The SPARADA Project

« SPAce RAdiation DAmage »

« 우주 방사선 피해 »

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In the news…

April 1st-11th, 2026

NASA/REUTERS

https://en.wikipedia.org/wiki/Artemis_II

NASA ramps up Moon missions, announces regular crewed visits and a permanent Moon base

NASA has announced new plans to return humans to the Moon

By Iain Todd

Published: March 25, 2026 at 10:42 am

NASA is ramping up its plans for crewed missions to the Moon and establishing a permanent settlement on the lunar surface.

Plans include an eventual target of sending astronauts to the Moon every six months, building habitable infrastructure on the lunar surface and sending rovers, instruments and technology demonstrations.

https://www.skyatnightmagazine.com/news/nasa-ignition-moon-announcements-march-2026

The SPARADA Project

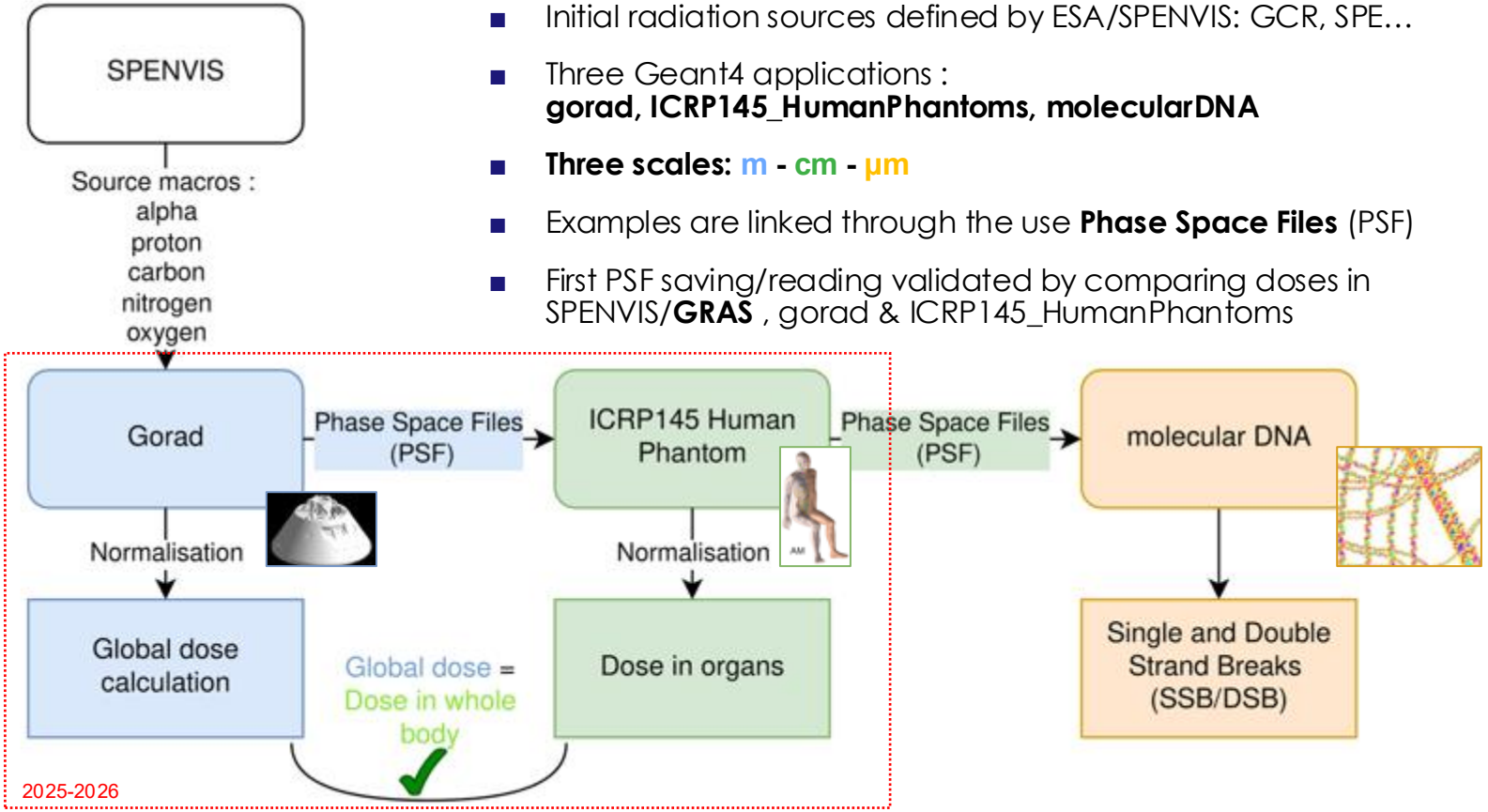
- **Objectives** of the project
- **2026 activities**
  - Principle of the multi-scale combination
  - Simulation of the radiation environment inside Orion spacecraft
    - Mission parameters (geometry, GCR & SPE spectra, exposure…)
    - Normalisation factor
    - Spectra inside the Orion spacecraft
  - Dosimetry in tesselated realistic human phantoms
    - Dosimetry in organs from GCR & SPE
    - Influence of phantom morphology
    - Influence of MC production cuts
  - Meetings & visits
- **2027 Proposal**
- Budget request

