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EASTERN TIME [GMT-4]

Monte Carlo Calculation of Radiation Exposure to Astronauts Using 4D Extended Cardiac-Torso (XCAT) Phantoms

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DUKE UNIVERSITY MEDICAL PHYSICS GRADUATE PROGRAM

INTRODUCTION

- The space radiation environment is influenced by distance from the Sun, solar activity, and the planetary atmosphere and magnetic fields.
- Monte Carlo methods are used extensively for space radiation estimation but have the following limitations:
  - Do not account for individual-specific anatomy or physiology
  - Cannot model populations of adults, children, and neonates
- Accurate evaluation of space radiation is critical to informing sound mission-planning decisions for both spaceflight and planetary habitats.
- Our solution is **ATOM - Atmospheric, Trajectory, and Orbital Modeling**, a GEANT4-based Monte Carlo simulation framework incorporating:
  a) highly detailed, anatomically realistic digital 4D extended cardiac-torso (XCAT) human phantoms, and
  b) sophisticated NASA models of planetary atmospheres, spaceflight trajectories, and galactic cosmic radiation.

METHOD

- **GEANT4:** GEANT4 is a Monte Carlo toolkit which accounts for a wide range of interactions across a variety of particles at energies from meV to GeV. It is capable of modeling complex geometries and permits the creation of any desired material. Versatile dose-tracking tools are also provided.
- **4D Extended Cardiac Torso (XCAT) phantoms:** XCAT phantoms, developed by our group, are a population of highly detailed computerized human body phantoms that model both anatomy and physiological processes. XCAT phantoms can be voxelized and loaded into ATOM.
  - Parameters: age, height, weight, BMI, gender.
- **JPL SPICE API:** SPICE is a NASA space observation geometry system.
  - Parameters: time, desired geometrical reference frame.
  - Outputs: positions, velocities, and attributes of the Sun and all the planets and their moons.
- **Badhwar-O'Neill (BON) Model:** The BON model is a mathematical model developed at NASA that describes the galactic cosmic radiation (GCR) environment in deep space. GCR radiation is isotropic.
  - Parameters: time (month/year), distance from the Sun, solar activity.
  - Outputs: differential energy spectra for each GCR ion.
- **NASA Planetary Global Reference Atmospheric Models (GRAMs):** NASA GRAMs provide empirical models of planetary atmospheres (Earth, Mars, Venus, Titan, and gas giants) based on spacecraft data.
  - Parameters: time (seasonal/diurnal), altitude, latitude, longitude.
  - Outputs: mean atmospheric density, temperature, pressure, and chemical composition.

METHOD

- **Solar Energetic Particles (SEPs):** SEPs are emitted from the Sun during solar flares or coronal mass ejections and are both unpredictable and unique in terms of spectral intensity. ATOM includes the measured spectra of recorded solar particle events and allows the user to specify whether to include such an event in a run. SEPs are nearly isotropic after about 1 astronomical unit from the Sun.

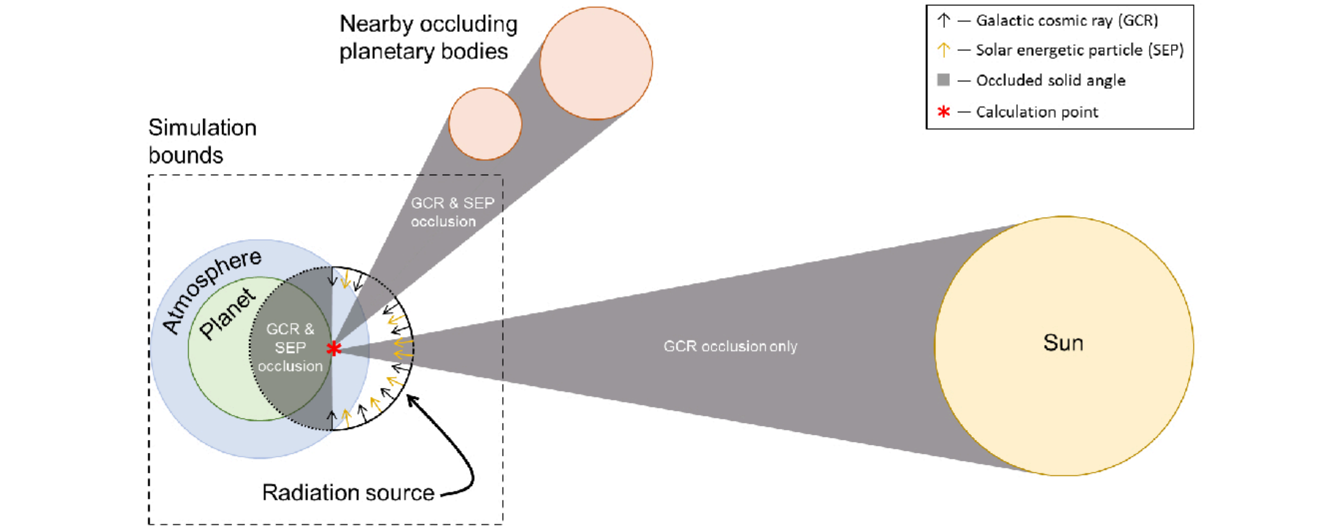


Figure 1: Simulation geometry. This geometry is Identical for spaceflight simulations sans planet and atmosphere. The source is a spherical surface centered at the target spacecraft or habitat, emitting particles toward random positions within a focal sphere bounding the target to ensure an isotropic radiation distribution within the region of interest.

