MIDSX: A Monte Carlo Interaction and Dosimetry Simulation of X-rays

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Introduction

- CT imaging is essential but carries ionizing radiation risks.
- Monte Carlo (MC) methods offer precise radiation estimation via photon transport simulations.
- Introducing MIDSX, an optimized open-source MC code for medical x-ray transport.
- MIDSX simplifies usage and is validated against benchmarks, proving its efficacy.

Simulation Geometry

The geometry of a transport simulation consists of the following objects:

- A source object for photon generation.
- Voxel grids in NifTI files for object/body geometries and material info.
- Tallies for tracking photon trajectories and energy metrics.
- A computational domain for object containment and background material specification.

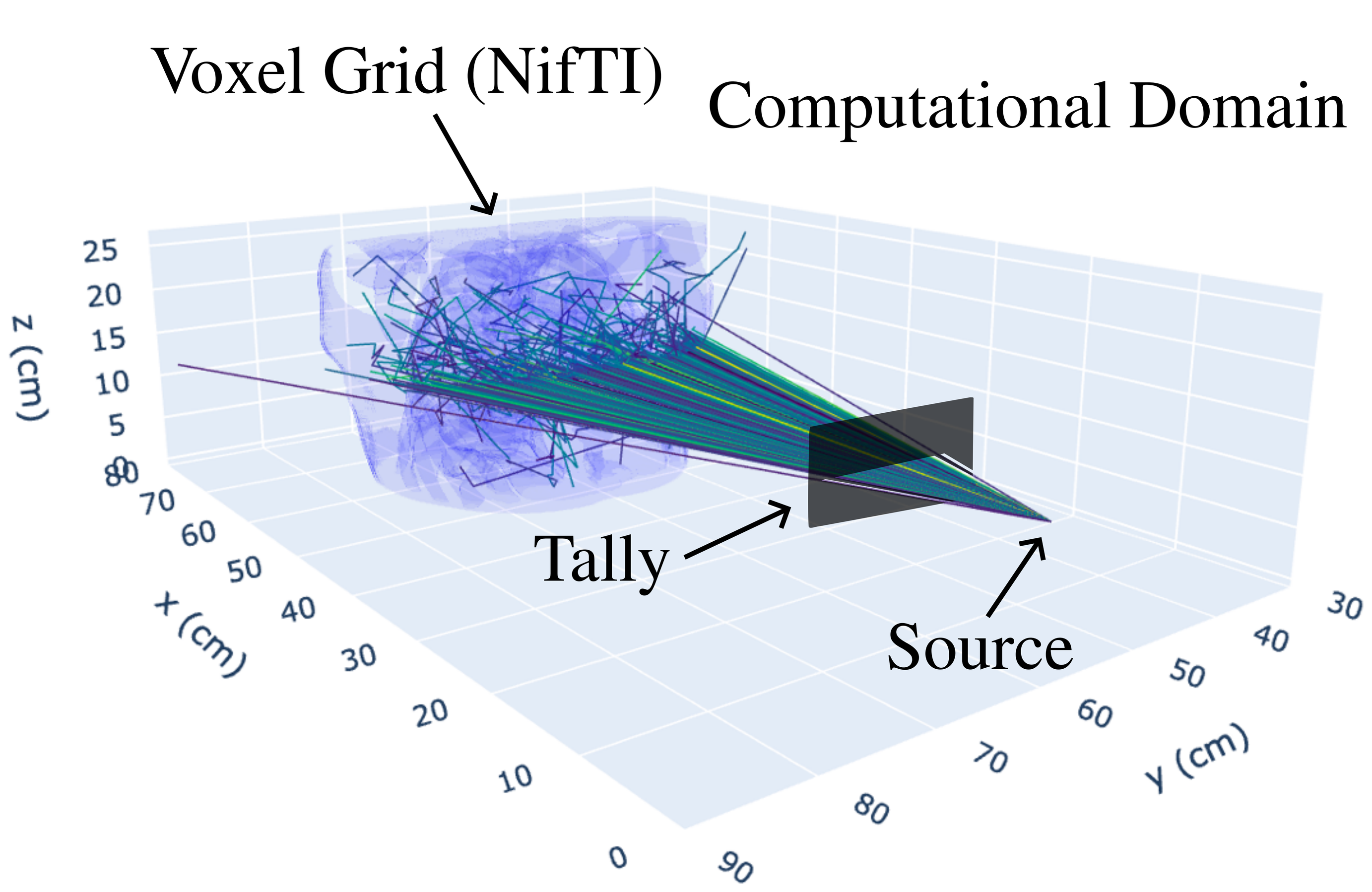

Figure 1. A typical transport geometry used in MIDSX.