Objectives of the project

- A consortium of collaborators between **Korea, France and US** to develop a prototype of **multi-scale simulation platform** based on the **Geant4** Monte Carlo simulation toolkit to simulate **early biological damage induced in the biological cells' DNA of the human body**
  - Fully open-source approach, based on Geant4 & Geant4-DNA
  - Will be added to Geant4
  - Extensible to other application domains involving ionising radiation
    - medical physics, environmental sciences…

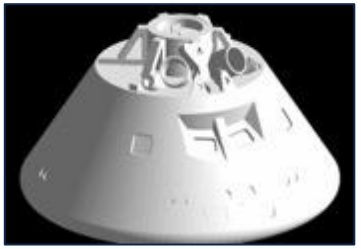
- **« Space exploration » use case**: irradiation of **realistic human phantoms** placed inside the **Orion spacecraft** or a **Moon habitat** model and determine the early DNA damage induced in cells of several organs of the phantom.
- **Four stages** : a « multi-scale » approach

Principle of the multi-scale combination



- Initial radiation sources defined by ESA/SPENVIS: GCR, SPE…
- Three Geant4 applications :
  gorad, ICRP145_HumanPhantoms, molecularDNA
- **Three scales: m - cm - µm**
- Examples are linked through the use **Phase Space Files** (PSF)
- First PSF saving/reading validated by comparing doses in SPENVIS/**GRAS** , gorad & ICRP145_HumanPhantoms

Simulation of the radiation env. within Orion

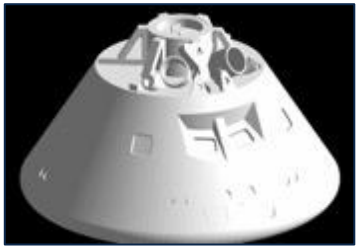


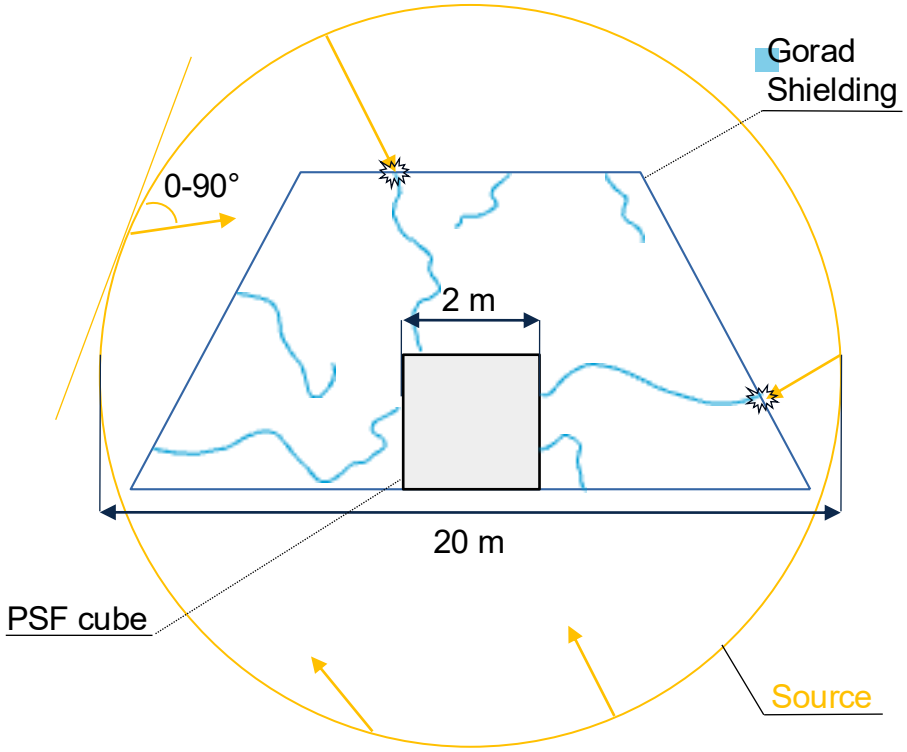
GORAD Orion NASA spacecraft

- "gorad" application
  - Gorad (Geant4 Open-source Radiation Analysis and Design) was written as a turn-key application built on top of Geant4 by M. ASAI with a grant from NASA
  - https://geant4.web.cern.ch/docs/advanced_examples_doc/example_gorad

- Details on **incident isotropic radiation from SPENVIS**
  - **GCR : P, He, C, N, O**
    - Spectra from Space Environment Information System (SPENVIS) at 1 AU from the Sun during solar minimum (May 1996) using the default ISO-15390 model (https://www.spenvis.oma.be)
  - **SPE at solar minimum & maximum (e.g. 1956 & 1989)**
    - King model
  - Mission duration: 365 days

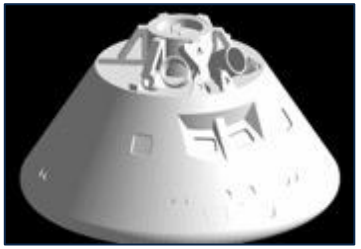
Simulation of the radiation env. within Orion (2)





- Spherical virtual source, SPENVIS spectra (GCR, SPE)
- Realistic GDML geometry provided by NASA, made of Aluminium
- Geant4 Physics lists :
  - **Electromagnetic option 4 & Shielding & Rad. decay**
  - **Production cut : 1 mm**
- No biasing (for now)
- Scoring in a water cube of 2 m size
- PSF files in Gorad created by M. Asai
  - PDG code, position, momentum, energy
  - Particles that reach the cube are saved, to be used in ICRP145_HumanPhantoms

