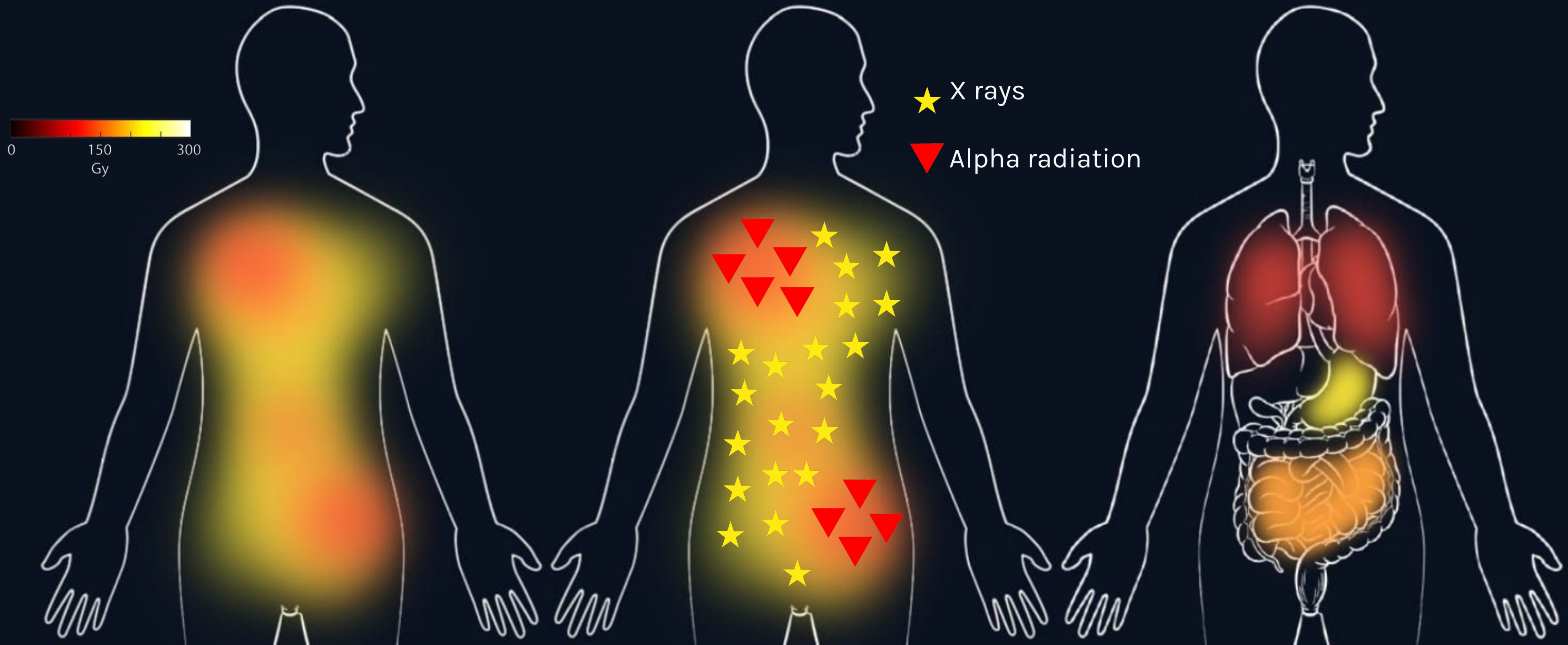
Exploring Methods for Computing Absorbed Radiation Dose in CT Imaging

Group 4 - Avanti Bhandarkar, Diana Vucevic, Sharvari Deshmukh

Types of Radiation Doses

Absorbed dose (Gray/Gy) → Equivalent dose (Sievert/Sv) → Effective dose (Sievert/Sv)



Why Does Dose Estimation Matter?

Effects of radiation exposure

- Deterministic effects - usually occur only at high doses → skin burns, hair loss, ARS
- Stochastic effects - can occur at any dose → cancer and genetic mutations

For e.g., while performing **dose estimation in pregnant women** [1,2]

- Fetal CT radiation increases (up to doubles [3]) the risk of childhood cancers
- May also lead to congenital malformations and growth restriction in extreme cases

Keep the radiation dose **ALARA**

$$\mathrm{CTDI_w} = \frac{1}{3} \times \mathrm{CTDI_{center}} + \frac{2}{3} \times \mathrm{CTDI_{periphery}}$$

