MATROSHKA – A Research Platform for Reducing Radiation Risk in Space

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Since January 2004, the International Space Station (ISS) is hosting a permanent guest – a human phantom which is the key part of the ESA MATROSHKA Facility. The phantom is equipped with thousands of radiation sensors helping the scientists to understand more precisely the dose and particle distribution in a human body for an improved radiation risk assessment. Having already completed three exposure measurement campaigns using the Russian Service Module, MATROSHKA just finished its fourth campaign in the Japanese KIBO Module. Now, it is back in the Russian segment after having twice passed the ISS "borders" from Russia to Japan.

Introduction

Even after nearly five decades, human spaceflight remains an endeavor with inherent and significant risks. The exploration of space exposes the human being to a hostile environment which, if not mitigated, would coercively lead to deleterious consequences. The radiation exposure in space to cosmic radiation can be reduced through careful mission planning and constructive measures, such as, for example, the provision of a radiation shelter, but it cannot be completely avoided. The reasons for that are the extremely high energies of particles in this field and their high penetration depths in matter. MATROSHKA is designed to determine the radiation distribution in the human body under different shielding conditions inside and outside the ISS and thereby serves as a more accurate radiation assessment radiation of humans in space.

The radiation environment in the Space Station orbit is determined by three primary sources: the galactic cosmic radiation (GCR), the solar particle radiation (SPR) and the charged particles trapped in the Earth's magnetic field (Van Allen Belts). The first source is comprised of protons, heavier particles, and electrons of all energies which impinge from all directions of the solar system. Regarding SPR, only particles from energetic solar particle events (SPEs), such as coronal mass ejections (CMEs), have sufficient energies to contribute directly to radiation exposures. These particles are mainly protons and electrons, along with varying, but usually small, amounts of heavier ions. The third source is composed of protons and electrons which are mainly produced by interactions of the first two sources with the Earth's atmosphere and are trapped by its magnetic field. In addition to its variation with location, the intensity and composition of the total radiation environment is subject to slow temporal variations due to oscillations of the solar activity in an approximately 11-year cycle and to impulsive disturbances caused by SPEs which may last for several days. While passing through this complex and variable external radiation field, the field inside the spacecraft and an astronaut's body becomes even more complex by the interactions of the primary particles with the atoms of the structural materials and finally with those of the body itself.

The exact determination of dose in space is a demanding and challenging task, and is fulfilled through a close cooperation of all the partners working on the International Space Station. The daily dose rates – up to a few hundred of μSv in Low Earth Orbit (LEO) – are the highest reached for humans working in a natural radiation environment. Various research activities – including the largest, current radiation experiment MATROSHKA – aim for a better understanding of the interactions of the space radiation environment within the human body, and for a better future radiation risk estimation for exploration missions – such as going to the Moon or Mars.

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Research Objectives

With extended mission duration and the shortage of launch capabilities, the radiation safety of the astronauts has become one of the most important biomedical problems during manned space flights. At the same time there is a requirement to provide a high level of safety for crews that ensures their capacity to work. Conservative approaches, such as those used in the past, cannot be continued; instead the effective dose (E,) as recommended by the International Commission on Radiological Protection (ICRP) needs to be determined as accurately as possible Given the fact that effective dose is the appropriate quantity to assess radiation cancer risk.

Effective dose – as a risk related quantity – is based on the determination of the doses in various organs of the human body. The current system of radiation protection in space provides each astronaut with his or her personal radiation dosimeter. With this detector, however, it is only possible to determine the dose at the skin surface, but not inside the body of the astronaut. (Figure 1 shows European Astronauts Christer Fuglesang, Thomas Reiter and Frank De Winne) wearing the European Crew Personal Dosemeter (EuCPD).

Fig. 1: *European Astronauts Christer Fuglesang, Thomas Reiter and Frank de Winne with the European Crew Personal dosemeters.*

To solve the problem of dose determination inside organs, the project investigates the dose distribution depth inside an anthropomorphous phantom inside and outside the International Space Station and considers the physical and biomedical aspects in its scientific program. The MATROSHKA experiment uses a human body model generally accepted for space experiments. It is designed to measure the dose distributions in critical organs, taking into account the mass distribution anisotropy of both the phantom itself and its shielding. As a result, it allows for a determination of the effective dose. Knowledge of the effective dose is a prerequisite for calculation of reliable cancer risk numbers for the astronauts.

