedagogic purposes



Primary beam, scattered beam

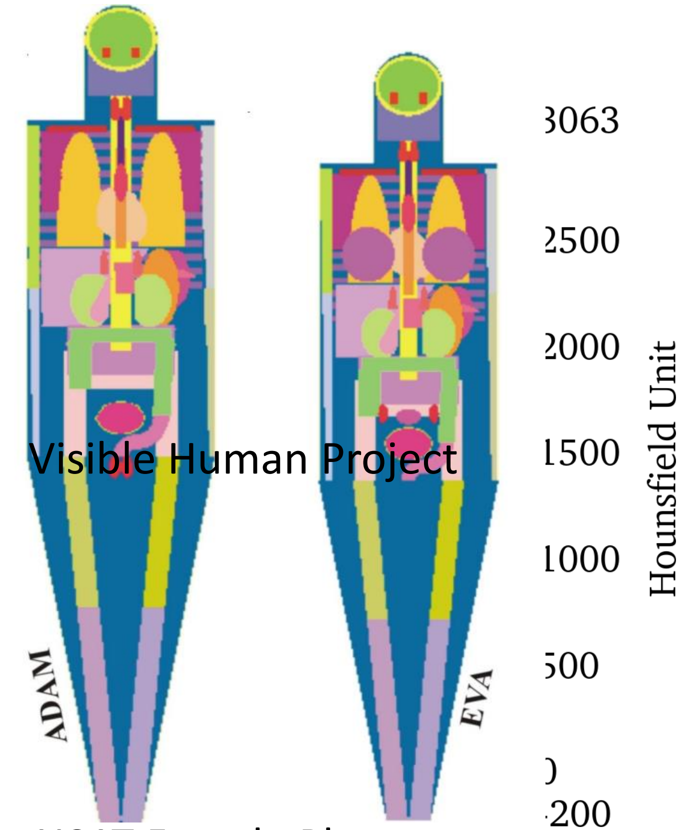
→ **Monte Carlo simulation particularly adapted to answer those problematics.**

- Deschler, T. (2018). *Development of a dosimetric system for interventional radiology* (Doctoral dissertation, Strasbourg).

Aerial

Patient representation in simulations

- How to represent patient in Monte Carlo simulations?
  - Realism is the key
- Mathematical phantoms
  - Approximation of patient…
- Anthropomorphic voxelized phantoms
  - Can be deformed to fit patient morphology
  - Organs already segmented
- CT scan patient images
  - in DICOM file format (*Digital imaging and communications in medicin*)
  - Example of Visible Human Project CT Datasets
  - Organ segmentation → complex task



Visible Human Project

XCAT Female Phantom

ADAM and EVA mathematical phantoms

- Kramer, R., Zankl, M., Williams, G., & Drexler, G. (1982). The calculation of dose from external photon exposures using reference human phantoms and Monte-Carlo methods Pt 1 (GSF-S--885). Germany
- Segars WP, Sturgeon G, Mendonca S, Grimes J, Tsui BM. 4D XCAT phantom for multimodality imaging research. *Med Phys*. 2010;37(9):4902-4915. doi:10.1118/1.3480985
- Ackerman MJ. The Visible Human Project: a resource for anatomical visualization. Studies in Health Technology and Informatics. 1998 ;52 Pt 2:1030-1032.

Integration of CT Scan images

Dicom Files

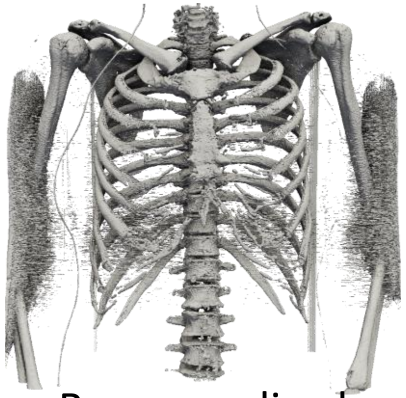
Slices

Supported natively by GATE

Voxelized image in Hounsfield unit

Supported natively by GATE

Organ Segmentation (Manual or using Hounsfield Unit)



Bone voxelized image

Skin Dose

Organ Dose

$$\text{Hounsfield Unit} = \left(\frac{\bar{\mu}}{\bar{\mu}_{\text{water}}} - 1\right) 1000$$

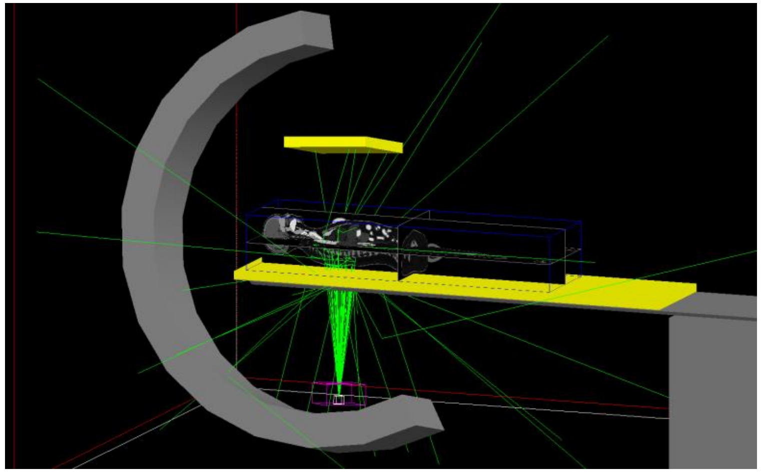
Sustance	HU
Air	−1 000
Lung	−500
Fat	−100 to −50
Water	0
Cerebrospinal Sluid	15
Kidney	30
Blood	+30 to +45
Muscle	+10 to +40
Grey matter	+37 to +45
White matter	+20 to +30
Liver	+40 to +60
Soft tissue	+100 to +300
Bone	+700 (cancellous bone) to +3 000 (dense bone)