Simulation of the radiation env. within Orion (3)



- Simulated deposited dose needs to be **normalized** to calculate **realistic dose** during a space mission

$$Dose_{Real} = Dose_{Simulated} \times NORM\_FACTOR\_SPECTRUM \times NORM\_FACTOR\_ANGULAR \times 4\pi R^2 \times \frac{1}{N_{Simulated}}$$

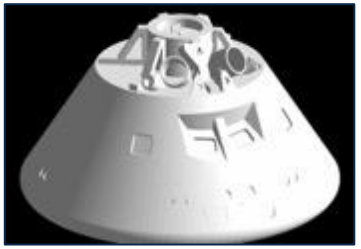
Accounts for
- the limited energy range of the simulated spectrum (from Emin to Emax),
- for the mission duration,
- for total solid angle (omnidirectional flux),
- and for unit conversion (cm^2)

Omnidirectional angular distribution from 0° to 90°

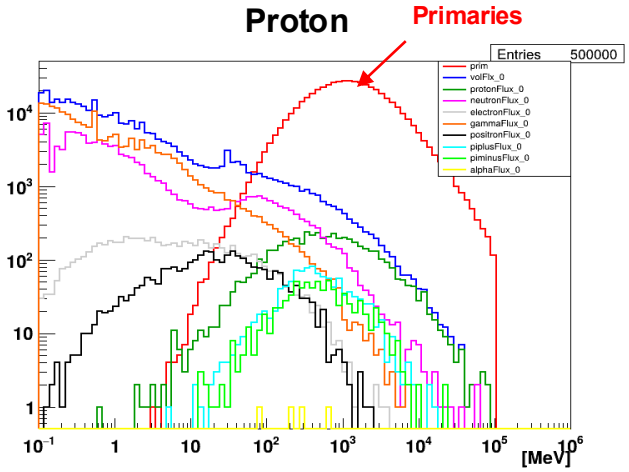
Radius of the virtual sphere

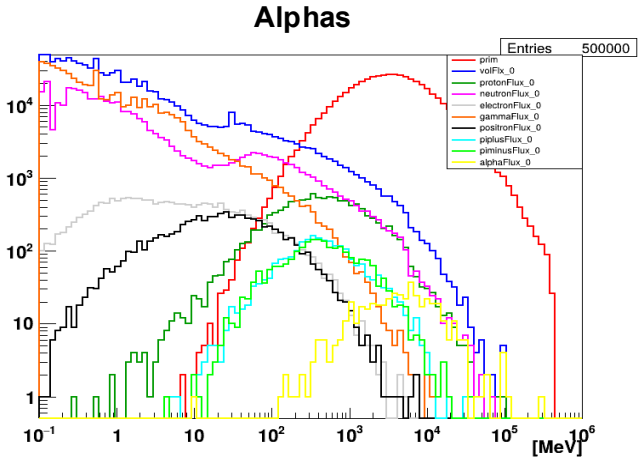
Number of primaries

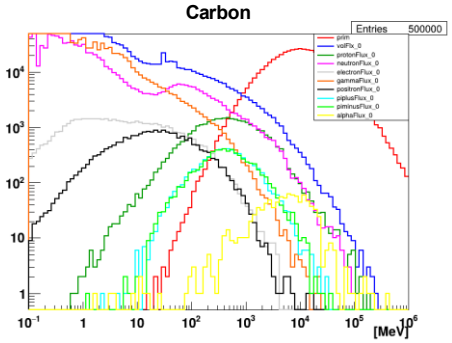
Simulation of the radiation env. within Orion (4)

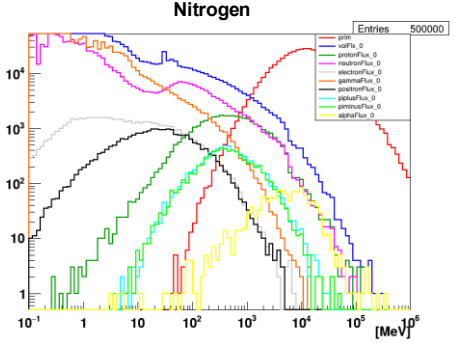


- Particle spectra within the module (for GCR)







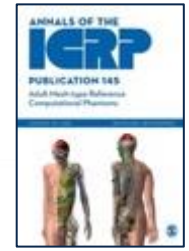


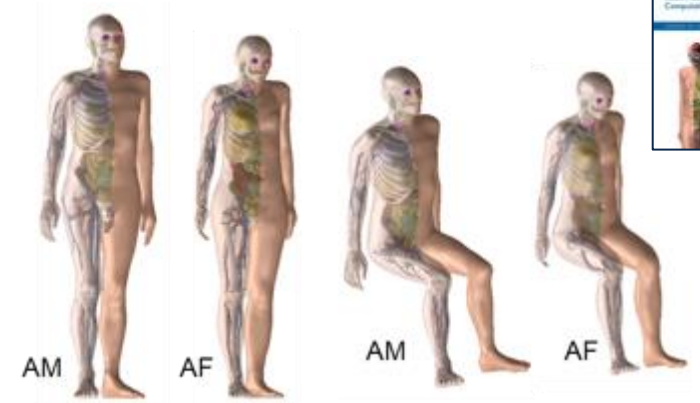
Dosimetry in human phantoms

- Yonsei U. partner can produce realistic human phantoms
  - **State-of-the-art** for computational dosimetry in humans: **ICRP Publication 145**
  - They are progressively added to Geant4, in the ICRP145_HumanPhantoms example application

