Radiation environment onboard spacecraft at LEO and in deep space

Conference Paper · March 2016

DOI: 10.1109/AERO.2016.7500765

Lembit Sihver
TU Wien

Iva Ambrožová
Academy of Sciences of the Czech Rep…

Radiation Protection Dosimetry Advance Access published May 15, 2015

Radiation Protection Dosimetry (2015), pp. 1–7 doi:10.1093/rpd/ncv330

RADIATION ENVIRONMENT AT AVIATION ALTITUDES AND IN SPACE

L. Sihver[1,2,*], O. Ploc[3], M. Puchalska[1], I. Ambrožová[3], J. Kubančák[3,4], D. Kyselová[3,4] and V. Shurshakov[5]
[1]Atominstitut, TU Wien, Stadionallee 2, Vienna 1020, Austria
[2]Chalmers University of Technology, Applied Physics, Göteborg, Sweden
[3]Nuclear Physics Institute of the AS CR, Prague, Czech Republic
[4]Czech Technical University in Prague, Institute of Experimental and Applied Physics, Horská 3a/22, Prague 128 00, Czech Republic
[5]Russian Academy of Sciences, State Research Center of Russian Federation Institute of Biomedical Problems, Russia

*Corresponding author: lembit.sihver@tuwien.ac.at

On the Earth, protection from cosmic radiation is provided by the magnetosphere and the atmosphere, but the radiation exposure increases with increasing altitude. Aircrew and especially space crew members are therefore exposed to an increased level of ionising radiation. Dosimetry onboard aircraft and spacecraft is however complicated by the presence of neutrons and high linear energy transfer particles. Film and thermoluminescent dosimeters, routinely used for ground-based personnel, do not reliably cover the range of particle types and energies found in cosmic radiation. Further, the radiation field onboard aircraft and spacecraft is not constant; its intensity and composition change mainly with altitude, geomagnetic position and solar activity (marginally also with the aircraft/spacecraft type, number of people aboard, amount of fuel etc.). The European Union Council directive 96/29/Euroatom of 1996 specifies that aircrews that could receive dose of >1 mSv y^{-1} must be evaluated. The dose evaluation is routinely performed by computer programs, e.g. CARI-6, EPCARD, SIEVERT, PCAire, JISCARD and AVIDOS. Such calculations should however be carefully verified and validated. Measurements of the radiation field in aircraft are thus of a great importance. A promising option is the long-term deployment of active detectors, e.g. silicon spectrometer Liulin, TEPC Hawk and pixel detector Timepix. Outside the Earth's protective atmosphere and magnetosphere, the environment is much harsher than at aviation altitudes. In addition to the exposure to high energetic ionising cosmic radiation, there are microgravity, lack of atmosphere, psychological and psychosocial components etc. The milieu is therefore very unfriendly for any living organism. In case of solar flares, exposures of spacecraft crews may even be lethal. In this paper, long-term measurements of the radiation environment onboard Czech aircraft performed with the Liulin since 2001, as well as measurements and simulations of dose rates on and outside the International Space Station were presented. The measured and simulated results are discussed in the context of health impact.