The aims of the experiments are the following:

- Measurement of the skin and depth dose distribution in a human phantom inside and outside the ISS.
- Determination of the organ dose of selected organs.
- Dose measurements on the ISS flight trajectory during a full solar cycle.
- Measurement of the ratio of skin to organ dose.

The main objective of the MATROSHKA experiment is to determine the empirical relations between measurable absorbed doses and the required tissue absorbed doses in a realistic human phantom exposed to the actual radiation field to be monitored. Since EVAs will form a substantial fraction of the work-schedule in the Space Station scenario, such measurements have highest priority. Once the ratios for the tissue absorbed doses and surface absorbed doses are known for a given radiation field around the human body, these values may be used in future exposures to determine the required tissue absorbed doses from measurements of surface absorbed doses only. Using these results will enable effective dose values for astronauts to be derived from the readings of their personal dosemeter systems.

MATROSHKA measurements will be used as benchmark for model calculations. Several institutes from Europe, Japan and the US contribute to the radiation measurement program.

History of Phantom Experiments

An essential parameter for the assessment of radiation risk on humans in space is the determination of the organ dose. Measurements inside tissue-equivalent phantoms are therefore essential in order to solve this complex task and to obtain a better knowledge of the dose distribution inside the human body. Based on ideas first developed by our group in 1987 -- to measure the depth dose distribution with an onion-like arrangement of detectors embedded in intermediate layers of absorbing materials – a proposal was made in 1992 to fly a human phantom equipped with radiation detectors. The name MATROSHKA was chosen based on the onion-like build-up of the Russian MATROSHKA puppet sets. Three years later, the experiment was selected by an international peer review for the flight on the ISS. ESA than performed a Phase A study and a performance study with the final result that the manufacturing of the ESA Facility was started in 2000 under the leadership of the German Aerospace Center (PM and PI Günther Reitz) and was launched in January 2004. After a further ESA call for proposals in 2004, a second peer review rated the continuation of the experiments as outstanding. Meanwhile, only three space experiments dealt with the determination of the depth dose profile inside tissue-equivalent phantoms. They contained measurements inside a phantom head and an Alderson phantom upper torso, applying a combination of various active and passive radiation detector systems. These experiments were performed on Space Shuttle flights, resulting in exposure time limited to the mission duration. In late 2001 during ISS Expedition 2 an Alderson phantom torso (Nickname “FRED”) was also flown inside the US Lab Module Human Research Facility (HRF) onboard the International Space Station. In addition, Russian scientists simplified the phantom to a spherical water-filled phantom, which was first exposed on Space Station MIR. Its successor – a tissue equivalent spherical phantom – is currently measuring the radiation field in the Russian segment of the ISS. MATROSHKA was used to make the first measurements of the radiation distribution inside a human phantom under EVA conditions.

The ESA-MATROSHKA Facility

MATROSHKA is an ESA-Multi-User research platform developed for studies of the depth dose distribution occurring in astronauts) exposed to cosmic radiation during an EVA (Extra Vehicular Activity). The MATROSHKA facility basically hosts a human upper torso phantom. At the site of the organs of interest, spaces are provided at the surface and in different depths inside the phantom in which active and passive dosimeter packages are accommodated. Thermoluminescence detectors (TLDs), plastic nuclear track detectors (PNTD) with and without converter foils, a silicon detector telescope, plastic scintillators and a tissue equivalent proportional counter make up the instrument suite. The phantom is mounted to an aluminum structure (Base Structure), which provides space for experiment and facility electronics and is enveloped by a carbon fiber structure (Container). The Container and Base Structure form a closed, pressurized volume of 1.05 atm for the phantom and therefore also protect the phantom material against the space environment factors like ultraviolet radiation and vacuum. The carbon fiber container provides shielding thickness of ~0.5 g/cm^2 which is comparable to the thickness of the EVA suit. The facility has a mass of 68 kg and occupies a cylindrical volume of 600 mm in diameter and a height of 1100 mm. MATROSHKA is designed to allow disassembly/assembly operations in order to exchange experiments inside the Russian Service Module (RSM).

Besides providing room for passive and active experiment packages (detectors), MATROSHKA has the capability for housekeeping (H/K) data acquisition (experiment / facility status, temperature and pressure) and experiment data acquisition. H/K and experiment data are temporarily stored and then transferred to the Russian onboard data management system. Temperature, pressure and the main status data are delivered continuously to the Payload Data Control Server (for facility status monitoring from the Mission Control Center in Moscow).