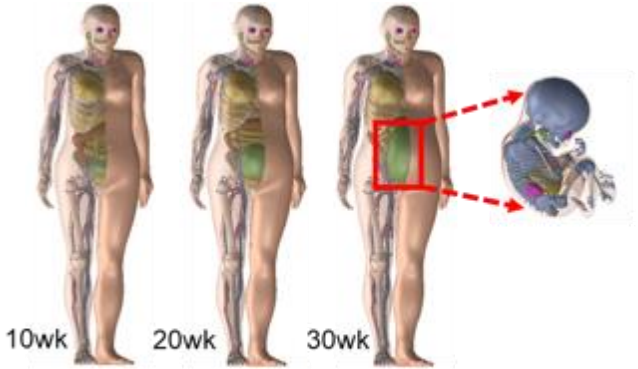
- The « ICRP145_HumanPhantoms » application
  - This example (by S. Guatelli) is used to **calculate organ doses in realistic human phantoms**
  - Energy deposition is scored in each organ of the mesh-type phantom and converted to dose using organ mass
  - **Extended to handle PSF in MT mode**

- Dosimetry in organs from GCR & SPE
  - Secondary particles recorded in PSF from the GORAD example are used to irradiate **different phantom types (standing, sitting, pregnant)**



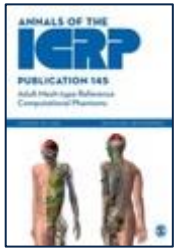


ICRP-145 phantoms (standing) *ICRP-145 phantoms (sitting)*



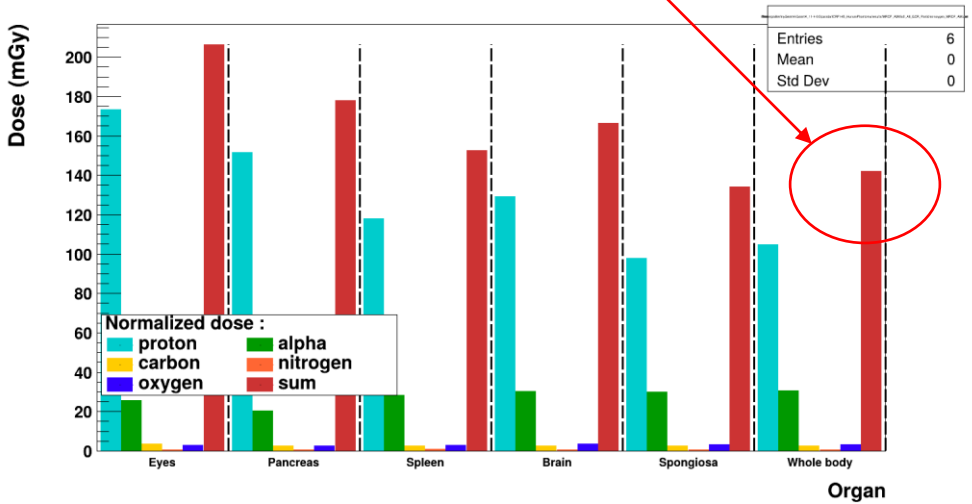
ICRP reference pregnant phantoms

Dosimetry in human phantoms (2)

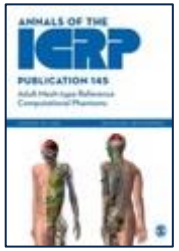


- Contribution of **each GCR particle type** to dose deposition by organ
  - $5x10^5$ incident particles (p, alpha, C, N, O)
  - Cut 1 mm
- Order of magnitude :
  - **Our results (Geant4/human phantom) : 0.389 mGy/day**
  - 0.4 mGy/day (Geant4/Timepix/**ARTEMIS I**) - Nature 634, 48–52 (2024)

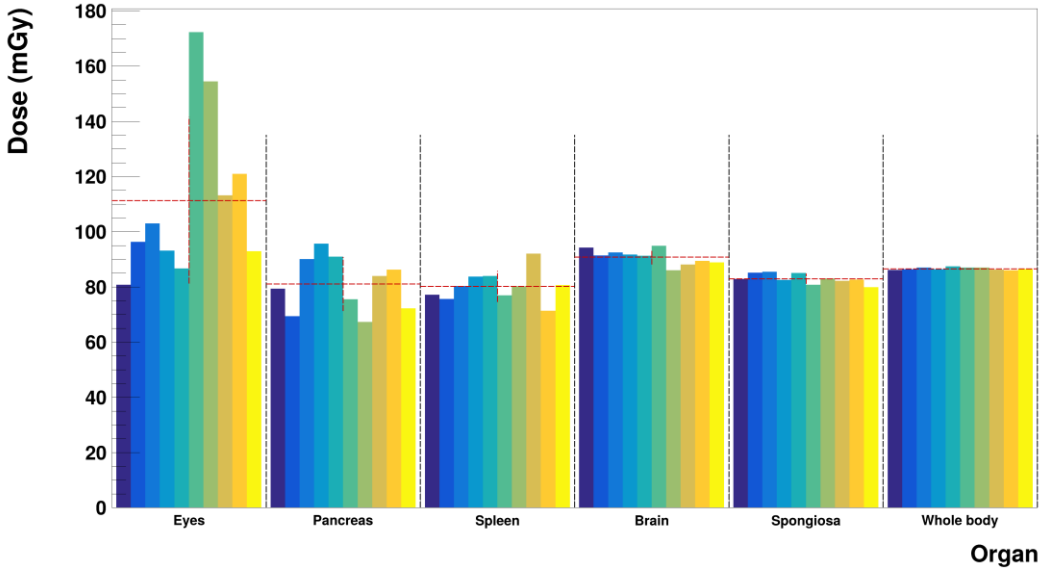
Absorbed dose for a mission duration of 365 days



