Review and Cross-comparison of MATROSHKA Phantom Measurements in Different Compartments of the International Space Station

Michael Hajek¹, Thomas Berger², Paweł Bilski³, Daniel Matthia², Monika Puchalska³, Andrea Zechner¹ and Günther Reitz²

¹ Institute of Atomic and Subatomic Physics, Vienna University of Technology, Stadionallee 2, 1020 Vienna, Austria
² Institute of Aerospace Medicine, German Aerospace Centre, Linder Höhe, 51147 Cologne, Germany
³ Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, 31-342 Krakow, Poland

Abstract | Astronauts working and living in space are exposed to considerably higher doses and different qualities of ionizing radiation than people on ground. MATROSHKA, a European Space Agency experiment coordinated by the German Aerospace Centre, represents the most comprehensive effort so far in radiation protection dosimetry in space using an anthropomorphic upper torso phantom known from radiotherapy treatment planning to map the dose distribution throughout a simulated human body on board the International Space Station (ISS). Absorbed dose and dose equivalent measured by nuclear track detectors and miniature thermoluminescence dosimeters embedded in a regular grid and at the site of vital organs are combined with detailed numerical models to allow for estimation of effective dose. Monte Carlo simulations using the transport codes FLUKA and GEANT4 that provide calculations of particle fluence and dose for various radiation environment conditions further support the experiment and improve cancer risk projections for future long-term space exploration beyond the Earth’s magnetosphere. The paper presents a review and cross-comparison of data acquired during four missions between January 2004 and March 2011, in which the phantom has been installed in different compartments of the Russian and Japanese segments of the ISS: outside and inside Zvezda, inside Pirs and inside Kibō.

Key words: Cosmic radiation; dosimetry; MATROSHKA; phantom; radiation risk.

1. Introduction

Cosmic radiation and its secondaries created in interactions with planetary atmospheres, spacecraft shielding structures and the human body itself constitute one of the most important hazards associated with human spaceflight. Crewmembers are facing exposures to radiation qualities that are known to produce distinct biological damage compared with radiation on ground [1], and dose levels that may easily exceed those routinely received by terrestrial radiation workers [2–4]. These aspects lead to large uncertainties in the projection of cancer and other health risks, and obscure evaluation of the effectiveness of possible countermeasures. On a microscopic scale, it becomes apparent that the cosmic-ray particles are likely to deposit their energy in a rather heterogeneous way. Although absorbed doses – averaged over a sufficiently large macroscopic mass element – might be small, there will be microscopic regions of extremely high local doses in close vicinity to the ion path.

The radiation environment in space is fed by galactic and solar sources and characterized by a high degree of complexity and dynamics [5]. Galactic cosmic radiation (GCR) originates from outside our solar system and is isotropic in distribution, i.e., it arrives at any point in deep space with equal intensity from all directions. The GCR spectrum consists of all naturally occurring chemical elements with energies beyond 10^{20} \text{eV} [6].

Solar cosmic radiation comprises the flood of low-energy electrons and protons called the solar wind, which increases by factors of the order of 10^6 during an active sun period to build into a torrential storm. Streaming out from the Sun’s corona, this plasma creates the interplanetary magnetic field (IMF), which varies according to the 11-year cycle of solar activity. GCR particles entering the heliosphere are scattered by IMF irregularities and undergo convection and adiabatic deceleration in the expanding solar wind. The GCR intensity is thus anti-correlated with solar activity, which is usually determined from the number of sunspots. Sporadically occurring solar particle events (SPEs) originate from impulsive solar flares, coronal mass ejections or shocks in the interplanetary medium. The emit-
Energetic particles trapped in the geomagnetic field are confined via magnetic mirroring in two radiation belts, which surround the Earth. The inner belt, extending from ~1 to 3 Earth radii in the equatorial plane, is mostly populated by protons with energies exceeding 10 MeV. The origin of these protons is thought to be the decay of albedo neutrons from the Earth’s atmosphere. The inner belt is fairly quiescent, and the lifetime of particles in the belt ranges from a few hours to 10 years. The outer belt, extending from ~3 to 9 Earth radii in the equatorial plane, consists mostly of electrons with energies below 10 MeV that are injected from the outer magnetosphere. Unlike the inner belt, the outer belt is very dynamic, changing on time scales of a few hours in response to perturbations emanating from the outer magnetosphere. In regions within ~10 Earth radii, the geomagnetic field can be approximated as a dipole field, which is tilted and translated with respect to the Earth’s rotational axis. This causes the radiation belts to come closer to the Earth’s surface in a region called the South Atlantic Anomaly (SAA), which is of great significance to space vehicles such as the ISS that orbit the Earth at several hundred kilometres altitude. Their orbits take them through the anomaly periodically, each time exposing them for several minutes to increased radiation levels.