INTRODUCTION

On the Earth, protection from cosmic radiation is provided by the magnetosphere and the atmosphere, but the radiation exposure increases with increasing altitude. The radiation exposure to aircrew is a result of a complex mixed radiation field resulting from primary and secondary space radiation originating from galactic cosmic rays (GCRs) and solar energetic particles (SEPs) penetrating the atmosphere[1, 2]. Aircrew and, in much higher degree, space crew members are therefore exposed to an increased level of ionising radiation. The radiation exposure to aircrew members is a topic that has gained much attention in recent years as more information becomes available regarding the radiation field at high altitudes. Dosimetry onboard aircraft and spacecraft is however complicated by the presence of photons, neutrons and high linear energy transfer (LET) particles. Depending on the frequency of flights and the route taken, the exposure can add up over time resulting in career exposures similar or even above those in the nuclear industry. In response, the International Commission on Radiological Protection (ICRP) recognised the occupational exposure of aircrew to cosmic radiation through its ICRP 60 Recommendations published in 1990[3]. In 1996, the European Union (EU) further suggested that a theoretical- and/or empirically based code can be used to manage such exposure through the EU Council directive 96/29/Euroatom of 1996[4]. When increasing the altitude above commercial flight routes, the dose increases and the radiation field is changing. It is well known that space radiation represents a major hazard to crew members on long-duration manned space missions, both at the International Space Station (ISS) and on the planned interplanetary missions, e.g. to Mars. It is therefore important to be able to predict the radiation environment in the spacecraft and inside the human body, as well as the short- and long-term biological consequences of the radiation exposure. However, the estimation of biological effects is very complicated and has large uncertainties. Using quality factors, based on LET spectra, absorbed doses can be converted into dose equivalents, which in turn are converted into risk estimations using appropriate risk coefficients. Although, these risk coefficients have very large uncertainties. Although knowledge of the dose is not sufficient for estimating the biological effects of radiation, it is an important component for the risk estimation. The most important parameters for determining the dose to space crew are the orbit of the spacecraft (inclination and altitude), the solar cycle phase and the thickness and material of the shielding. Radiation monitoring during long-term space missions aboard the MIR and ISS demonstrates that the crew member effective dose can be as high as 0.1–0.3 Sv after a 1 y space flight, i.e. ∼0.4–0.8 mSv d^{-1}[2, 5, 6]. For long-term interplanetary missions, the radiation constitutes a potentially limiting factor since current protection limits for low-Earth orbit missions may be approached or even exceeded. The Mars Science Laboratory (MSL) spacecraft, containing the Curiosity rover, was launched to Mars on 26 November 2011, and travelled for 253 d, 560 000 000 km to Mars. The Radiation Assessment Detector (RAD) on the spacecraft showed that the dose equivalent for even the shortest round-trip Earth–Mars, with current propulsion systems and comparable shielding, is found to be 0.7 ± 0.1 Sv[7]. Even if the dose rate is lower on the surface of Mars, an Astronaut would still get around 40 % of the dose rate in deep space, so effective countermeasures must be developed before humans will be able to safely travel and stay on Mars.

AIRCREW DOSIMETRY

Aircrew dosimetry is routinely performed using computer codes approved by national radiation protection authorities. However, such codes should be periodically verified by measurements not only because of the recommendation given by Ref. [8] but also because of exploration of systematic errors in the routine method of aircrew dosimetry.

Annual effective doses received by aircrew in the Czech Republic have been calculated using the computer code CARI-6 according to an approved routine individual dosimetry procedure[9]. The airline operators provided datasets containing the date, aircraft type, identification numbers of aircrew, origin and destination airports for each flight. Actual flight profiles were replaced with typical flight profiles; for instance, the ascend and descend times were set to 30 min for all flights longer than 1 h, and the flight levels of the B737 and A310 aircraft models were set to FL350 and FL370, respectively. Typical parameters were set so that the calculation slightly overestimated the effective dose, to get conservative results. The calculation was performed at the Nuclear Physics Institute in Prague and results were sent to the airline operators. This procedure was verified via a series of measurements and calculations[10–12]. Results are plotted in Figure 1.