The phantom inside MATROSHKA is an anthropomorphic upper torso made of tissue equivalent polyurethane, which comprises a human skeleton (RANDO®, The Phantom Laboratory, Salem, NY, USA) (see Fig. 2 A-D). It is cut horizontally into 33 slices, each 25 mm in thickness.

FIG. 2: *The MATROSHKA phantom from left to right: A) anthropomorphic upper torso equipped with active detector systems, B) torso with poncho and hood equipped with passive detector systems for skin dose measurements, C) carbon fibre container to simulate the astronaut's space suit, D) facility ready for launch equipped with multi-layer insulation (MLI) for thermal protection*

The phantom torso (see Fig. 2) is equipped with 4,800 TLDs distributed in 354 polyethylene tubes in the 33 slices, enabling determination of the absorbed dose and depth-dose distribution at over 1600 measurement points in a 2.5 cm x,y,z grid.

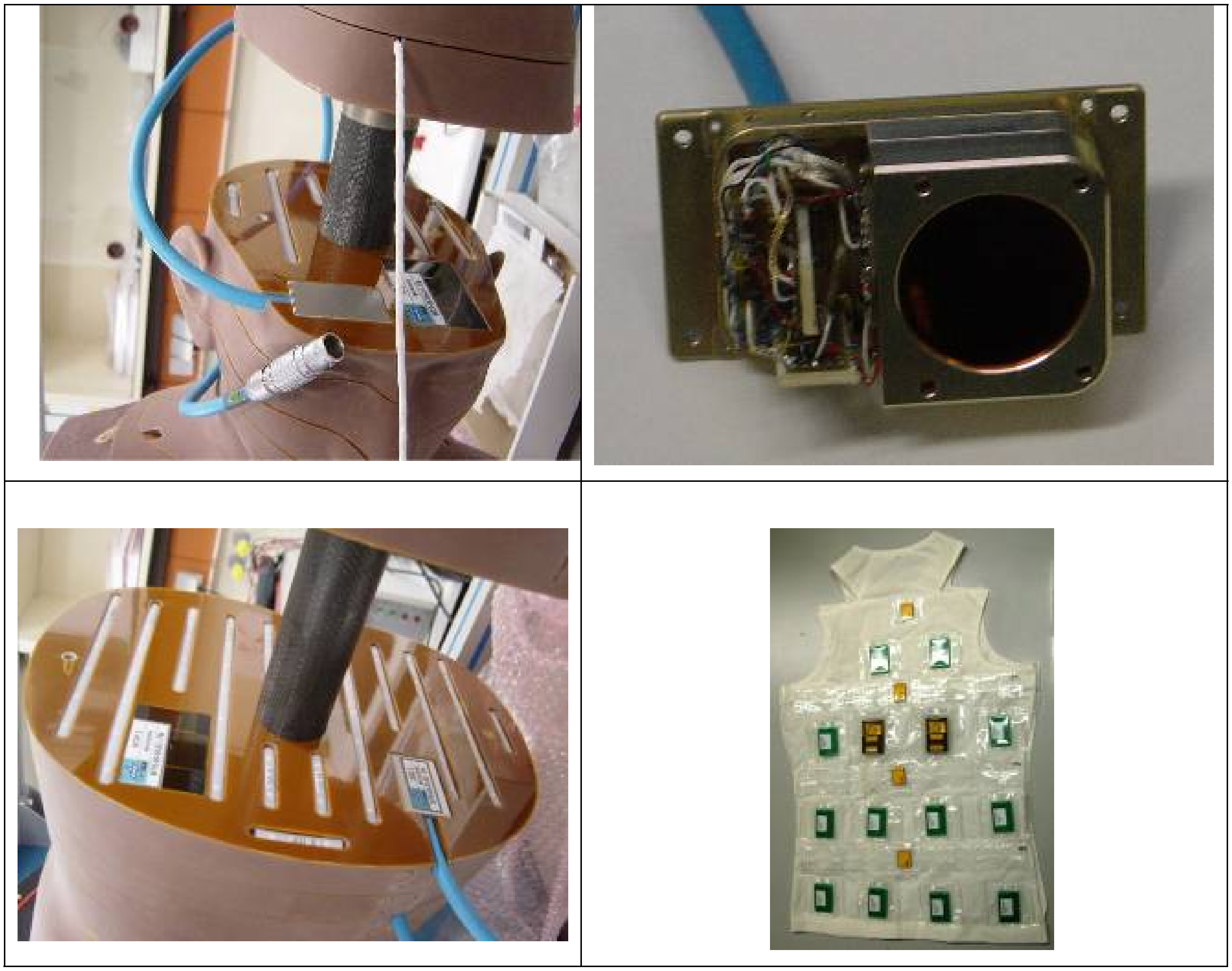


FIG. 3. *A. View of the phantom head of MATROSHKA. It shows the head of the phantom with the integrated passive and active radiation detectors. Passive detectors are integrated in polyethylene tubes and in the "organ dose" packages. The sensor for the active Silicon-Scintillator Device (SSD) is shown with the blue cable connecting to the base structure. The white cable connects to a temperature sensor in the head of the phantom. B. DOSTEL sensor head which is mounted on the head of the phantom C. same as a, but section in the middle of the phantom was chosen. D. Phantom Poncho which is equipped with TLDs sewn in plastic stripes and neutron dosemeters. The pictures were taken during detector integration prior to the launch of the facility.*

Combinations of TLDs and plastic nuclear track detectors assembled in polyethylene boxes (60 x 40 x 25mm) are placed at selected organ locations (eye, lung, stomach, kidney and intestine) as well as in a NOMEX® travel jacket (´Poncho´). For determination of the skin dose, detectors are sewn into polyethylene strips directly on the phantom surface, thereby measuring average dose at a depth of 0.6 mm. Seven active radiation detectors monitored the instantaneous dose rate. Five scintillation detectors (SSD) were installed at the positions of the above mentioned organs to monitor the