Dosimetry in human phantoms (3)



- Influence of MC **randomness**



- 10 identical simulations (incident **10^7 GCR protons** only)
- Cut 1 mm for Gorad & 10 um for ICRP145_HumanPhantoms
- Variability due to randomness of simulations
- Mean +- standard dev. shown in red
- Standard deviation is **0.5 mGy for the whole body, for a mean of 86.6 mGy (0.5%)**

Eyes 111.335 ± 30.1388 (mGy)

Pancreas 81.0236 ± 9.78703 (mGy)

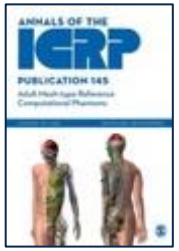
Spleen 80.1749 ± 5.63014 (mGy)

Brain 90.8186 ± 2.76357 (mGy)

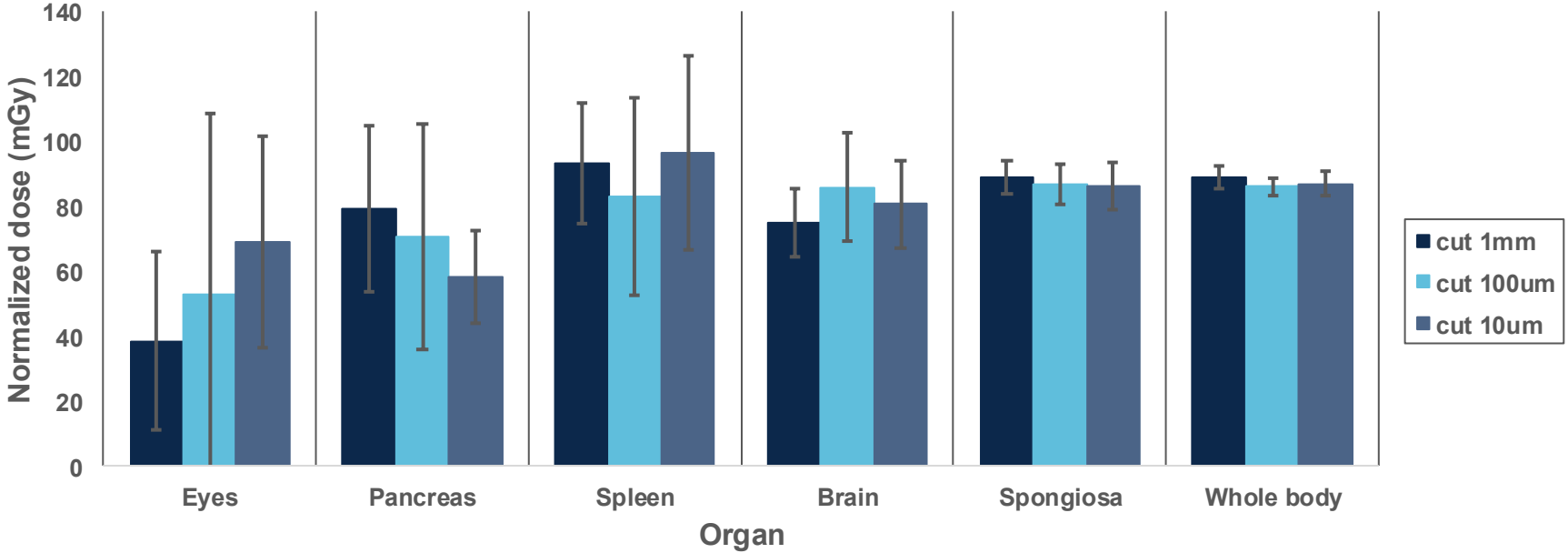
Spongiosa 82.9325 ± 1.82399 (mGy)

Whole body 86.5891 ± 0.462028 (mGy)

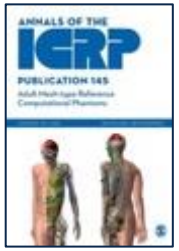
Dosimetry in human phantoms (4)