The systematic errors of the routine dosimetry method include: (i) uncertainties of the calculation models used in the computer codes; (ii) simplified flight profiles used as input for calculation programs; (iii) only effective doses from the GCR are calculated (effects of SEPs are not taking into account) and (iv) new radiation weighting factors for protons and neutrons introduced in ICRP 103 recommendation[13] are not considered in the CARI-6 code. According to Mares *et al.*[14] and the EXcel-based Program for calculating Atmospheric Cosmic-ray Spectrum (EXPACS)[15, 16], the effective doses at flight altitudes calculated using the ICRP 103 weighting factors are between 19 and 25 % (depending mainly on altitude and the vertical cut-off rigidity) lower than those calculated using ICRP 60 weighting factors, see Figure 2. CARI-6 also does not consider shielding by the structure of the aircraft; the total effective dose

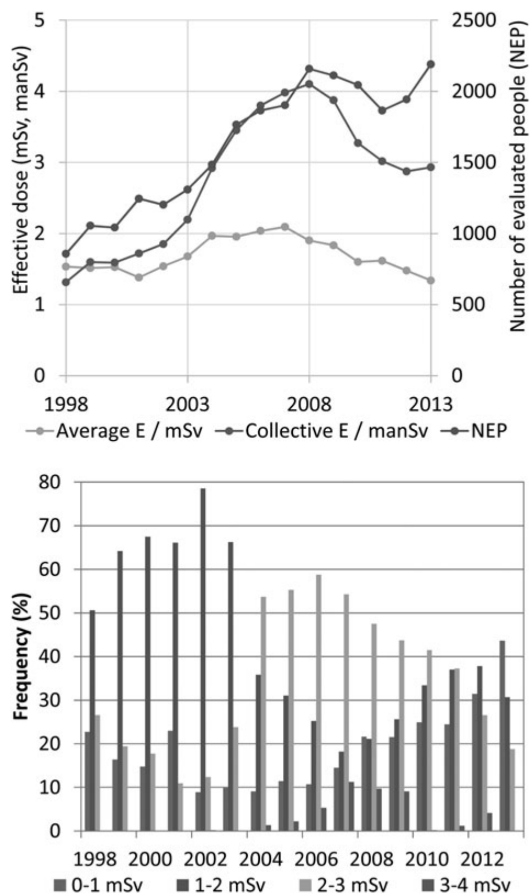

Figure 1. Aircrew dosimetry in the Czech Republic from 1998 to 2013: average and collective effective doses (up) and distribution of effective doses (down) calculated using CARI-6 code.

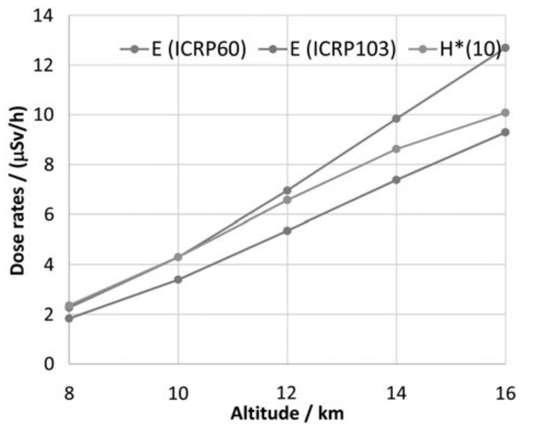

Figure 2. Aircrew dosimetry in the Czech Republic from 1998 to 2013: average and collective effective doses (up) and distribution of effective doses (down) calculated using CARI-6 code.

rates (E) are calculated in free atmosphere. The real doses inside the plane can be lower (depending on the types of aircraft, position inside, amount of fuel, number of passengers etc.)[17]. Therefore, measurements with detectors onboard aircraft are important to include the influence of the construction materials of aircraft, and the other effects mentioned before. Many measurements have been performed at flight altitudes[18]. This group has focused on the long-term measurements to observe also the effect of solar radiation, especially to increase the probability of detection an SEPs onboard aircraft.