Clinical Dose Metrics

$$\mathrm{CTDI_w} = \frac{1}{3} \times \mathrm{CTDI_{center}} + \frac{2}{3} \times \mathrm{CTDI_{periphery}}$$

$$\mathrm{CTDI_{vol}} = \frac{\mathrm{CTDI_w}}{\mathrm{pitch}}$$

$$\mathrm{DLP} = \mathrm{CTDI_{vol}} \times \text{scan length}$$

Limitations of Clinical Dose Metrics	How Can Monte Carlo Simulations Help?
Lack of Personalization Across Patients	Patient-Specific Modeling
Oversimplification of Dose Distribution	Enhanced Dose Distribution Tracking
Limited Relevance for Risk Prediction	Ability to Generate a Cumulative Dose Profile
Cannot Incorporate Motion / Scanning Parameters	Better Handling of Complex Scanning Parameters

How are Monte Carlo Simulations Used for Dose Estimation?

Photon Generation

↓

Photon Transport

↓

Energy Deposition

Photon Generation: Generate photon energies using the cumulative distribution function (CDF) of X-ray energies $E_{\text{photon}} = F^{-1}(r)$

Photon Transport: Calculate attenuation as photons pass through different tissues, using $I = I_0 e^{-\mu x}$

Energy Deposition: Energy transferred to tissue per unit mass, calculated using

$$D = \frac{E_{\text{transferred}}}{m}$$

Key Scanner Parameters and Their Relation to Dose [4]

Parameters	Relation to Dose
Pitch	Inversely proportional
Rotation Time	Directly proportional
X-ray Tube voltage (kVp)	Directly proportional
Source to image distance (SID)	Related by the inverse square law

Dose Modulation/Reduction in CT Scans

Tube Current Modulation (TCM)

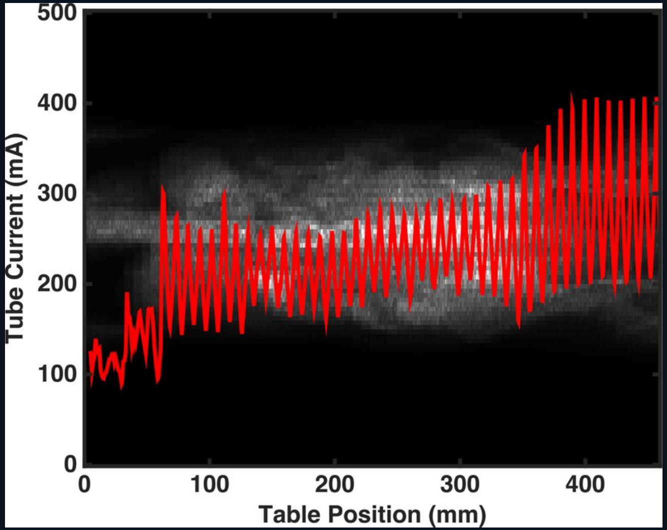


Figure 1. TCM [5]

Physical filters

Figure 2. Bismuth Shielding [A]

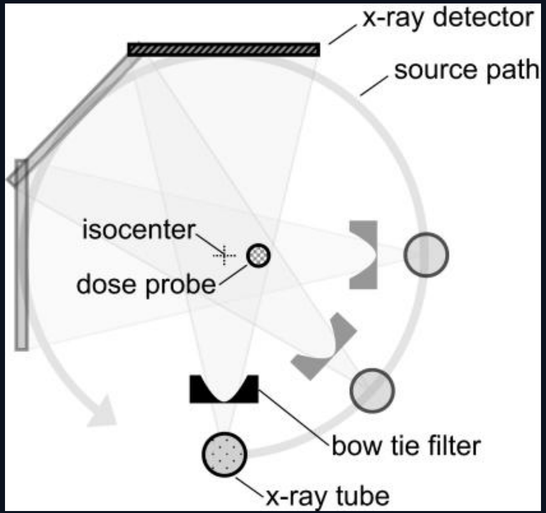


Figure 3. Bow-tie Filters [B]

Dataset [5,6] for Our MC Simulations

Scanner (SOMATOM Definition AS 64) characteristics

- SID, Tube V, Bowtie specific source model (CDF)