Transport Theory

- As a photon take "steps" through a homogenous computational domain, its position after taking the n-th step is represented by the parametric ray equation:

$$\vec{\mathbf{r}}_n = \vec{\mathbf{r}}_{n-1} + \hat{\mathbf{d}}t, \tag{1}$$

where $\vec{\mathbf{r}}_{n-1}$ is the position before the n-th step, $\hat{\mathbf{d}}$ is a unit vector in the direction of the step, and t is the length of the n-th step.

- For a photon of energy E in material M, MIDSX randomly samples t for use in Eq. 1 from the following probability distribution function (PDF):

$$p(t) = n\sigma \exp\left[-t(n\sigma)\right], \tag{2}$$

where n is the number density of M and $\sigma = \sigma(E, M)$ is the atomic cross-section of M at E.

- σ can be interpreted as the effective interaction area of a molecule in M.
- Using the inversion method for sampling a PDF on Eq. 2, random values of t can be generated from

$$t = -\frac{1}{n\sigma}\ln\gamma, \tag{3}$$

where γ is a uniformly distributed random number in the interval $[0, 1)$.

Photon-Matter Interactions

At the end of each step, an interaction is sampled. There are 3 fundamental photon-matter interactions in the medical x-ray energy range that MIDSX implements:

Common Variables

E - Energy of incoming photon
θ - Angle of scattered photon
θ_e - Angle of ejected electron
U_i - Binding energy of subshell

1. Photoelectric Effect

- Photon interacts with electron of target atom, resulting in an electron being ejected with $E_e = E - U_i$ and the photon being absorbed.

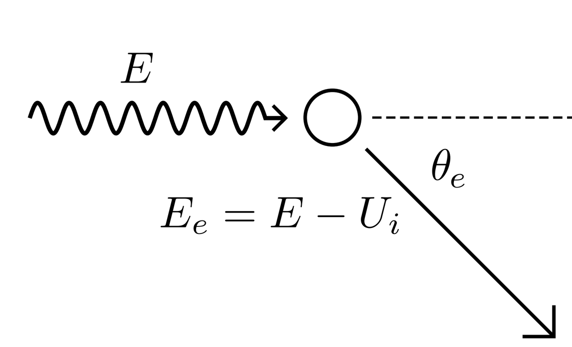

Figure 2. A diagram representing the photoelectric effect.

2. Compton Scattering

- Photon interacts with electron of target atom, resulting in a scattered photon of energy E' and a released electron with energy $E_e = E - E' - U_i$.

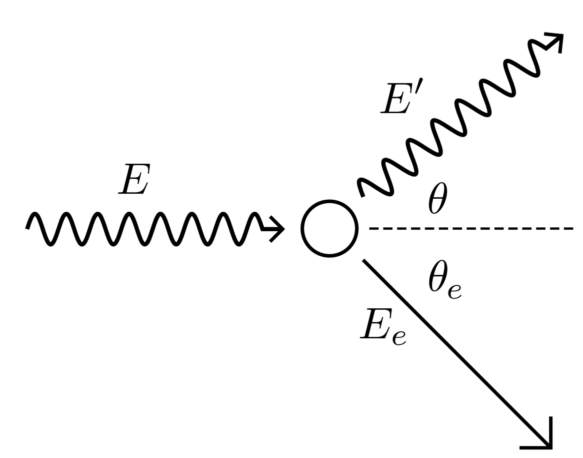

Figure 3. A diagram representing Rayleigh scattering.

3. Rayleigh Scattering

- Photon interacts coherently with atom, resulting in photon scattering with no energy loss.

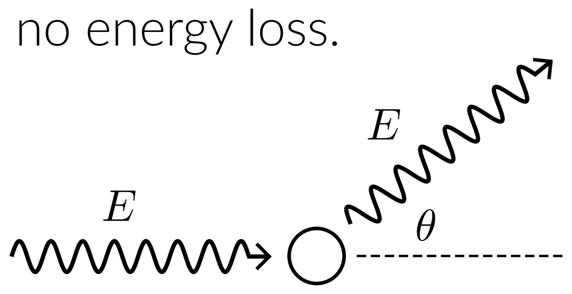

Figure 4. A diagram representing Compton scattering.

Implementation

For coherent and incoherent scattering, the methodology of [1] was adapted for use in MIDSX, neglecting Doppler energy broadening and the production of secondary particles. For the photoelectric effect, the photon is terminated and all energy is deposited at the location of interaction.

