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MC simulations:
Use Cases for Precision Nuclear Medicine

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Background-Aim: Realistic MC Simulations

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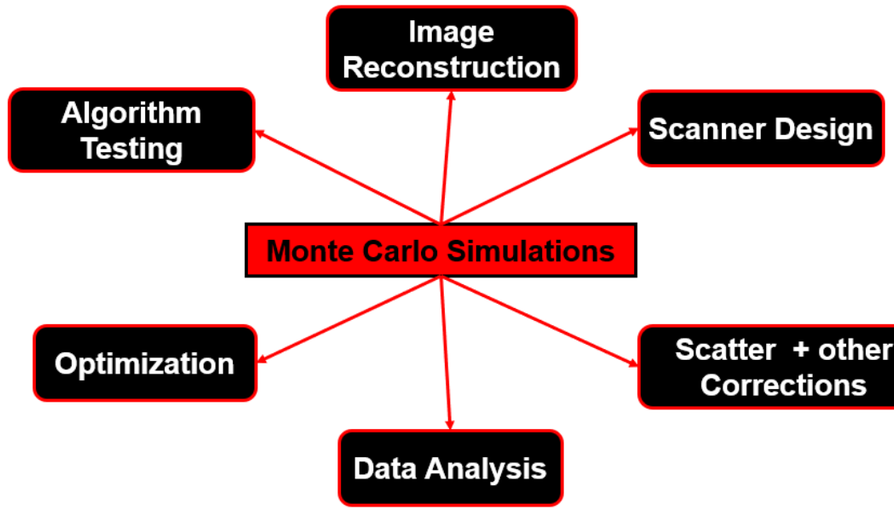
Perform Realistic Monte Carlo (MC) Simulations for Clinical Use

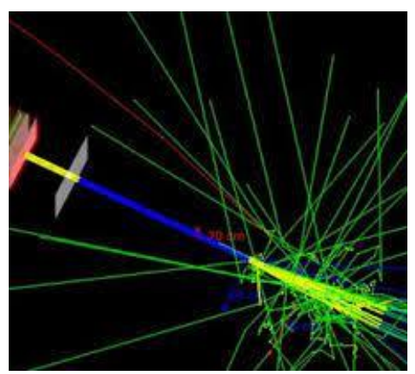
MC simulations serve as a powerful tool in medical physics providing insights into complex radiation transport phenomena and the ground truth for dosimetry protocols.

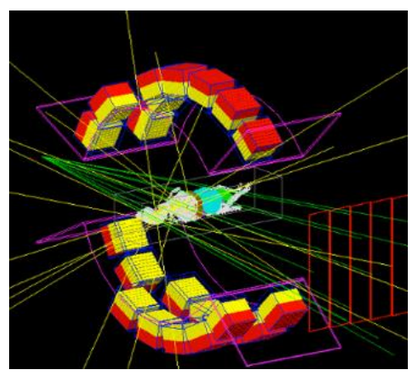
- ✓ **Model complex physical processes:**
  Crucial for advancing our comprehension of medical radiation applications

- ✓ **Model realistic anatomical geometries:**
  Crucial for precision medicine and optimizing clinical and pre-clinical, diagnostic and therapeutic protocols.

GATE







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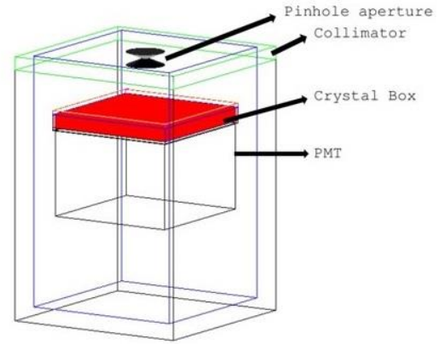
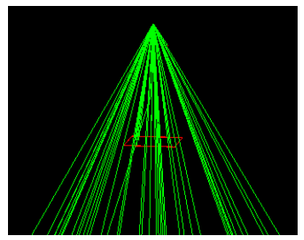
A) Imaging MC simulation for Nuclear Medicine

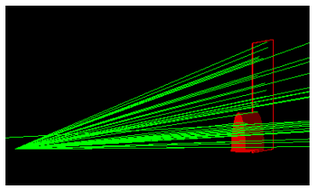
i. <u>SPECT system</u>: Investigation of system's parameters for constructing a small FOV pinhole camera for Lu-177 clinical applications.



ii. <u>CT Breast</u>: Realistic simulation of 3D digital breast phantoms using clinical settings. Validation of the X-ray beam using geometrical phantoms.