- Schneider, W et al. "Correlation between CT numbers and tissue parameters needed for Monte Carlo simulations of clinical dose distributions." *Physics in medicine and biology* vol. 45,2 (2000): 459-78. doi:10.1088/0031-9155/45/2/314

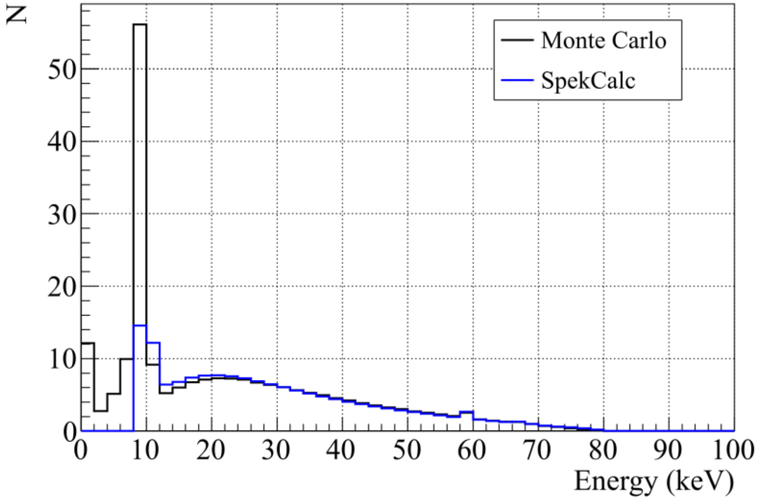
Solving patient problematic

- Software developed during thesis to reconstruct patient dosimetry after interventional radiology procedures using:
  - DICOM RDSR (*radiation dose structured report*) files of the procedure (containing data of the procedure: peak energy of the X-Rays, intensity of the tube, C-arm angulation, …)
  - GATE v8.1
  - XCAT phantoms (patient CT scan not available in most cases)
  - X Ray spectrum generated using SpekCalc (simulation of X-Ray tube very time consuming)