interior heavy ion and neutron component. A silicon telescope (DOSTEL) on top of the phantom head and a tissue equivalent proportional counter (TEPC) in front of the torso monitored its ambient exposure rate. For comparison with dose rates inside the ISS, additional detector packages were stored at several reference locations. The MATROSHKA facility was launched in January 2004 onboard a Russian

Progress cargo supply spacecraft from the spaceport of Baikonur and mounted in a fixed orientation outside the Zvezda module on February 26th, 2004 (see Fig. 4.).

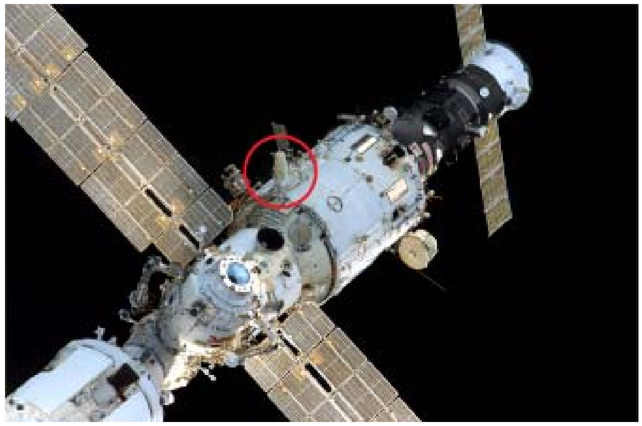


FIG. 4: *The MATROSHKA facility mounted outside the Zvezda Module on the ISS. The facility (encircled) was mounted outside the Zvezda Module on February 26, 2004 by Expedition 8 crew Alexander Kaleri and Michael Foale. It stayed outside for 539 days until August 18, 2005 and was brought back by Expedition 11 crew Sergei Krikalev and John Phillips. (Photo courtesy of NASA)*

Selected Results of the MATROSHKA Outside Exposure (MTR 1)

For the determination of the radiation exposure – and thereby the assessment of the effective dose -- of an astronaut, the sum of all organ dose equivalents is needed. One way to determine organ doses is to use a combination of TLDs and plastic nuclear track detectors -- in this case polyallyl diglycol carbonate with the trade name CR39. The absorbed dose of sparsely ionizing particles up to an energy deposit of 10 keV/μm is calculated from the TLDs. The contribution of the densely ionizing component (above 10 keV/μm) is obtained from energy deposit (LET) spectra measured in the CR39 detectors.

Different detector groups contribute to the overall results, but thanks to intense calibration activities on the ground, the results received from the outside exposures agree well among each other. The depth dose distribution measured with TLDs is shown in Figure 5A. Compared to the first measurement point at 8 mm depth in the phantom, the dose rate decreases by a factor of about 2 at the innermost organs. The significantly higher rates in the head, neck and shoulder region reflect the smaller self-shielding of the body. The shielding of the ISS accounts for occurrence of the lowest rates at the bottom of the torso.