Patient information

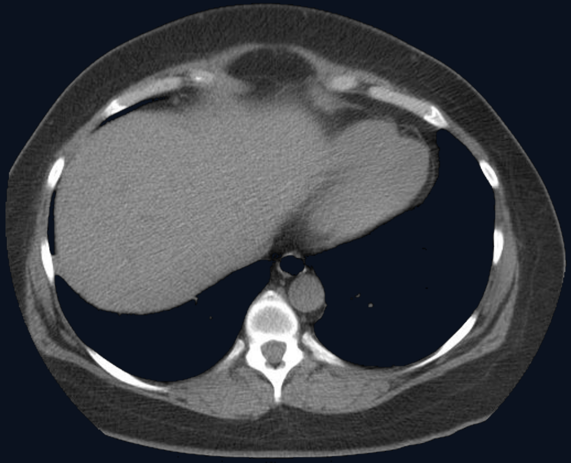
- DICOM files, gestational age, $D_{w,\,topo}$, $D_{w,\,image}$

Exam specifications

- Rotation time, pitch, max/mean/effective tube current, $CTDI_{vol}$, nominal beam collimation, etc.

Fetal dose simulation and estimates

- No. of photons, MC output, absolute organ dose, Normalised output and organ dose



Sample CT scan of Patient

Anatomy-Aware Voxelized Models

Tissue categories: darker = denser

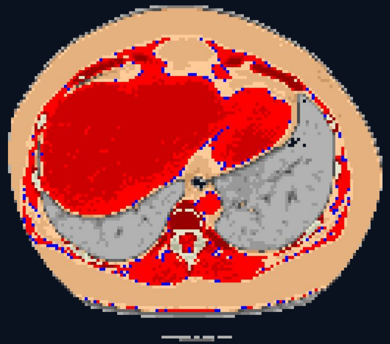
- Gray - Lung tissue
- Brown - Fat / soft tissue
- Red - Muscle
- Off-white and Gray - Bone

Pregnancy-specific tissues

- Off white - Fetal bone
- Lavender - Fetal tissue
- Green - Gestational sac
- Pink - Uterus

Non-anatomical materials

- Blue - Water
- White - Air



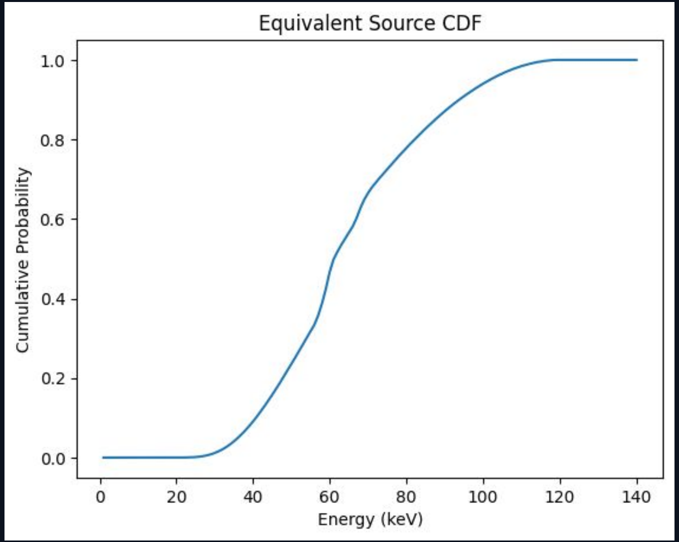
Coronal view

Axial view

Sagittal view

MC Simulations: Methodology

- Voxelized Anatomical Models using DICOM and MCNPX input files
- Mapped tissue code to densities for tissue segmentation
- Downsampled slice image to 1 / 4th to decrease computation time
- TCM vs FTC for CDF of photon energies from source



MC Simulations: Methodology

- Number of photons : 100 per 10^0 angle per voxel
- Used image position, orientation and SID to calculate distance between source and voxel
- Attenuation constant approximation
- Energy to dosage conversion

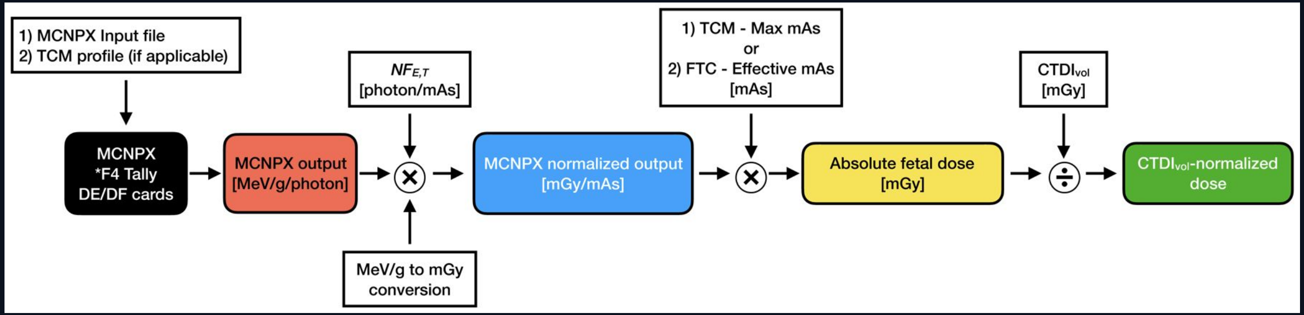


Figure 4. Process of obtaining absolute and normalised fetal dose [5]