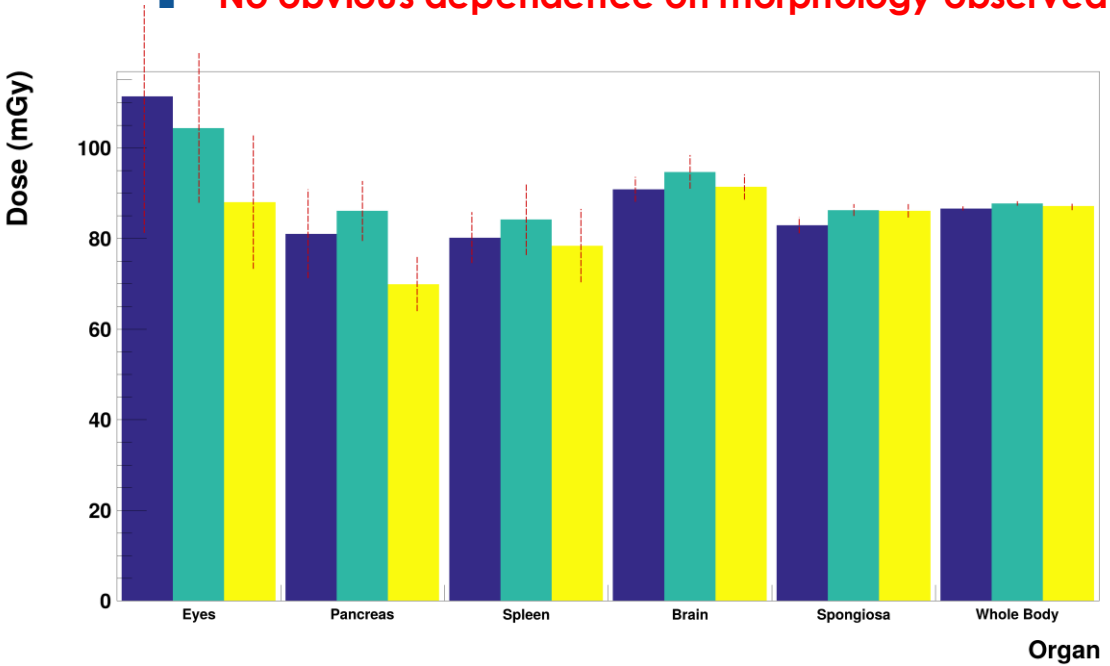
- Influence of **Geant4 secondary production cut**
  - In **both** gorad and ICRP145_HumanPhantoms
  - 5x10^5 incident GCR protons only, 13 simulations for each production cut
  - Will be needed for the ICRP145_HumanPhantoms (mm) & molecularDNA (sub-mm) combination
  - **No obvious dependence on morphology observed with this statistics**

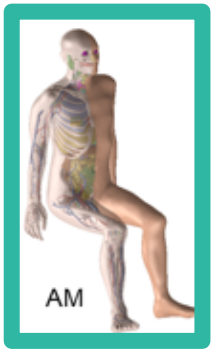


Dosimetry in human phantoms (6)

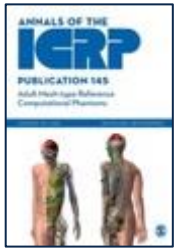


- Influence of **phantom morphology**
  - 10^7 incident GCR protons only, 10 simulations, **cut 10 um**
  - **No obvious dependence on morphology observed with the statistics**

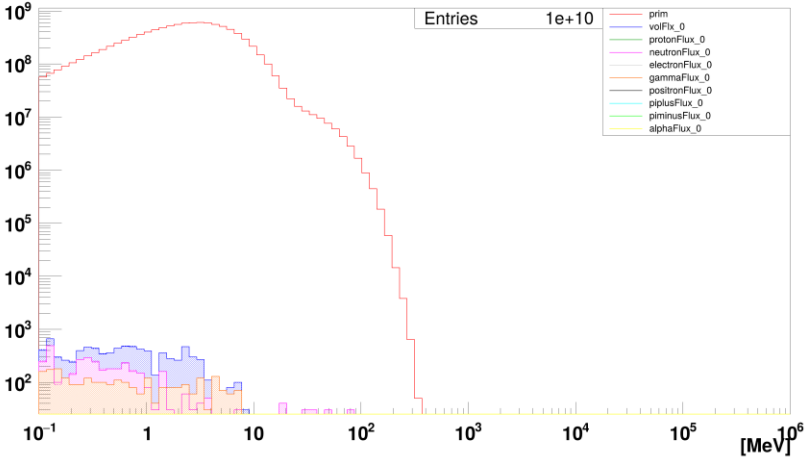


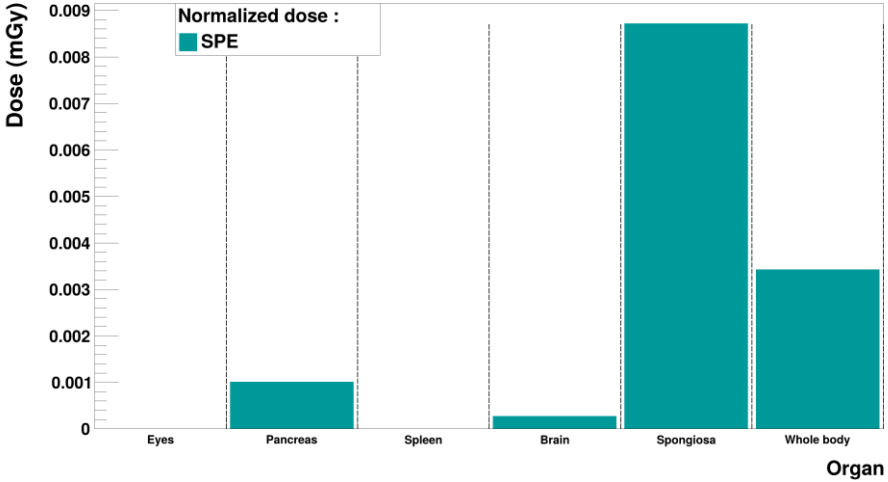


Dosimetry in human phantoms (7)