The depth dose distribution of dose rates, including the skin measurement, highlight the very steep decline by a factor of about ten within the first 8 mm, as shown in Figure 5B. From this depth-dose distribution, an average organ dose rate was determined for each critical organ as the average of the dose rates in the volume elements that were assigned to it in a Voxel model. Figure 5C shows the organs of the Zubal phantom mapped and scaled into the Voxel representation of MATROSHKA that was obtained from computer tomography (CT) slides. The calculated skin dose rate represents an average of the outermost 3 mm. With a dose rate of about 1 mGy/d, it is by far the highest, followed by the dose rate in the eye. With the exception of the breast and the salivary glands, the dose rates for the other organs are in the range from 0.2 to 0.3 mGy/d (see Figure 5).

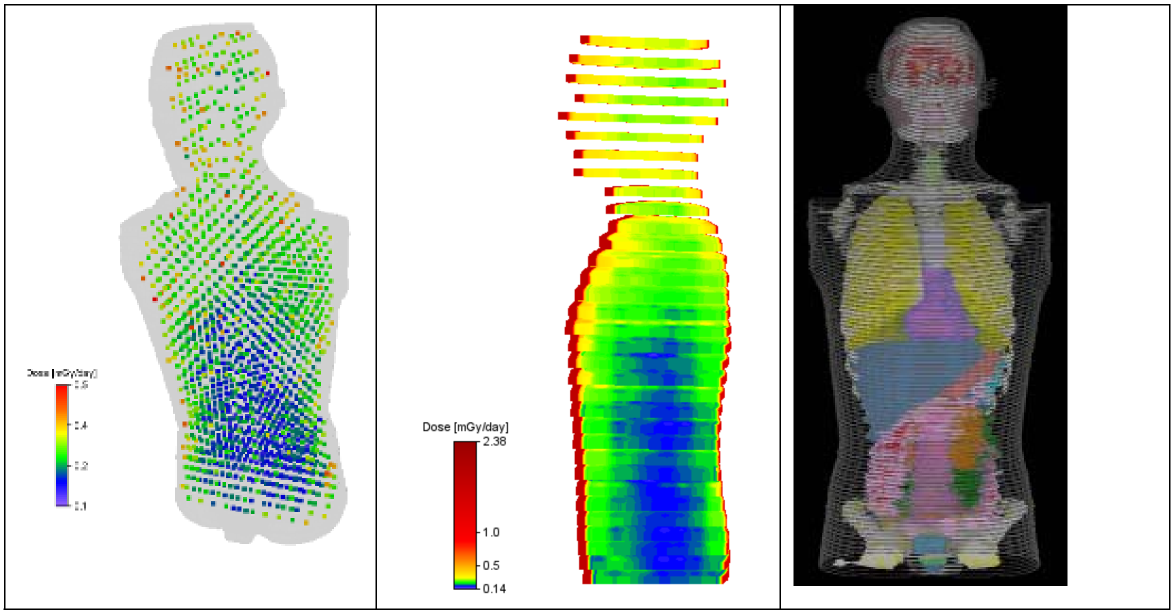


***Fig. 5**: A. Depth dose distribution of absorbed doses measured with TLDs inside the human phantom; B. Inclusion of the absorbed doses measured with the Poncho detectors; C. Location of organs based on the Zubal phantom.*

The values for the skin represent measurements for the Poncho, calculated for a skin depth of 3 mm. Relative precisions for organ dose values range between 4 and 8 % and for $<Q_T>$ between 9 and 12%.