→ Dose to skin, dose to organs, Equivalent dose, Effective dose



Visualization of a Gate simulation

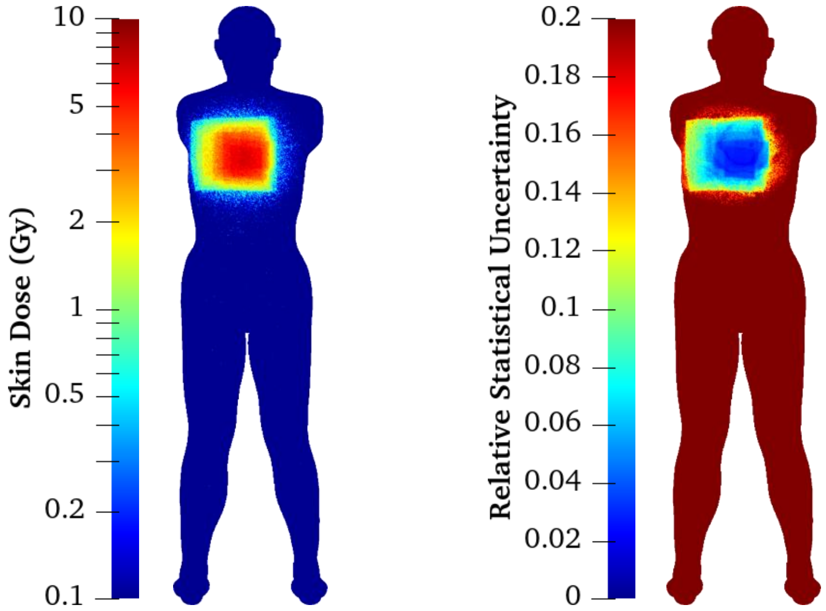


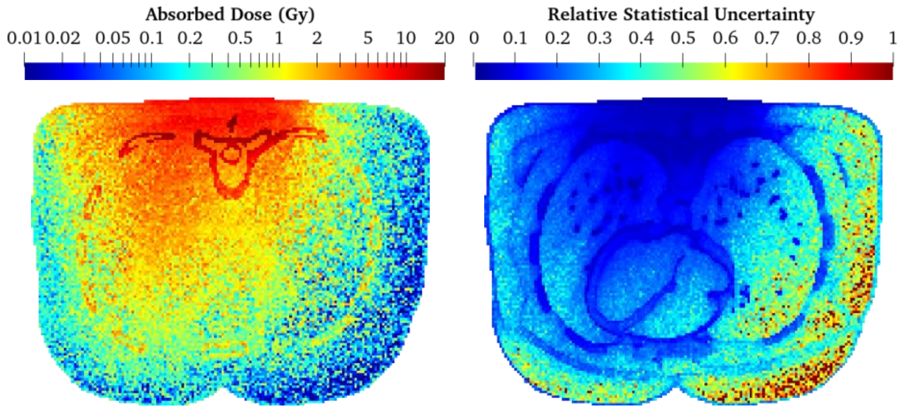
Comparison between X-Ray spectrum obtained with SpekCalc and MC Simulation

- Deschler, T. (2018). *Development of a dosimetric system for interventional radiology* (Doctoral dissertation, Strasbourg).
- Poludniowski GG, Evans PM. Calculation of x-ray spectra emerging from an x-ray tube. Part I.Electron penetration characteristics in x-ray targets.Med. Phys., 34(6Part1):2164–2174 (2007).
- Poludniowski GG. Calculation of x-ray spectra emerging from an x-ray tube. Part II. X-ray production and filtration in x-ray targets.Med. Phys., 34(6Part1):2175–2186 (2007).

Solving patient problematic

- Computation Time: (info proc)
- Dose skin max.: 9.0 Gy (3.1%)
- Dose organes: (stat. ucty <2%)
  - Heart: 510.9 mGy
  - Poumons: 646.3 [L:869.1-R:437.6] mGy
  - Stomac: 430.3 mGy
  - Liver: 228.6 mGy
  - Pancreas: 160.8 mGy
  - Spleen: 680.1 mGy
  - Skin: 102.3 mGy
- Effective dose: 207 mSv (1.6%)



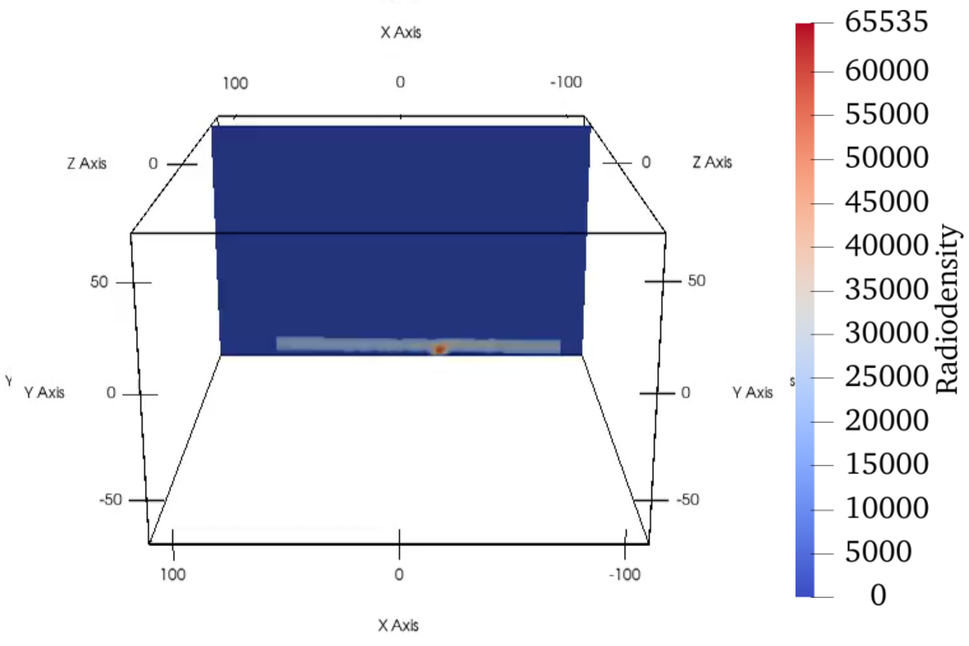


- Deschler, T. (2018). *Développement d'un système dosimétrique pour la radiologie interventionnelle* (Doctoral dissertation, Strasbourg).

Industrial Examples

Industrial Example 1

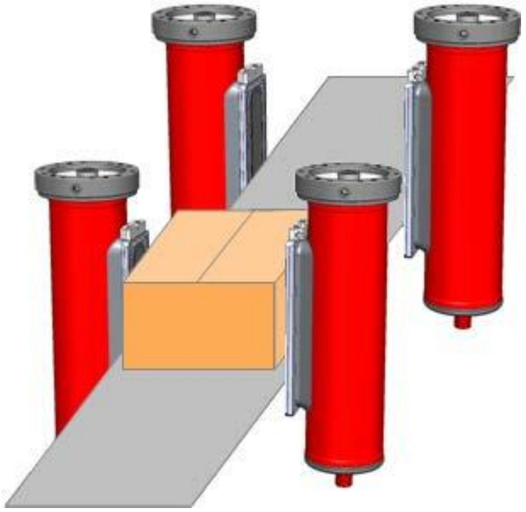
- Cherries Crate
  - Packaging size: 210x160x100mm
- Product numerized with a CT scan on a conveyor belt
  - DICOM image with 288 slices
  - Voxel resolution: 1x1x1.48 mm^3