For long-term measurements, the Liulin detector[19] has been installed onboard aircraft since 2001[20]. Spectra of energy deposited to its silicon diode were recorded in 10-min intervals during the flights. After several weeks of operation, the device was removed, data from its memory were transferred to a computer and the ambient dose equivalent rates, H*(10), were calculated using calibration coefficients determined at the CERN-EU high-energy reference field (CERF) facility. Measured values of H*(10) were compared with E calculated with CARI-6 for both solar minimum and maximum. Relative differences between measured and calculated values were $\leq$0.3 for 97 % of flights, $\leq$0.2 for 86 % and $\leq$0.1 for 61 % (but 95 % in 2001 and 2002). The differences are mostly within 30 %, which is acceptable according to ICRU[21]. One point, which is high above the $\pm$30 % confidence band in 2001, was caused by the Ground Level Enhancement (GLE) 60. The GLE 60 occurred on 15 April 2001 and it was fully detected by Liulin at FL350[22]. One should bear in mind that the Liulin detector provides H*(10) from both the galactic and solar component of cosmic radiation, CARI-6 only calculates the galactic component.

Table 1. Overview of phantom experiments in space.

Experiment	Date	Location
Anthropomorphic phantom head	1989–1990	Space Shuttle
Water-filled spherical phantom	1997–1999	MIR
Anthropomorphic phantom torso ‘Fred’	2001	ISS
Spherical phantom MTR-R	2004–ongoing	ISS
Anthropomorphic phantom torso MTR	2004–2011	ISS

SPACE DOSIMETRY

Space radiation hazards are recognised as a key concern for human space flights. For long-term interplanetary missions, they constitute a potentially limiting factor since current protection limits might be approached or even exceeded. In such a situation, an accurate risk assessment requires knowledge of the radiation quality, as well as equivalent doses in critical radiosensitive organs rather than skin doses or ambient doses from area monitoring. In addition to that, different risk coefficient for different radiation caused illnesses and diseases must be developed. One of the main objectives of space dosimetry is to characterise the complex space radiation environments to provide reliable input data for the risk projection. The use of human phantoms, simulating an astronaut's body, can provide detailed information of the depth–dose distributions, and radiation quality, in radiation sensitive organs inside the human body. This is essential information for evaluating short- and long-term radiation risks. In Table 1, the main phantom experiments performed in space so far are listed.

These experiments include the USSR Torso phantom, which can be seen on the left side in Figure 3. This torso was made of epoxy resin mixed with wheat seeds and flied around the Moon onboard the Zond-7 unmanned spacecraft[23]. The following phantom experiments used an anthropomorphic head[24], seen in the middle of Figure 3; a water-filled spherical phantom aboard the Mir orbital station[25–27] shown on the right side in Figure 3, as well as an anthropomorphic phantom torso (see Figure 4), called ‘Fred’, aboard the Space Shuttle[28, 29]. The latter was also exposed in the U.S. laboratory of the ISS[30, 31].

Another spherical phantom called MATROSHKA-R (MTR-R), which is made of tissue-equivalent material, started recording data in the Russian Segment of the ISS in 2004[5, 32–37], is shown in Figure 4.

In Figure 5, the average daily absorbed doses and dose equivalents, measured with CR39 and thermoluminescent dosimeter (TLD) inside the