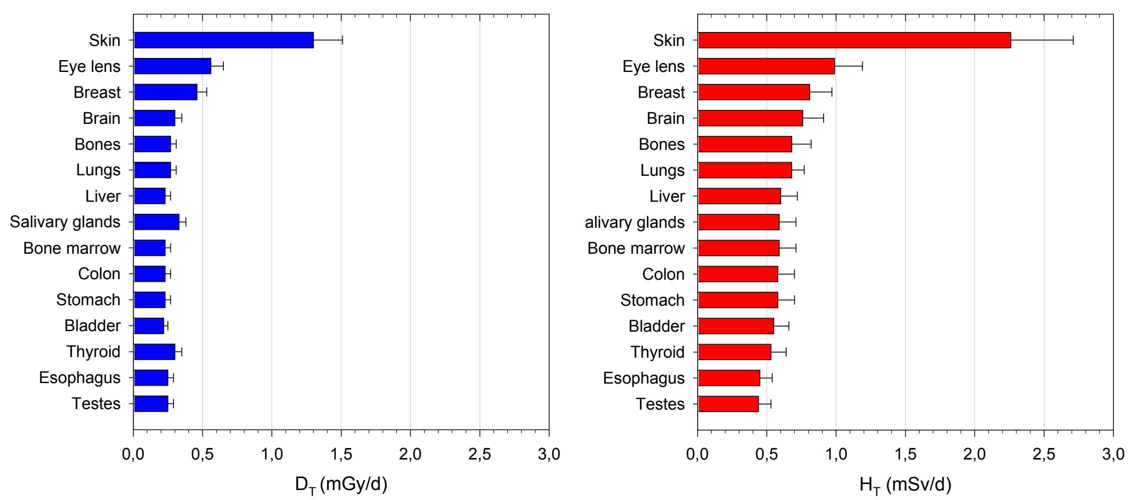
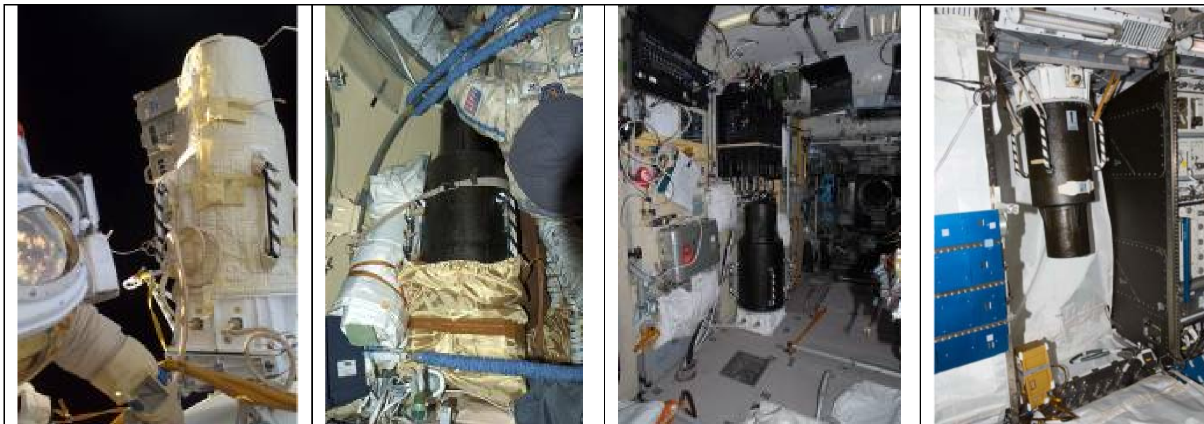


***Fig. 6**: Calculated organ absorbed doses (left) and organ dose equivalents*

The effective dose as sum of all organ doses weighted with tissue weighting factors defined by ICRP approaches the value of 0.59 ± 0.04 mSv/d. Comparing the MATROSHKA "personal" dosemeters result with this value, it was determined that an astronaut's personal dosemeter would yield an effective dose that was a factor of 2.1 greater than this exposure, which is a quite strong overestimate.

MATROSHKA – Operations onboard the ISS

Up to the time this article was written, four experiment phases had been performed with the MATROSHKA facility outside and inside the ISS. Figure 6 shows photos of MATROSHKA taken during all four phases.

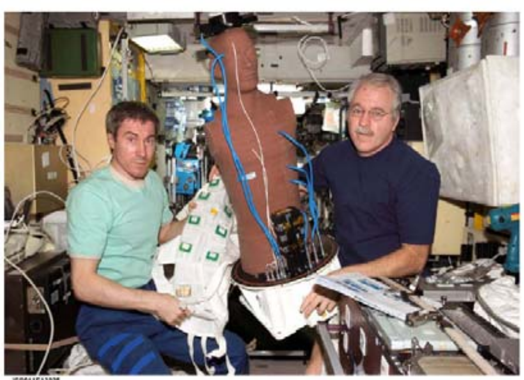


MTR 1 (2004 – 2005)	MTR 2A (2006)	MTR 2B (2007 2009)	MTR-KIBO (2010-2011)

Fig. 6: *MTR 1 exposure outside the Service Module; MTR2A and 2B both are inside exposures*

Inside the module the container of MATROSHKA Facility needs to be removed, and an extension rod on top of the phantom needs to be mounted to allow the lifting of the phantom slices in order to remove the passive detector packages. This is illustrated in Figure 7.