Validation

To validate the accuracy of MIDSX, simulations were performed and compared to reference data (PENELOPE, EGSrnc, Geant4, and MCNP) obtained by the American Association of Physicists in Medicine Task Group Report 195 (TG-195) [2].

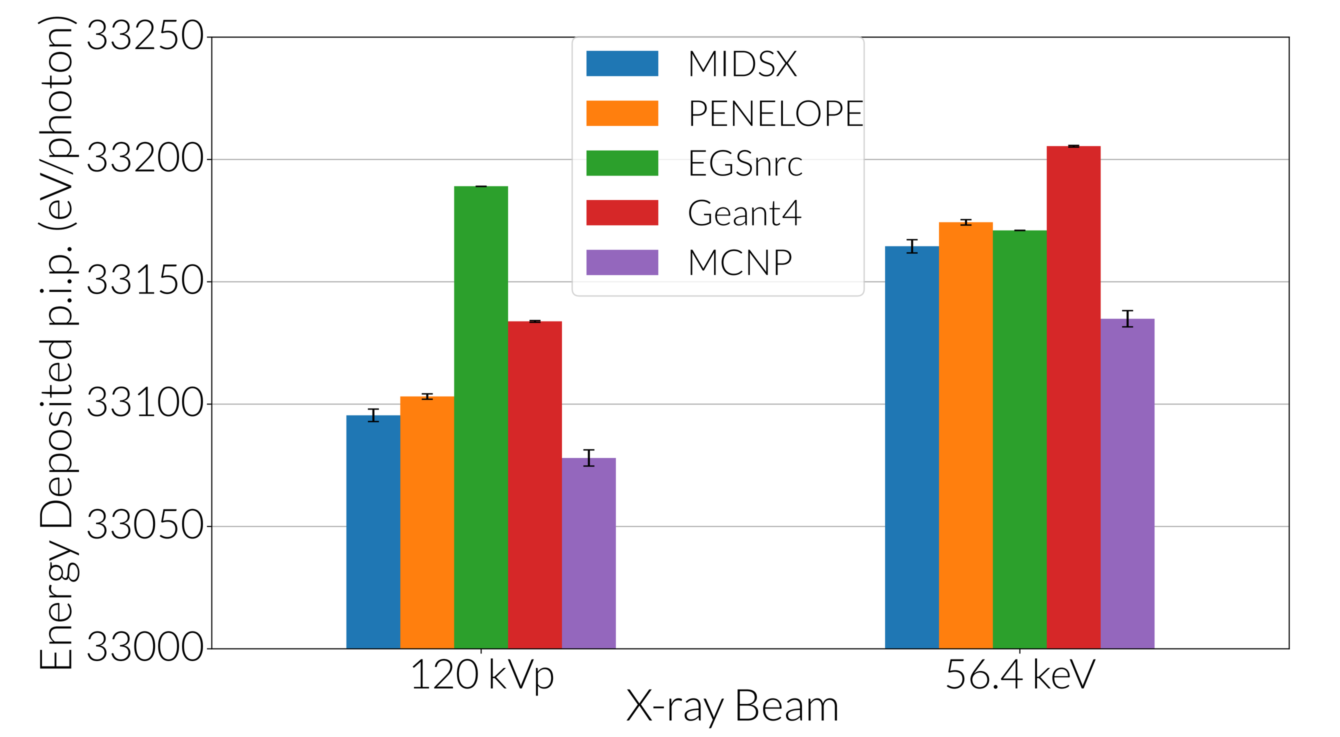

Figure 5. The energy deposited per initial photon (p.i.p.) (eV/photon) in the simulated tissue for the full-field simulation as described by Case 2. The simulation was performed at 56.4 keV and 120 kVp at 0°, with the 120 kVp spectrum provided by TG-195.