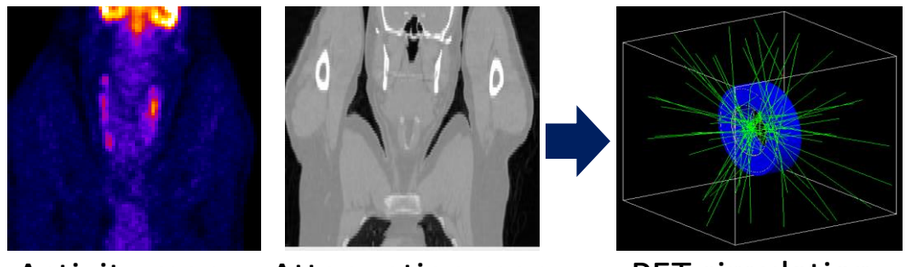


Flat field irradiation



Semi-cylinder phantom

iii. <u>PET Oncology</u>: Realistic PET head & neck oncological cases were simulated using anthropomorphic computational models incorporating delineated tumors to generate a dataset of digital patients.

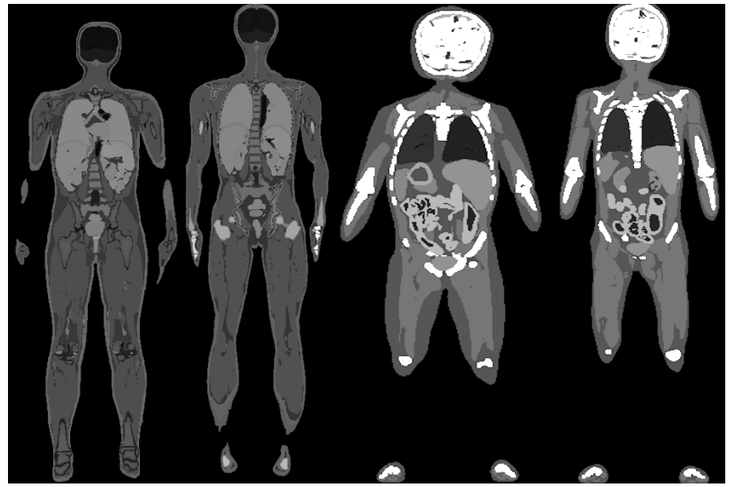


Activity map Attenuation map PET simulation

PET simulation using clinical data in GATE

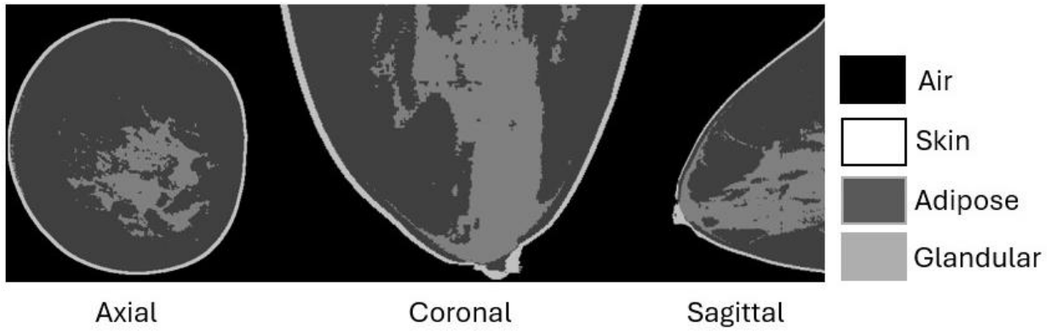
B) Dosimetry MC simulations in clinical applications

i. <u>Pediatric dosimetry</u>: A pediatric population was used to evaluate the absorbed dose per organ and the variations in dosimetry due to anatomical differences among patients.