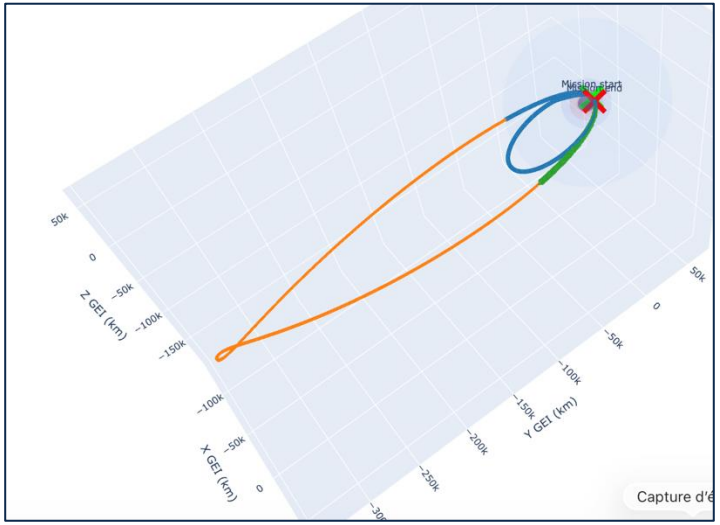
- Influence of **SPE**
  - SPENVIS / King model (1974), protons
  - Averaged over the 365-days of the mission
  - 10^{10} protons, 1 mm cut
  - Dose about **10^{-5} smaller than for GCR**





A more realistic trajectory ?

- Allows to estimate influence of **trapped protons and electrons**
  - Trajectory from NASA / S. Gano : https://www.gano.name/shawn/artemis2/
  - Three phases defined for SPENVIS
    - **Before cislunar** (up to 70000 km, beyond VA belts)
      - trapped protons, electrons, SPE
      - **1.25 days**
    - **Lunar transit** :
      - GCR
      - **7.62 days**
    - **After cislunar** :
      - trapped protons, electrons, SPE
      - **0.19 days**



- Doses
  - Trapped electrons not sufficiently energetic to cross Orion
  - Trapped protons : **1.8 E-2 mGy** before, **2.9 E-3 mGy** after
  - Dose due to **trapped protons** at least **100 times smaller** than dose due to GCR protons during lunar transit (1.9 mGy)

European Lunar Symposium 2026

- Our first results will be presented at the **Europaen Lunar Symposium 2026**
  - Nancy, France, June 22-26, 2026
  - ESA & NASA - https://sservi.nasa.gov/els2026/
- Abstract submitted
  - A. Paillet, J. W. Choi et al.
  - « A MULTI-SCALE GEANT4-BASED SIMULATION PLATFORM FOR THE PREDICTION OF EARLY BIOLOGICAL DAMAGE DURING SPACE MISSIONS »

A MULTI-SCALE GEANT4-BASED SIMULATION PLATFORM FOR THE PREDICTION OF EARLY BIOLOGICAL DAMAGE DURING SPACE MISSIONS. A. Paillet[1], J. W. Choi[2], M. Asai[3], A. Le Postollec[4], M. Dobrijevic[4], H. N. Tran[1], Y. S. Yeom[2], S. Incerti[1], [1]Université de Bordeaux, CNRS, LP2I, UMR 5797, F-33170 Gradignan, France, [2]Radiation Convergence Engineering, Yonsei University, Wonju, South Korea, [3]Thomas Jefferson National Accelerator Facility, 12000 Jefferson Avenue, Newport News, VA, USA, [4]Univ. Bordeaux, CNRS, LAB, UMR 5804, F-33600 Pessac, France.

Introduction: Being able to simulate, at the cellular scale, the mechanistic effects of ionizing radiation-induced biological damage during manned space exploration missions remains a technical challenge. We introduce a multi-scale simulation platform based on the Geant4 general-purpose Monte Carlo simulation toolkit [1-4] to simulate early DNA damage induction in cells from physical interactions and radiolysis. The feasibility of such an approach has recently been demonstrated [5]. In this work, we propose to simulate early biological damage induced in cosmonauts' cells in the context of the ARTEMIS II mission.

Materials and methods:

The platform is based on a combination of three existing examples provided with the Geant4 toolkit that deal with three different geometry scales. The first is the *gorad* example [6], used to simulate the radiation environment surrounding the realistic spacecraft geometry (meter scale). The second application is the *ICRP145_HumanPhantoms* example [7], which enables irradiation of realistic tessellated male and female human phantoms across various irradiation fields (cm scale). Finally, the third example is the *moleculardna* example [8], which can simulate the induction of early biological damage at the single-cell level (sub-micrometer scale). We seamlessly combine these examples with interconnecting phase-space files that contain all necessary information for simulating ionizing particles across three different scales.

Data and code: All data and codes used are open-source. Moreover, a coherent set of scripts will be made available to the community to simplify platform use. For example, by providing a GCR spectrum as an input parameter, we aim to provide a quantitative estimate of DNA damage in a few organs of interest (brain, eyes, spleen, pancreas, etc.).

Preliminary results: As a first step, we calculated the dose delivered to standing male and female phantoms placed at the center of the Orion module using Geant4 version 11.4.0. For a fictive mission duration of one year, considering GCR spectra (protons, alpha particles, C, N, and O ions), the typical absorbed doses in organs are presented.

Conclusion and perspectives: The initial results presented in this study are encouraging. We are currently working to predict early radiation-induced damage at the single-cell level from exposure to GCR and SPE across different organs in human phantoms, adopting different positions (e.g., seating phantoms). The platform will also be adapted to a lunar habitat [9].