Sergei Krikalev and John Philips (August 2005)



Yuri Lonchakov , Expedition 18 Flight Engineer

Fig.7: *Removal of the Poncho (left) and removal of the detectors from inside the phantom by lifting up the MATROSHKA slices*

Ground Segment

Calibration of TLDs and CR39 as well as for the active experiments were performed at several proton and heavy ion accelerators like Loma Linda, NASA Space Radiation Laboratory (NSRL) at the Brookhaven National Laboratory (BNL), Brookhaven, USA and the Heavy Ion Medical Accelerator, HIMAC, at the National Institute for Radiological Sciences (NIRS), Chiba Japan as part of the Intercomparison for Cosmic-rays with Heavy Ion Beams At NIRS (ICCHIBAN) Program which has its home base at the National Institute for Radiological Sciences (NIRS) in Japan. The MATROSHKA project also uses the phantom for depth dose studies using detector and kidney cells in the ESA IBER (Investigations into Biological Effects of Radiation) program. The IBER program is a European effort to contribute to an improved understanding of the radiation risk of cancer and also non-cancer effects. It recognizes that radiation, along with physiology and microgravity, are limiting factors for exploration missions. An ESA topical team chaired by Marco Durante, GSI, Germany, advises ESA on this topic. It should be stressed that the problem of radiation exposure in interplanetary missions, which represents a major operational risk for acute radiation syndrome and limitation of mission duration, can only be solved with a large accelerator-based research program. In a second MATROSHKA phantom exposure, the impact of a solar particle event was simulated at the NSRL in Brookhaven. In this experiment blood cells were exposed together with detector systems to visualize the depth dose effect in a human body and to provide a benchmark for radiation transport calculations. Ground experiments are an essential part of the MATROSHKA program and will be continued in the future.

Computer simulations present a strong cornerstone in the MATROSHKA program. Since it is not possible to perform measurements for all potential projectile-target-energy-geometry combinations, computer simulations using particle and heavy ion transport codes are the only way to estimate the radiation risks for humans onboard a spacecraft. Because of the complexity of space radiation fields and shielding, transport models need to be carefully benchmarked. As one example, recent calculations using the PHITS code are chosen. In the simulation, the phantom and the container were placed on the aluminum foundation of 1 g/cm^2 thickness. The inside of the foundation and the inside of the container were filled with air. The container together with the foundation were located on a simplified ISS, shaped like an aluminum cylinder with a thickness of 15 g/cm^2. Although calculations still differ from measurements by up to a factor of two, the results are very promising.

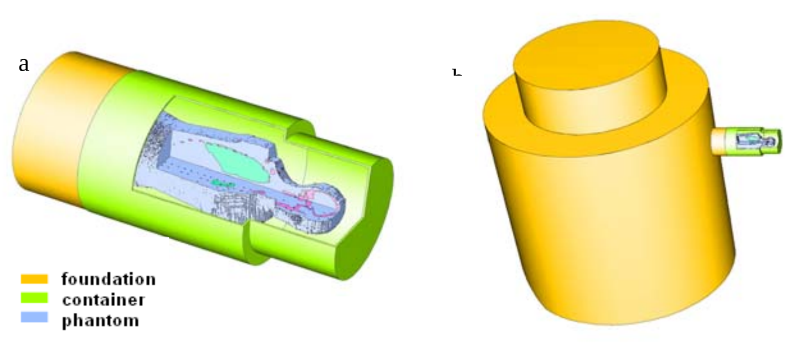


Fig. 8*: Simulated geometry of the phantom, container and foundation (a) and the simplified ISS geometry with the MTR facility attached.*