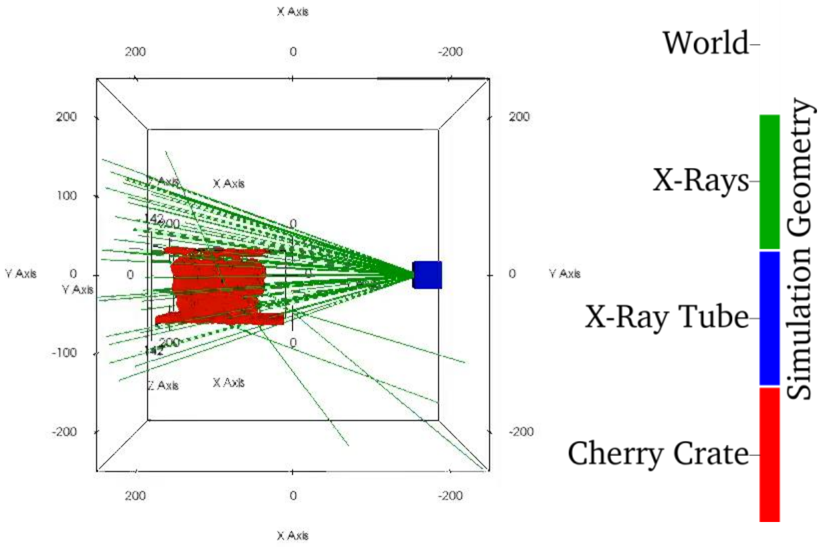


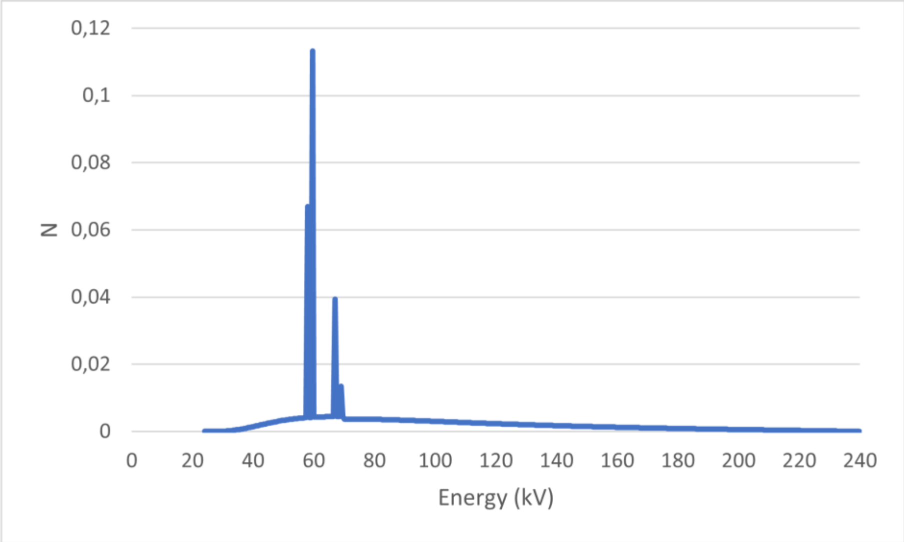
Courtesy of Nuctech Company, Ltd

Simulation Geometry

- Irradiated with X-Rays of 240 kVp
- X-ray spectrum generated from SpekCalc.
- The cherries crate is irradiated one side after another in the simulation.
  - Half particules on each side.
  - The crate is automatically rotated in Gate.