2. Materials and Methods

2.1. The MATROSHKA Facility

MATROSHKA, a European Space Agency (ESA) experiment coordinated by the German Aerospace Centre (DLR), that received its name from the traditional Russian set of nesting dolls is the most comprehensive effort so far in radiation protection dosimetry in space, using an Alderson Rando™ anthropomorphic upper torso phantom known from radiotherapy treatment planning to map the dose distribution throughout a simulated human body on board the ISS. The facility was developed within the European Programme for Life and Physical Sciences and Applications Utilizing the ISS (ELIPS), with a natural human skeleton cast inside a proprietary urethane formulation that is radiologically equivalent to soft tissue [8, 9]. The phantom lungs are designed of lower-density material to simulate human lungs in a median respiratory state and moulded to fit the contours of the natural human rib cage. Unlike previous phantom experiments on different space vehicles [10–15], MATROSHKA is covered by a skin substitute, aka poncho, as well as a carbon fibre container and a multilayer thermal insulation to resemble the shielding properties of an astronaut’s extravehicular activity (EVA) space-suit (Figure 1). Skin dose was determined from detector assemblies that had been sewn in the poncho to measure the dose at a depth of 0.6 mm. The facility further contains a complete set of active and passive instrumentation to account for the cosmic-ray charge and energy spectrum [16]. The experimental results are combined with detailed numerical models of the human organism to improve cancer risk projections for long-term human space exploration and support benchmarking of radiation transport codes.

MATROSHKA was launched to the ISS on 29 January 2004 with an unmanned Russian resupply spacecraft (Progress 13P) from Baikonur, Kazakhstan, and mounted outside the Russian Service Module (Zvezda) on 26 February 2004. After 539 days of exposure (MTR-1), the facility was retrieved and transferred to the inside of the ISS on 18 August 2005. Since then, MATROSHKA assessed the radiation exposure under intravehicular activity (IVA) conditions. To assess the influence of variable shielding configurations, the facility was moved to different segments of the ISS: the Pirs Docking Compartment (MTR-2A), the Zvezda Service Module (MTR-2B) and, most recently, the Japanese Experiment Module (JEM) Kibō (MTR-2K). After each phase, the passive detector systems were removed and returned to ground by Soyuz (TMA) or Space Shuttle (STS) for processing and evaluation in the participating laboratories. Data from active instrumentation were stored on memory cards or (partly) transmitted directly to ground via U.S. voice link. Figure 2 illustrates the MATROSHKA experiment timeline, while Figure 3 provides additional photographic documentation.
Figure 1. The urethane-based phantom body of the MATROSHKA facility is dressed with a Nomex® travel jacket, aka poncho, that simulates the skin. A carbon fibre container, thermally protected by a multilayer insulation, resembles the shielding properties of an extravehicular activity spacesuit.

Matroshka Experiment Timeline

<table>
<thead>
<tr>
<th>13P</th>
<th>TMA-6</th>
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<tbody>
<tr>
<td>MTR-1 Zvezda, ext.</td>
<td>MTR-2A Pirs</td>
</tr>
<tr>
<td>26/02/04</td>
<td>18/08/05</td>
</tr>
<tr>
<td>20P</td>
<td>STS-116</td>
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<tr>
<td>05/01/06</td>
<td>07/12/06</td>
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<tr>
<td>STS-126</td>
<td>MTR-2B Zvezda</td>
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<tr>
<td>18/10/07</td>
<td>25/11/08</td>
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<tr>
<td>TMA-11</td>
<td>37P</td>
</tr>
<tr>
<td>04/05/10</td>
<td>MTR-2K Kibō</td>
</tr>
<tr>
<td>TMA-01M</td>
<td>10/03/11</td>
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Figure 2. The MATROSHKA experiment successfully accomplished four missions, with the phantom being exposed in- and outside the International Space Station. The dates shown correspond to the time of detector exposure in the MATROSHKA facility.