References:

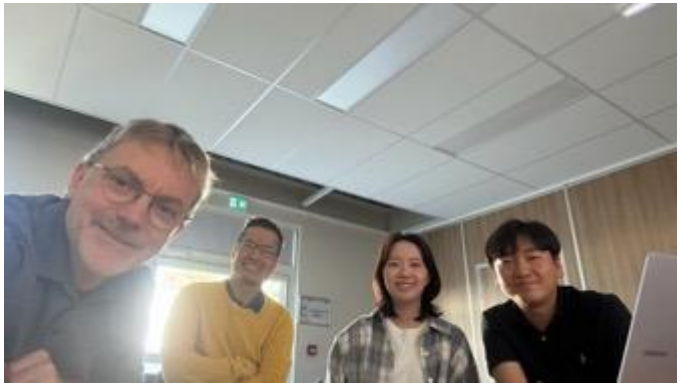
[1] Agostinelli S. et al. (2003) *Nucl. Instrum. Meth. A*, 506, 250-303. [2] Allison J. et al. (2006) *IEEE Trans. Nucl. Sci.*, 53, 270-278 [3] Allison J. et al. (2016) *Nucl. Instrum. Meth. A*, 835, 186-225. [4] https://geant4.org [5] Archer J. W. et al. (2025) *Radiat. Phys. Chem.*, 229, 112448. [6] https://geant4.web.cern.ch/docs/advanced_examples_dos/example_gorad [7] ICRP (2020) *ICRP Publication*, 145. *Ann. ICRP* 49(3). [8] https://moleculardna.org [9] ESA "BioRad III" project.

Meetings and visits

1. **Visit of Korean partner to LP2i, France**
   - Sep. 6, 2025
   - First benchmarking of Orion simulations

2. **Geant4-DNA tutorial in South-East Asia**
   - Between the Princess Srisavangavadhana Faculty of Medicine of the Chulabhorn Royal Academy of Thailand, Yonsei U. & LP2i
   - March 16-22, 2026
   - First time in Thailand, 50 participants

3. **6-month visit of Ji Won CHOI at LP2i (PhD)**
   - March-Aug. 2026
   - Fully funded by a Yonsei U. grant
     - LP2i & Yonsei U. support to attend FKPPN 2026



LP2i

https://indico.in2p3.fr/event/36861/

Princess Srisavangavadhana Faculty of Medicine

2026 Proposal

- Basis for the **PhD thesis of Mrs Ji Won Choi**
  - "Geant4-DNA-Based Multi-Scale Dosimetry for Estimating Early DNA Damage in Astronauts During Space Missions."
  - Common supervision Yonsei U. & CNRS/LP2i, till **end of 2028**
- **At the "human" scale:**
  - With the "ICRP145_HumanPhantoms" Geant4 application, simulation of absorbed doses in human phantoms' organs in different positions: standing up phantom, seated, pregnant woman… with more stat.
  - Addition of a space protection suit around phantoms to estimate its impact on dosimetry
  - Addition of the possibility to place micrometric virtual spheres in organs (in a parallel geometry) and creation of the corresponding phase space files (PSF)
- **Then, at the "cellular" scale:**
  - Import of these PSF into the "moleculardna" Geant4-DNA application to simulate early DNA damage induction in individual biological cells
  - Addition of neutron interactions in Geant4-DNA
  - Simulation of DNA damage induction from GCR and SPE spectra using the combination "gorad" + "ICRP145_HumanPhantoms" + "moleculardna"
- **Globally:**
  - Automatization of the whole sequence by developing corresponding (Linux) scripts

Open science & outreach

- Boost the visibility & usage of Geant4 in Korea
  - All software available in open access in Geant4 after publication
    - equal access, reproducibility of results
- Opportunities
  - **Geant4 & Geant4-DNA international tutorials**
    - Last one in **February 2025** at the **Pohang Accelerator Laboratory**
    - **Next Geant4 & Geant4-DNA tutorial in Daejeon in Dec. 2026 (confirmed)**
    - Nice occastion to showcase the multiscale simulation platform (lecures & hands-on)
  - **Series of conferences « International Geant4 User Conference at the Physics – Medicine – Biology Frontier »**
    - **2028: first time in Seoul, Korea ?**
    - 2026: Melbourne, Australia (tba)
    - 2024: Osaka, Japan
    - 2022: Napoli, Italy
    - 2018, Bordeaux, France
    - 2013: Bordeaux, France
    - 2005: Bordeaux, France

Geant4 & Geant4-DNA tutorial, Pohang Accelerator Laboratory, 2025

Budget request for 2026

- From **Korea** side
  - 1 trip to LP2i (Y. S. YEOM: 5000 euros to Yonsei U.)

- From **France** side
  - 2 trips to Korea: 3000 euros to **IN2P3**
    - FKPPN-FJPPN 2027 workshop (A. PAILLET) (in priority)
    - Support to Geant4-DNA tutorial in Dec. 2026 in Daejeon (S. INCERTI) – some support appreciated

- Additional support (secured)
  - Adrien Paillet, Postdoctoral fellow @ LP2i, with us till Aug 2027
  - Trip of Ji Won CHOI to FJPPN-FKPPN 2026 paid by LP2i

- **We are also applying to PHC-STAR 2027**

Thank you very much !
정말 감사합니다 !