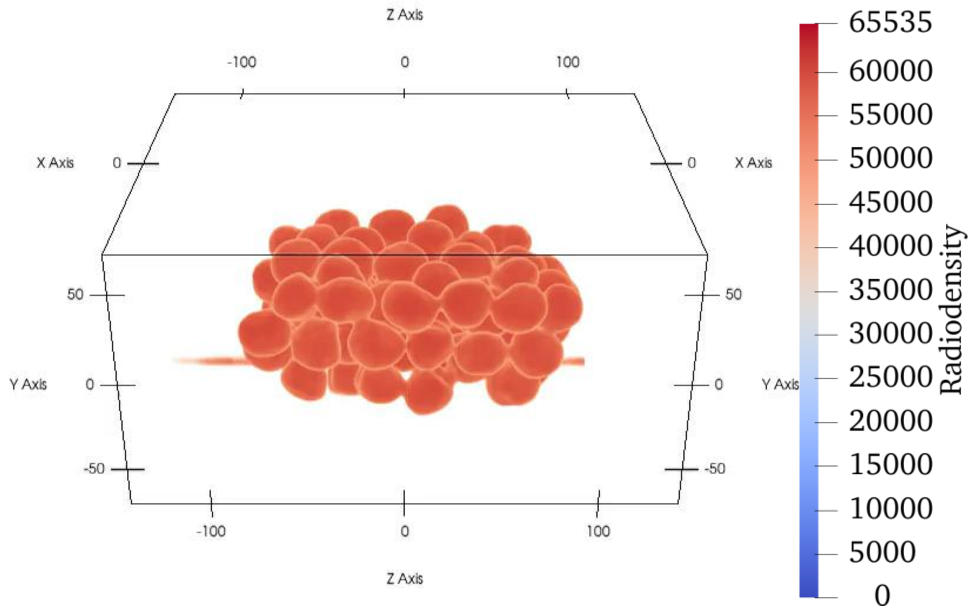




Simulation Segmentation

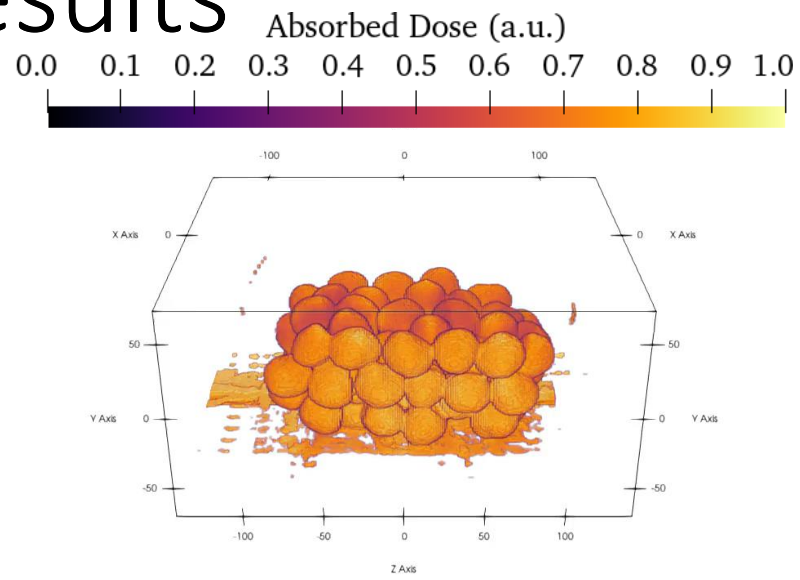
- **Segmentation problem:** Associate a material to an interval of radiodensity
- Selecting only cherries
  → radiodensity over 40k
- In simulation:
  - Under 40k: Air
  - Over 40k: Water

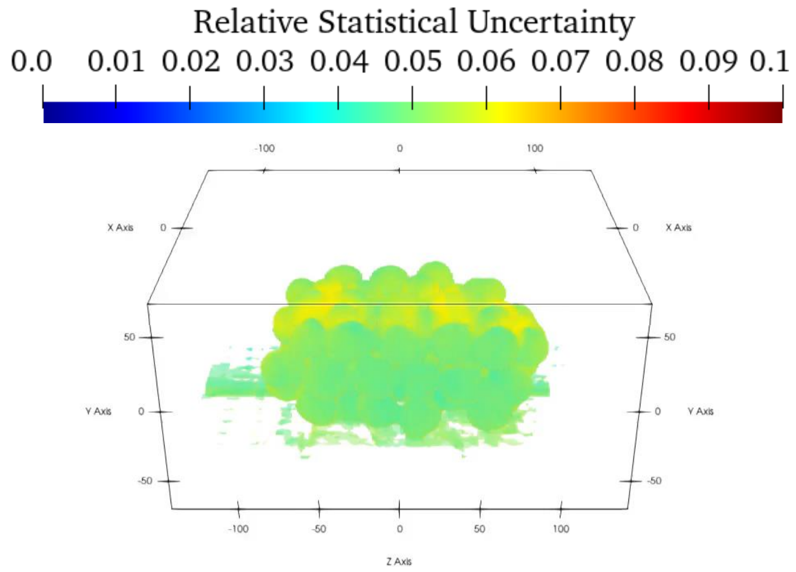
→ clean segmentation between volumes



Simulation Results

- Parallelized simulations: $2^{e}8$ X-Rays on 16 cores (Intel Xeon Platinum)
- Total number of X-Rays: $3.2^{e}9$
- Computation Time: ~22hours/per core
- Relative statistical uncertainty: μ=5.2% σ=0.3%