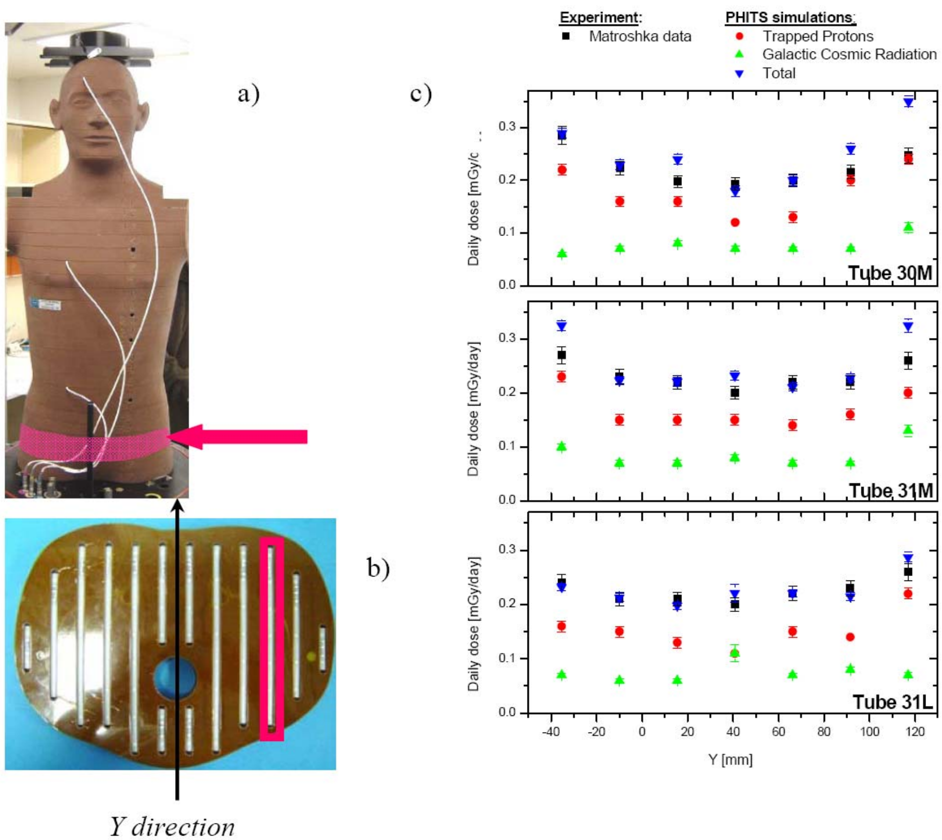


Fig.9. *Calculated and measured MATROSHKA absorbed doses (c) along the tubes M and L located in slices 30-31 of the phantom torso (a). The Y direction of the tubes is shown for tube 30M in (b).*

Summary

The exact determination of tissue and organ dose in space is a demanding and challenging task, and is fulfilled in a close cooperation of all the partners working on the International Space Station. MATROSHKA is the only current human phantom experiment in which organ doses are calculated based on depth dose measurements. The effective dose was determined and it was shown that personal dosemeters overestimate the dose during an EVA by more than a factor of two. The detailed investigation of the MATROSHKA results is part of the FP7 HAMLET project.

Benefits of the MATROSHKA data products are:

- Determination of doses absorbed by crucial organs of astronauts and radiation exposure under various geo- and heliophysical conditions and determination of the radiation hazard under IVA and EVA conditions. Determination of doses experienced by crews in different shielding locations and under low protection conditions.
- Benchmarking of models used for the calculation of radiation transport through spacecraft shielding and through tissue material in order to calculate organ doses.
- Improved methods for assessing absorbed and equivalent doses for future better risk assessment for long duration space flight.
- Assessment of space suit shielding efficiency.

- Provision of source data for experimental assessment of the Station shielding efficiency in different compartments not only in the units of dose, but also in the units of radiation risk.
- Updating of models describing the radiation field on near-Earth orbits (Earth's radiation belts, galactic cosmic rays, solar cosmic rays, planet distribution for geomagnetic cut threshold under various conditions).
- Definition of the requirements for equipment needed for fundamental and application studies of radiation safety in the framework of the international program of ISS space research.

Perspectives and Outlook

Four MATROSHKA exposures have been performed outside (MTR1) in the PIRS module (MTR 2A in 2006), in the Zvezda module (MTR 2B from 2007 - 2009) and inside the Japanese Experimental Module (MTR-KIBO from 2010-2011). A potential second outside exposure is being considered. MATROSHKA has operated more than 7 years onboard the Space Station and is the biggest collaboration in space dosimetry so far. The data gathered are immense and will be populated in a database which could be used as reference for radiation risk estimate calculations (www.fp7-hamlet.eu). The studies provide prerequisite information needed to set up a ”human computer model” in interplanetary space, to allow the assessment of radiation risk for future manned flights to Mars.

MATROSHKA Science Team Members

The results could be achieved only through an international cooperation with 19 institutions located in US, Japan, Russia, Japan and Europe, which are listed below, and with the efforts of Jan Dettmann, ESA, who act as ESA MATROSHKA Project Manager.

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