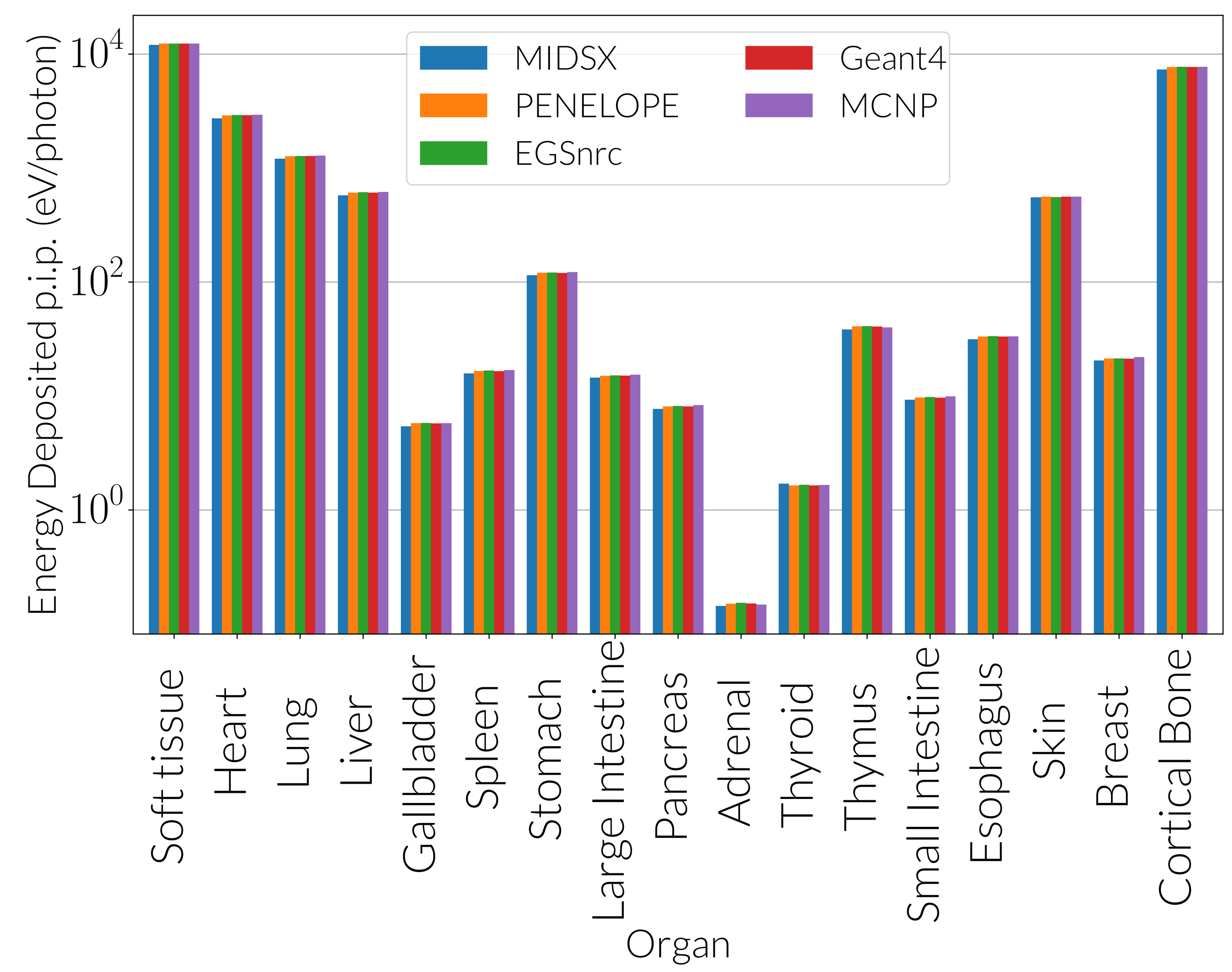

Figure 6. The energy deposited per initial photon (p.i.p.) (eV/photon) in the organs composing a voxelized human phantom for the 0°, 120 kVp simulation as described by Case 5.

Discussion

- MIDSX demonstrates varied but reasonable agreement with TG-195 reference code systems, with excellent agreement in Case 1 and 2.
- For Case 5, all organ energy depositions were lower than reference codes, except for the thyroid. The max mean percent error observed was 6.3%.
- Future work will focus on investigating the implementation of scattering events, cross-section data initialization, and interpolation errors in MIDSX.

References

[1] Amanda L Lund and Paul K Romano. Implementation and validation of photon transport in OpenMC. Technical report, Argonne National Lab.(ANL), Argonne, IL (United States), 2018.

[2] Ioannis Sechopoulos, Elsayed S. M. Ali, Andreu Badal, Aldo Badano, John M. Boone, Iacovos S. Kyprianou, Ernesto Mainegra-Hing, Kyle L. McMillan, Michael F. McNitt-Gray, D. W. O. Rogers, Ehsan Samei, and Adam C. Turner. Monte Carlo reference data sets for imaging research: Executive summary of the report of AAPM Research Committee Task Group 195. *Medical Physics*, 42(10):5679–5691, October 2015.