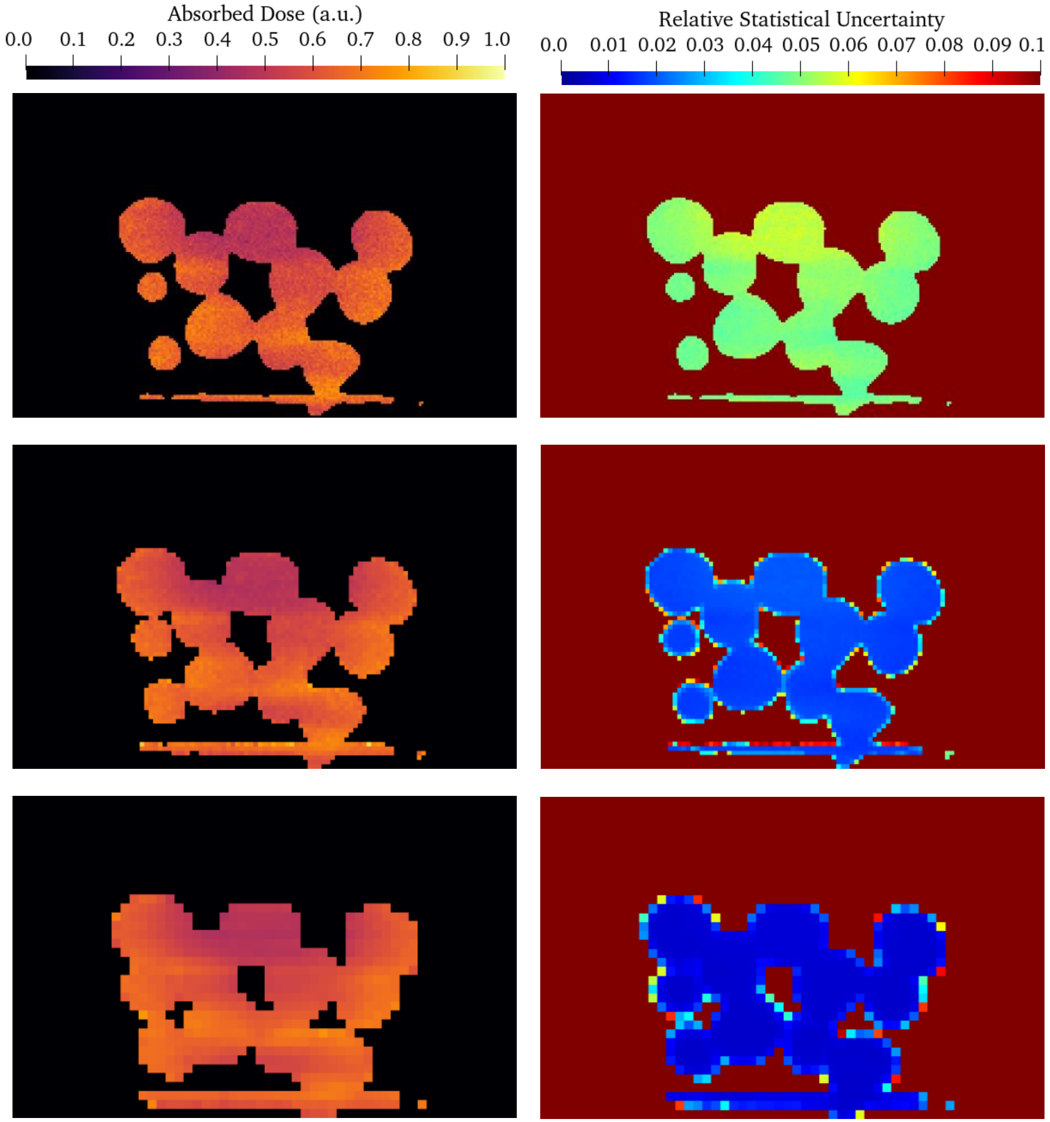


Variance Reduction: Dosel Size

- **<u>Dosel:</u>** *Dose Map Voxel*
- More particles interacting in a volume
  → less statistical uncertainty
- Volume augmentation of a factor 8 (~2x2x2mm^3)
  - Mean relative statistical uncertainty: 2.4%
  - Can achieve a mean statistical uncertainty of 5% in 5h
- Volume augmentation of a factor 64 (~4x4x4mm^3)
  - Mean relative statistical uncertainty: 1.3%
  - Can achieve a mean statistical uncertainty of 5% in 1h30

$$\sigma \propto \frac{1}{\sqrt{n}} \propto \frac{1}{\sqrt{t}}$$

Dosel Size	$\overline{\Delta}$ (%)	Ratio	f_{time}
Origin	5.2	1	22h



- Deschler, T., et al. "Dose calculations in heterogeneous volumes with the GATE Monte Carlo software for radiological protection." *Radioprotection* 54.2 (2019): 125-132.

Variance Reduction: Dosel Size

- Dose mapping in product qualification (PQ):
  - Interesting to estimate dose hot/cold spots in a minimum of time.
  - And to optimize the placement of dosimeters
- But spatial resolution is greatly diminished…
  - Cannot be used for surface dose mapping…