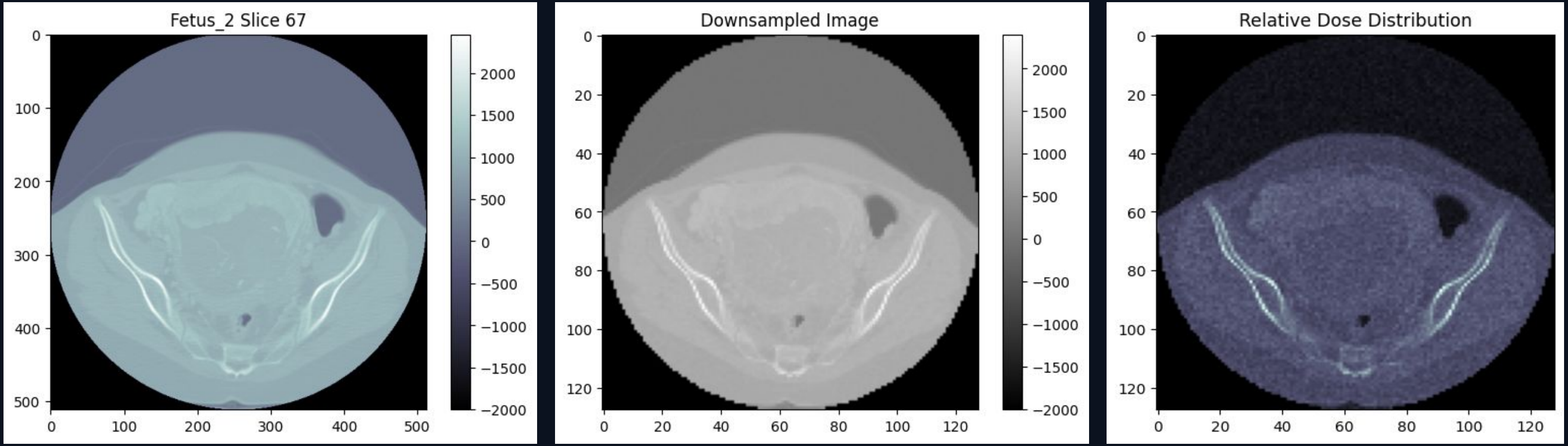
MC Simulations: Limitations & Approximations

Constraints: Complexity, Time, Computational Resources

Approximations:

- Simplified Anatomical Model
- Energy Cutoff and Local Deposition
- Scanner Geometry and Parameters
- Simulation parameters
- Photon & Tissue interactions
- Uncertainty factor