Digital pediatric population of IT'IS and XCAT phantoms

ii. <u>Breast CT dosimetry</u>: Dose assessment was conducted in breast regions of 3D digital phantoms undergoing CT irradiation.



Digital breast phantom with corresponding planes

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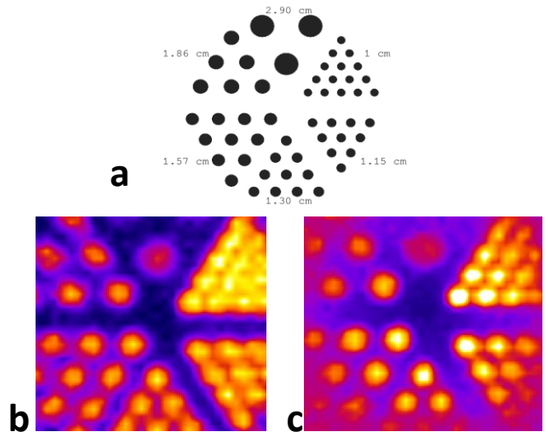
A) Imaging MC simulation for Nuclear Medicine

i. **Small FOV pinhole SPECT** camera for Lu177 clinical applications.

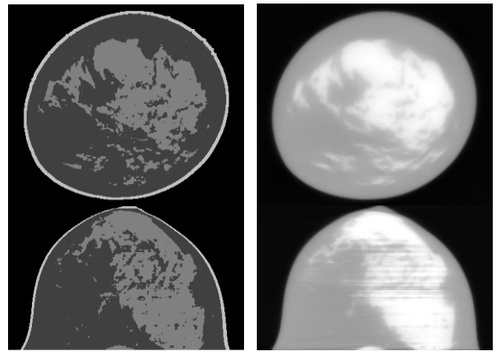


a) Derenzo phantom

b) MC simulation output

c) Experimental output

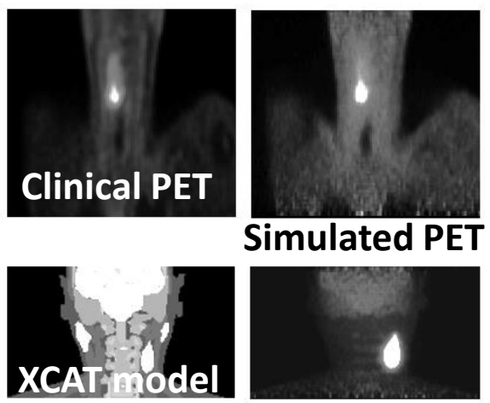
ii. **3D breast CT** imaging from clinical MR data.



Left: 3D breast phantom

Right: Simulated CT

iii. **PET head & neck** oncology cases to generate a simulated dataset of digital patients.