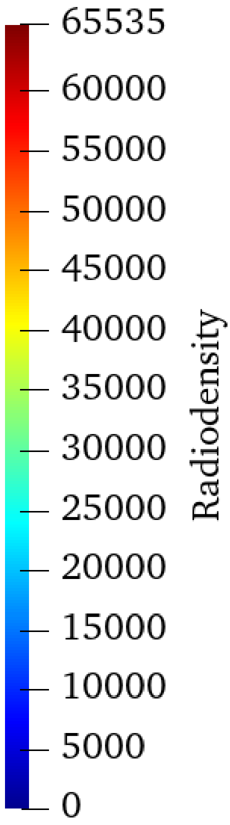
Industrial Example 2

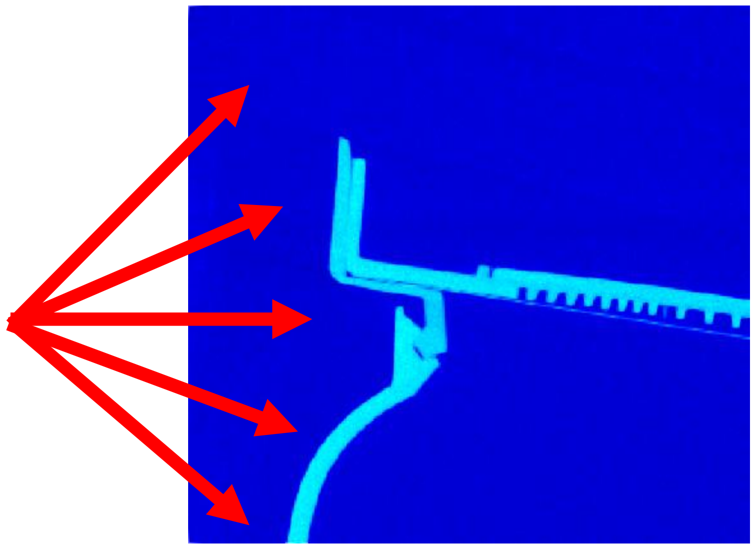
- Industrial product acquired with CT scan of very good resolution
- Original voxel size: 32.4x32.4x32.4µm^3
- Original voxel count: near 4.5 billion
- Size of the file: 9 GB

  → **Need to resample image in order to optimize computing resources**
- Resampling to voxel size: 135.6x136.2x130.7µm^3
- New size of the file: 120 MB

  → **Way better**
- Segmentation using radiodensity of materials:
  - between 18k and 25k → Water
  - other → Air
- Simulation:
  - Irradiation with a monoenergetic electron beam of 400 keV

Scanned product (cropped)