Figure 3. From left to right: launched on 29 January 2004, the MATROSHKA facility had been exposed extravehicularly (MTR-1), in the Pirs Docking Compartment (MTR-2A), the Zvezda Service Module (MTR-2B) and the Japanese Experiment Module Kibō (MTR-2K).
2.2. Dose Mapping

To facilitate detailed mapping of the dose distribution throughout the body, the phantom was sliced into sections of 25.4 mm thickness. Hole grids were drilled through the phantom’s soft tissue material to accommodate a total number of up to 5,800 thermoluminescence dosimeters (TLDs) located at equidistant points in 354 polyethylene tubes, which enabled the depth distribution of absorbed dose to be determined in a 25.4-mm orthogonal grid. While the efficiency of most of the applied thermoluminescent (TL) phosphors with respect to gamma-rays (that are commonly used to calibrate the dosimeters) is close to unity for particles of unrestricted linear energy transfer (LET) in water < 10 keV/µm, it was found to decrease rapidly with LET for particles of higher charge (Figure 4). This effect was compensated by implementing additional plastic nuclear track detectors (PNTDs), which are capable of measuring the LET spectrum ≥ 10 keV/µm into polyethylene boxes of 60 × 40 × 25 mm³ at the sites of selected organs (eye, lung, stomach, kidney and intestine). Seven active, i.e. power-consuming, radiation sensors monitored the instantaneous dose rate: five silicon scintillation detectors (SSDs) were installed at the organ sites specified above to monitor the interior heavy-ion and neutron flux; a dosimetry telescope (DOSTEL) at the top of the head and a tissue-equivalent proportional counter (TEPC) in front of the torso evaluated the ambient exposure rate.

![Figure 4. The generally decreasing TL response (shown here for glow peak 5 of LiF:Mg,Ti) for particles of unrestricted LET in water ≥ 10 keV/µm is compensated by the excellent PNTD registration efficiency for particles of higher charge. Colour and grey symbols represent TL response of different manufacturer’s batches.](image)

The operational radiation safety programme for astronauts [17] proposed that for the complex mixtures of high- and low-LET radiations prevailing in low-Earth orbit (LEO), organ dose equivalent (based on absorbed dose and the quality factor relationship as a function of LET) should be used as the approximation for equivalent dose. Organ dose equivalent was derived from computational modelling and compared with TLD/PNTD measurements in selected organs of the MATROSHKA phantom. From these data, an assessment of the effective dose was provided for the radiation field in- and outside the ISS.
3. Results and Discussion

3.1. Space-borne Experiments

Effective scientific exploitation of dosimetric data obtained individually by the participating laboratories was achieved within the European Community’s 7th Framework Programme (FP7) collaborative project HAMLET (http://www.fp7-hamlet.eu). Based on experimental input as shown in Figure 5, a three-dimensional computational model was developed that allowed assessing the distribution of absorbed dose and dose equivalent, particularly in vital organs of the human organism (right-hand side of Figure 6). This model shall further be used to provide the basis for refining projection of radiation risks on long-term exploratory missions.

As an example, the dose distribution assessed for extravehicular exposure of the MATROSHKA phantom is shown in Figure 6. The dose equivalent determined for different organs and tissues is illustrated in Figure 7. The effective dose rate was calculated to be $0.59 \pm 0.04$ mSv/d. The skin dose equivalent rate of $1.30 \pm 0.06$ mSv/d measured in the poncho certainly provides a conservative and failsafe estimate for the effective dose. The pronounced dose gradient from the surface towards the deeper organs entailed the absence of hot spots in the human body, as it might have been expected from the peculiarities of energy deposition of charged particles along their path through matter.