- Eight XCAT phantoms (all voxelized at 2 mm isotropic resolution) as shown in **Fig. 2** were positioned at the Mars Science Laboratory (MSL) landing site in Gale Crater on the Martian surface.
- Three individual runs were performed with three different shielding configurations:
  1. Unshielded
  2. Within a cuboidal 50 cm thick shielding enclosure made of ice
  3. Within a cuboidal 50 cm thick concrete shielding enclosure composed of Martian regolith
- Each run was set at local high noon on Jan 1, 2013, at which time MSL was recording radiation data.
- Each run consisted of 13,650,000 primary events, equivalent to a time of 8.55 seconds on Mars.
- No solar particle events were simulated.

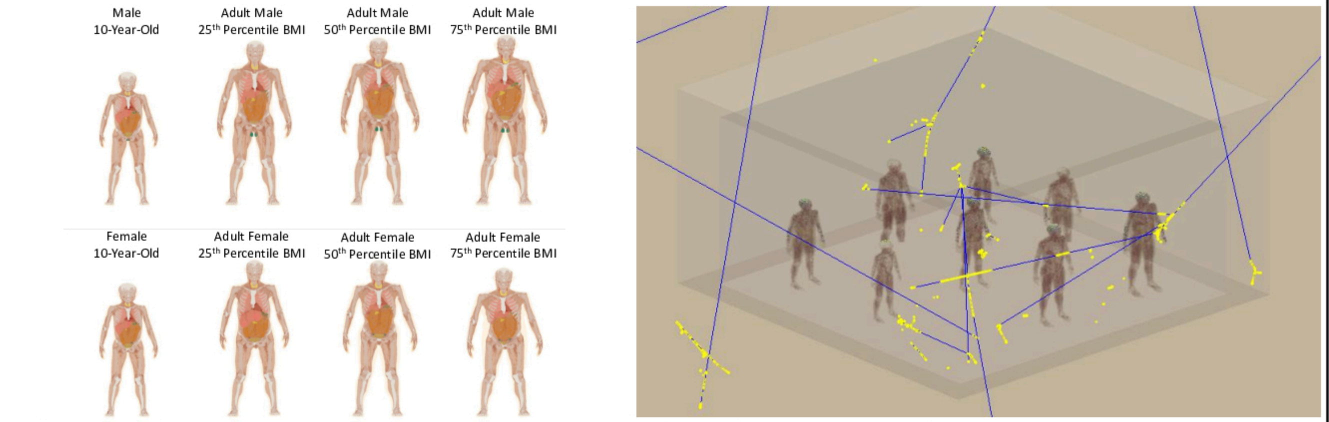
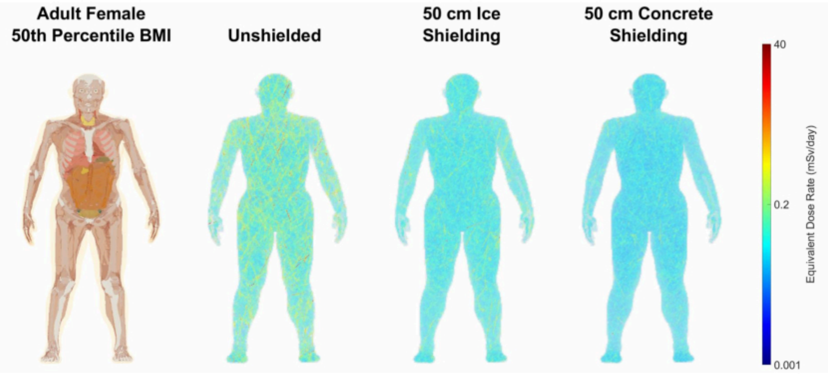


Figure 2: Left: XCAT phantom population used in this study. Right: ATOM screenshot with XCAT phantoms within a shielding enclosure on Mars. Blue lines indicate particle tracks. Yellow dots indicate radiation interaction points.

RESULTS



Video 1: 3D dose rate maps for the adult female 50th percentile BMI phantom under each of the three shielding configurations.