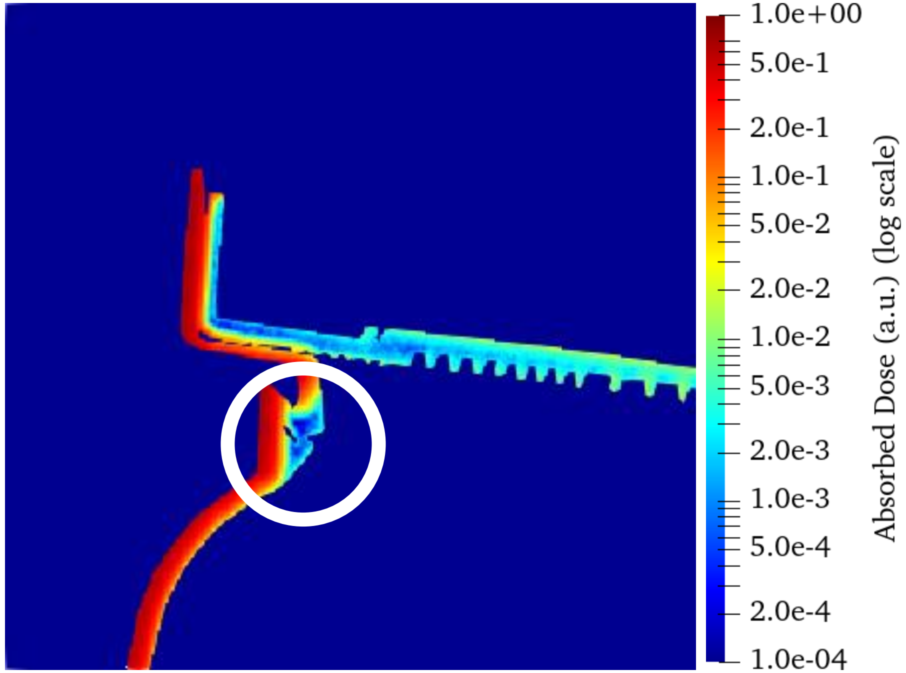


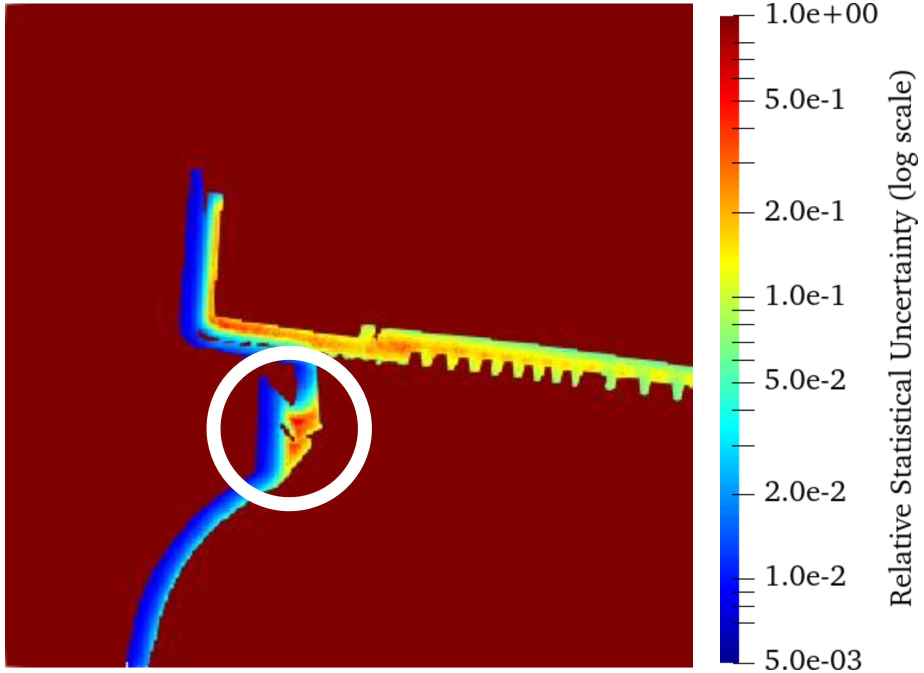


Results

- 45 cores (Intel Xeon Platinum)
- Number of electrons: 2e8 per core (9e9 total)
- Simulation time: 8h per core
- 2.5 GB of RAM per core (113 GB total)

- Very good uncertainty at entrance surface (< 5%)
- Dose distribution can easily be visualized (cold/hot spots)





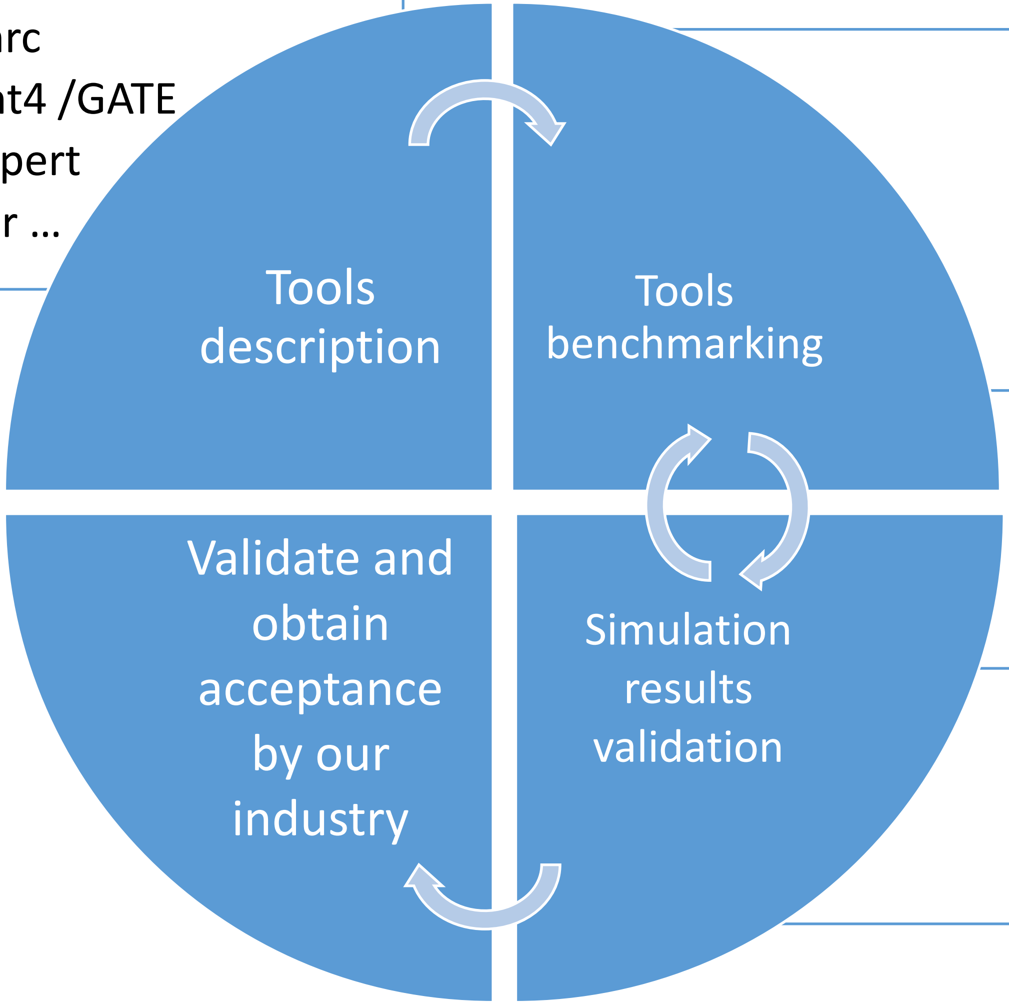
Limitations

- Voxelized image resolution limitations:
  - Too low:
    - - blurry interfaces
    - - difficulties to segment product materials
    - + less time to converge
  - Too high:
    - - large memory consumption
    - - high computation time to converge
    - + high precision of dose maps

→ Voxel resolution optimization is a key point to master

Acceptance by our industry and validation

- MCNP
- EGSnrc
- Geant4 /GATE
- RayXpert
- Other …



- Select irradiation configurations /geometries/modalities…
- Compare simulation results

- Define validation plan
- Compare to experimental results

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La bonne dose d'innovation*

* the best dose of innovation