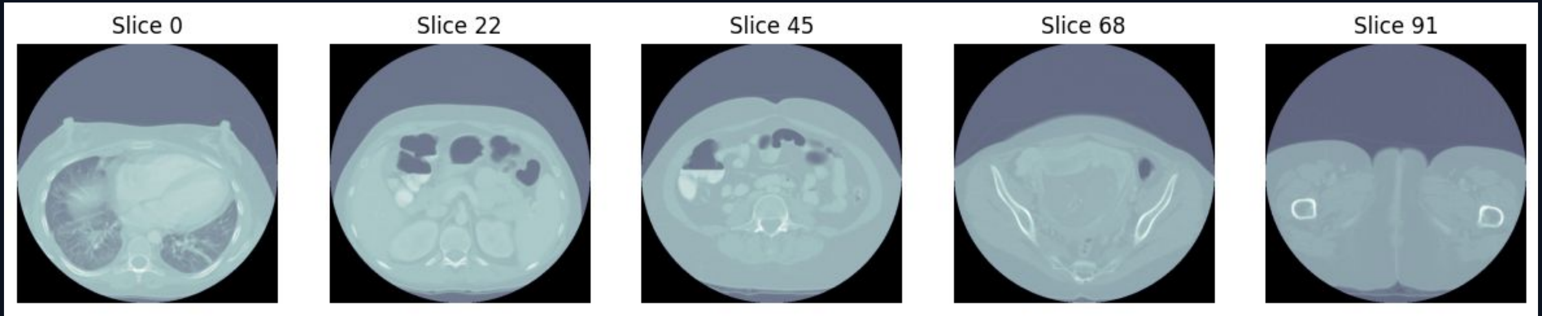
MC Simulations: Results

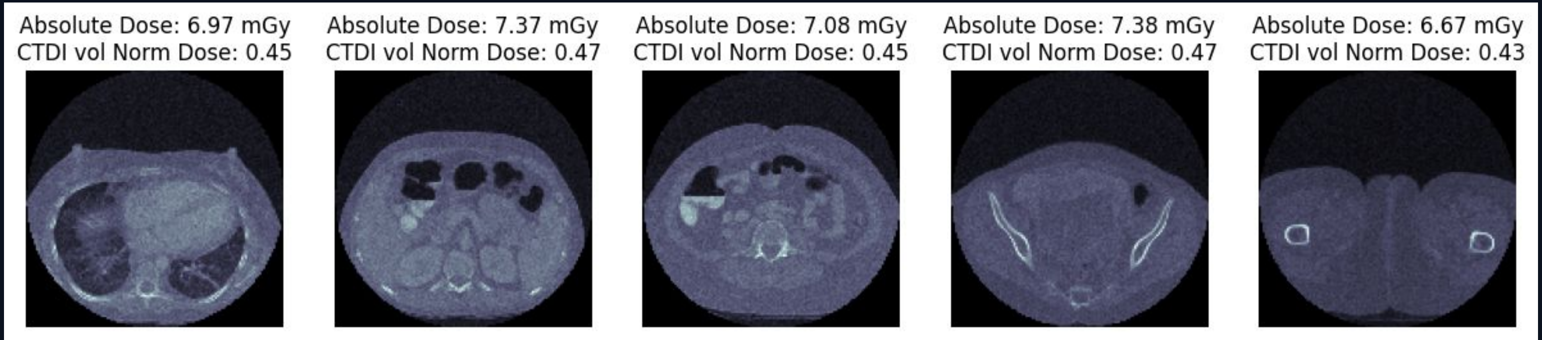


Absolute dose for slice: 7.4 mGy

$CTDI_{vol}$ Normalized dose for slice: 0.47

MC Simulations: Results





References

Papers

[1] Sadro, Claudia T., and Theodore J. Dubinsky. "CT in pregnancy: risks and benefits." *Applied radiology* 42.10 (2013): 6.

[2] Chen, Morie M., et al. "Guidelines for computed tomography and magnetic resonance imaging use during pregnancy and lactation." *Obstetrics & Gynecology* 112.2 Part 1 (2008): 333-340.

[3] Goldberg-Stein, Shlomit, et al. "Body CT during pregnancy: utilization trends, examination indications, and fetal radiation doses." *American Journal of Roentgenology* 196.1 (2011): 146-151.

[4] Goo, Hyun Woo. “CT radiation dose optimization and estimation: an update for radiologists.” Korean journal of radiology vol. 13,1 (2012): 1-11. doi:10.3348/kjr.2012.13.1.1

[5] Hardy, Anthony J., et al. "Reference dataset for benchmarking fetal doses derived from Monte Carlo simulations of CT exams." *Medical physics* 48.1 (2021): 523-532.

[6] Angel, Erin, et al. "Radiation dose to the fetus for pregnant patients undergoing multidetector CT imaging: Monte Carlo simulations estimating fetal dose for a range of gestational age and patient size." *Radiology* 249.1 (2008): 220-227.

References and Resources

Images

[A] Karim, M.K.A, Rahim, N.A et al. “The effectiveness of bismuth breast shielding with protocol optimization in CT Thorax examination” Journal of X-Ray Science and Technology, vol 27, no. 1, pp. 139-147, 2019.

[B] McKenney, Sarah E., et al. "Experimental validation of a method characterizing bow tie filters in CT scanners using a real-time dose probe." *Medical Physics* 38.3 (2011): 1406-1415.

Websites

CT Dose: https://radiopaedia.org/articles/ct-dose?lang=us

Radiation Dose Reporting: https://health.ucdavis.edu/radiology/radiationdose.html

Dataset

Reference Dataset for Benchmarking Organ Doses Derived from Monte Carlo Simulations of CT Exams

Accessed from https://zenodo.org/records/3959512 on October 18, 2024

Our Code

https://github.com/186shades/ct-dose-estimation

Thank You!