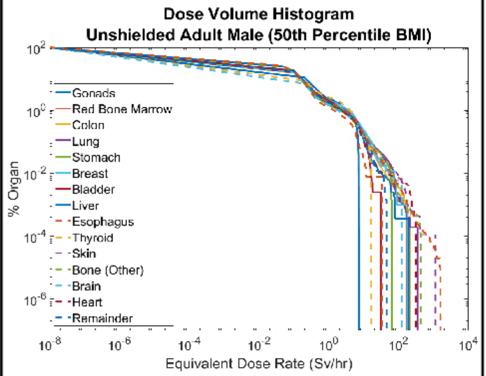


Figure 3: Dose volume histograms for the adult male 50th percentile BMI phantom.

Table 1: Organ equivalent dose rates for the adult male 50th percentile BMI phantom under each shielding configuration. All values are in mSv/day (±uncertainty).

	Gonads	Marrow	Colon	Lung	Stomach	Breasts	Bladder	Liver	Esophagus
Unshielded	0.1373 (8.7%)	0.1405 (1.3%)	0.1365 (2.6%)	0.1462 (1.5%)	0.1277 (3.8%)	0.1548 (2.8%)	0.1253 (3.0%)	0.1238 (1.5%)	0.0842 (5.8%)
50 cm Ice Shielding	0.0513 (4.8%)	0.0736 (1.3%)	0.0686 (1.5%)	0.0671 (1.0%)	0.0654 (1.7%)	0.0692 (3.7%)	0.0594 (2.3%)	0.0719 (1.7%)	0.0704 (6.8%)
50 cm Concrete Shielding	0.0419 (5.7%)	0.0470 (0.9%)	0.0472 (1.2%)	0.0470 (0.7%)	0.0466 (1.6%)	0.0514 (1.4%)	0.0514 (4.9%)	0.0400 (0.7%)	0.0522 (3.2%)

	Thyroid	Skin	Bone	Salivary glands	Brain	Heart	Remainder
Unshielded	0.1487 (8.9%)	0.1499 (1.6%)	0.1400 (1.3%)	0.1225 (8.9%)	0.1283 (3.1%)	0.1259 (2.7%)	0.1450 (0.4%)
50 cm Ice Shielding	0.0517 (5.2%)	0.0790 (1.0%)	0.0700 (1.0%)	0.0764 (4.0%)	0.0692 (1.2%)	0.0658 (2.0%)	0.0751 (0.3%)
50 cm Concrete Shielding	0.0527 (5.6%)	0.0490 (0.7%)	0.0451 (0.7%)	0.0478 (6.0%)	0.0505 (1.3%)	0.0423 (1.5%)	0.0485 (0.2%)

Colour scale: 0, 0.1, 0.2, 0.3, 0.4, 0.5

Table 2: Whole-body equivalent dose rates for each phantom under each shielding configuration. All values are in mSv/day (±uncertainty).

	Male, 10-Year-Old	Male, 25th %tile BMI	Male, 50th %tile BMI	Male, 75th %tile BMI	Female, 10-Year-Old	Female, 25th %tile BMI	Female, 50th %tile BMI	Female, 75th %tile BMI	Average
Unshielded	0.1430 (0.2%)	0.1472 (0.2%)	0.1440 (0.2%)	0.1433 (0.2%)	0.1575 (0.2%)	0.1504 (0.2%)	0.1447 (0.2%)	0.1522 (0.2%)	0.1478 (0.5%)
50 cm Ice Shielding	0.0754 (0.1%)	0.0767 (0.2%)	0.0743 (0.1%)	0.0741 (0.1%)	0.0737 (0.1%)	0.0733 (0.1%)	0.0748 (0.1%)	0.0773 (0.1%)	0.0750 (0.3%)
50 cm Concrete Shielding	0.0512 (0.1%)	0.0469 (0.1%)	0.0481 (0.1%)	0.0518 (0.1%)	0.0494 (0.1%)	0.0483 (0.1%)	0.0479 (0.1%)	0.0490 (0.1%)	0.0491 (0.2%)

Colour scale: 0, 0.1, 0.2, 0.3, 0.4, 0.5

CONCLUSIONS

- We have shown that XCAT phantoms together with NASA models of planetary atmospheres, spaceflight trajectories, and galactic cosmic radiation can be combined within GEANT4 as a comprehensive space radiation simulation framework (ATOM).
- Voxelized dose rate maps were generated and analysed for each individual in a diverse population of eight XCAT phantoms under three different shielding configurations on Mars at the MSL landing site.
- Under each shielding configuration, the total equivalent dose rate across all phantoms was consistent.
- The average whole-body equivalent dose rate across all phantoms for the unshielded configuration of 0.1478 ± 0.5% mSv/day was slightly more than four times smaller than values reported by MSL of 0.64 ± 18.8% mSv/day. This difference is expected to be reduced as the physics of ATOM is refined.