The effective dose rate for IVA exposure conditions (MTR-2A/2B/2K) was on average 25% lower than for EVA, where astronauts are protected by a spacesuit. It essentially resembled the distribution of shielding masses, as did the measured neutron fluence rate. The ratio of the skin dose to the effective dose, however, decreased from a value of 2.1 for MTR-1 to 1.3 for MTR-2A, still making the skin dose a conservative estimate for whole-body exposure.

Figure 5. Three-dimensional point distribution of absorbed dose rate throughout the MATROSHKA phantom for extravehicular exposure at the International Space Station (MTR-1). The diagrams show the build-up of the dataset from measurements by three different laboratories at more than 1,600 points in a 25.4-mm orthogonal grid.
Figure 6. Left: Interpolated distribution of absorbed dose rate in the MATROSHKA phantom (including skin doses) for extravehicular exposure at the International Space Station (MTR-1). Right: Mapping of organ geometries in the Zubal phantom, scaled to the CT-based voxel representation of MATROSHKA (reproduced from [18]).

Figure 7. Dose equivalent rate for different organs and tissues computed from the MTR-1 experimental dataset using the scaled Zubal phantom shown in the right-hand side of Figure 6 (reproduced from [19]).
3.2. Ground-based Studies

In order to harmonize the experimental protocols used by the participating laboratories, cross-calibrate detector response and validate radiation transport codes, a dedicated ground-based programme was conducted at several accelerator facilities: the Brookhaven Booster Accelerator at the NASA Space Radiation Laboratory (NSRL), Upton, NY, U.S.A.; the Heavy Ion Medical Accelerator (HIMAC) at the National Institute of Radiological Sciences (NIRS), Chiba, Japan; the NIRS-930 Cyclotron, Chiba, Japan; and the Heavy Ion Synchrotron (SIS) at the GSI Helmholtz Centre for Heavy Ion Research, Darmstadt, Germany. While it is virtually impossible to simulate every detail of the charge and energy spectrum of all cosmic-ray components by a few terrestrial facilities, it was plausible to mimic the major aspects of the cosmic radiation climate. This allowed for investigating detector responses to a small but well-defined subset of the space radiation environment and validating radiation transport codes, such as FLUKA, Geant4 and PHITS, against experimental data (Figure 8). The following particles and nominal energies were used in the ground-based studies:

- Proton ($^1\text{H}^+: 30, 50, 70, 200, 235$ and $450$ MeV,
- Helium ($^2\text{H}^{4+}: 50$ MeV/u,
- Carbon ($^{12}\text{C}^{6+}: 400$ MeV/u,
- Neon ($^{20}\text{Ne}^{10+}: 230$ MeV/u,
- Silicon ($^{28}\text{Si}^{14+}: 490$ MeV/u,
- Argon ($^{40}\text{Ar}^{20+}: 500$ MeV/u,
- Iron ($^{56}\text{Fe}^{26+}: 500$ and $1000$ MeV/u.

Particle energies at the target could be varied by means of PMMA binary filters in order to cover a broad range of LET.

Conclusions

The European Space Agency (ESA) MATROSHKA facility, is a comprehensive and overarching international dosimetry programme coordinated by the German Aerospace Centre (DLR), which supports assessment of potential biological implications on the health of space crew. Both for extra- and intravehicular exposure conditions, dose hot spots in the human body could not be encountered, and the skin dose proved to be a conservative and failsafe estimate for the effective dose in both instances. The significant dose equivalent rate to the lens of the eye might, however, give rise for concern in long-duration missions, possibly even beyond the magnetosphere. Epidemiological studies among
astronauts, atomic bomb survivors, Chernobyl clean-up workers, radiological technicians and residents of contaminated buildings along with recent surveys of staff in interventional cardiography indicated a potentially increased incidence of lens opacities at doses below 1 Gy [21]. These findings not only triggered an on-going debate whether or not to revise the eye dose limit for occupational radiation exposure on ground (as recently proposed by the International Commission on Radiological Protection), but also make us aware that cataracts induced by exposure to cosmic radiation might be an issue for future human space exploration.

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