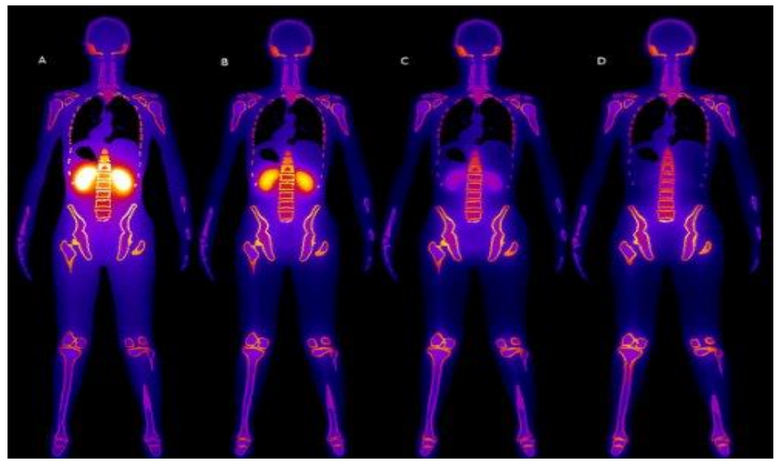


Top: Reproduction of clinical oncology PET case

Bottom: Simulation of XCAT phantom with tumor

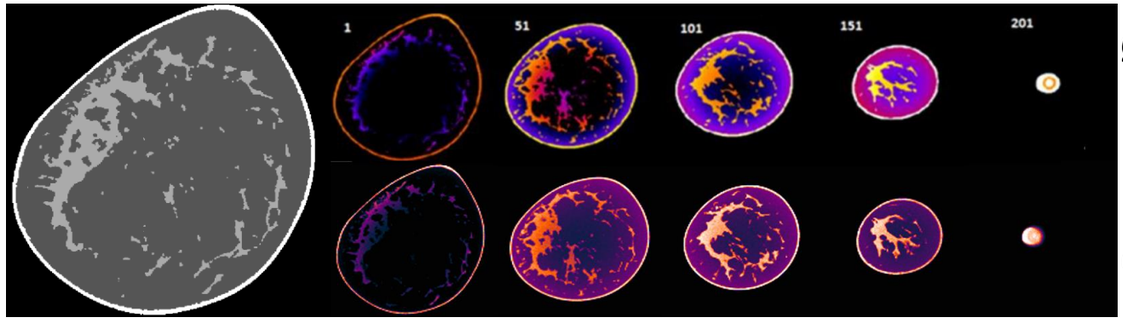
B) Dosimetry MC simulation

i. A simulated database of absorbed doses per organ was developed using a digital pediatric population to train a ML model for personalized dose prediction based on each patients' anatomical characteristics.



Dose maps of Tc-99m MDP at 4 different time points

ii. Dosimetry in 3D breast phantoms using clinical CT irradiation. GATE was compared with a CUDA-based MC code with differences up to 8%. The statistical uncertainty was kept low (<2% in organs of interest).



Comparison of 3D dose maps from a breast CT irradiation

Conclusions: MC for Precision Medicine

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- ✓ GATE is a **well validated** MC tool both for imaging and dosimetry simulations
- ✓ MC simulations can serve as **gold standard** for standardizing procedures and evaluating clinical protocols.
- ✓ Advanced computational resources are required (e.g. HPC) for achieving **low statistical uncertainty** with high accuracy simulated results.
- ✓ MC simulations can serve for generating **synthetic data** and enhancing datasets for AI-based models.
- ✓ Simulated datasets combined with AI techniques can be used for **developing novel software tools** such Decision Support Systems (DSS).
- ✓ MC simulation is still a basic tool for optimizing protocols and investigating personalized approaches for **precision medicine**.

References: BIOEMTECH's MC Literature

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BIOEMTECH's reference papers on MC simulations:

- Kostou T et al., "**A preclinical simulated dataset of S-values and investigation of the impact of rescaled organ masses using the MOBY phantom**" Phys Med Biol. 2016
- Papadimitroulas P. "**Dosimetry applications in GATE Monte Carlo toolkit**" Phys Med. 2017
- Papadimitroulas P et al., "**A personalized, Monte Carlo-based method for internal dosimetric evaluation of radiopharmaceuticals in children**" Med Phys. 2018
- Kostou T et al., "**Size-specific dose estimations for pediatric chest, abdomen/pelvis and head CT scans with the use of GATE**" Phys Med. 2019
- Chatzipapas K. et al., "**Standardization and Validation of Brachytherapy Seeds' Modelling Using GATE and GGEMS Monte Carlo Toolkits**" Cancers. 2021
- Sarrut D et al., "**Advanced Monte Carlo simulations of emission tomography imaging systems with GATE**" Phys Med Biol. 2021
- Sarrut D et al., "**The OpenGATE ecosystem for Monte Carlo simulation in medical physics**" Phys Med Biol. 2022
- Eleftheriadis V et al., "**A framework for prediction of personalized pediatric nuclear medical dosimetry based on machine learning and Monte Carlo techniques**" Phys Med Biol. 2023
- Koch M et al., "**HPC+ in the medical field: Overview and current examples**" Technol Health Care. 2023

Relevant literature:

- Segars WP et al., "**Population of anatomically variable 4D XCAT adult phantoms for imaging research and optimization**" Med Phys. 2013
- Sarrut D et al., "**A review of the use and potential of the GATE Monte Carlo simulation code for radiation therapy and dosimetry applications**" Med Phys. 2014
- Merlin T et al., "**CASToR: a generic data organization and processing code framework for multi-modal and multi-dimensional tomographic reconstruction**" Phys Med Biol. 2018