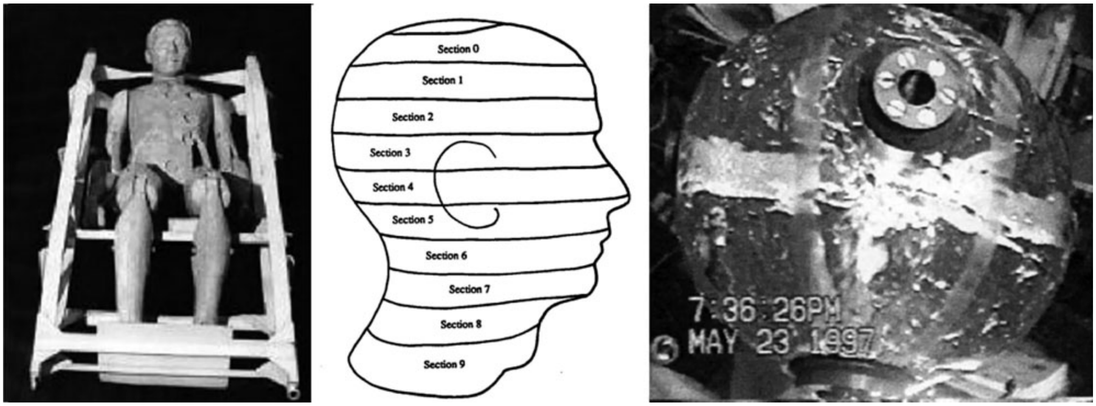

Figure 3. To the left is the USSR Torso phantom, which was made of epoxy resin mixed with wheat seeds and flied around the Moon onboard the Zond-7 unmanned spacecraft. In the middle, the anthropomorphic head aboard the Space Shuttle[24] is shown, and to the right, the water-filled spherical phantom aboard the Mir orbital station.

Figure 4. To the left, the anthropomorphic phantom torso 'Fred', used aboard the Space Shuttle and the ISS, is shown. In the middle and to the right, the MTR-R phantom, which has been located in the service module, Piers-1 module, MIM- and MIM-2 module, and in the Kibo module of the ISS, can be seen.

MTR-R phantom during 2007–11, are shown together with the solar activity given as sunspot numbers.

In Table 2, the mean surface dose equivalents ($D_{\text{mean-surface}}$), mean tissue dose equivalents ($D_{\text{mean-tissue}}$) and mean effective doses for the MTR-R phantom, in the crew quarter during 11 August 2004 to 10 October 2005 (425 d), Piers-1 module during 12 May 2007 to 20 February 2008 (285 d) and in MIM2 from 30 April 2010 to 26 November 2010 (210 d), are listed.

Around the same time as the MTR-R phantom started recording data in the Russian Segment of the ISS in 2004, the MATROSHKA (MTR) anthropomorphic phantom torso was installed on the exterior of the ISS. MTR can be seen in Figure 6.

The multilateral scientific experiments using the MTR phantom represent the most comprehensive effort to date in radiation protection dosimetry in space[6, 39–50]. Dose measurements were mainly performed using thermoluminescence phosphors arranged in a regular grid inside the phantom torso. The results were combined with detailed numerical models of the human body to provide the data needed for cancer risk projections for long-term human space exploration and support benchmarking of radiation transport codes[41, 42].

The results from the measurements in these Phantoms have showed that the crew member dose on the ISS is in the order of 0.4–0.8 mSv d^{-1}, depending on solar cycle, shielding and the orbit. The results from MSL RAD, described in the introduction, show that the dose from GCR achieved during a Mars Mission will be of the order 0.7–1.0 Sv, depending on the solar cycle and duration of the journey. If the Astronauts will be exposed to large SPEs, the dose can increase to lethal doses up to 4–6 Sv.

CONCLUSIONS

The radiation environment at aviation altitudes is well known and the health risks seem to be limited, even if there is still a need for more research about the health consequences of low-dose ionising radiation since in the effective dose rate region <100 mSv y^{-1}, bystander effects and cell-to-cell communication, as well as genomic instability, inflammatory response, adaptive response etc., play a role that is not yet fully understood. However, for long-term missions on the ISS, and in deep space, the doses are significantly increased and the type of radiation is very different from that achieved at aviation altitudes. The air crews are mainly exposed to photons, neutrons, muons, pions, electrons and positrons, but at ISS and in deep space the radiation also includes heavy charged particles with high LET. These particles cause high ionisation density when passing through human tissue and organs, and the risk for clustered DNA damages is high. Compared with isolated lesions, the clustered damages can be repaired with decreased effectiveness depending on the types of lesions, their spatial distribution and physical location. The biological effects of clustered damages are difficult to investigate due to their stochastic character; however, it has been confirmed that they have a high lethal and mutagenic potential compared with isolated damage sites. Even though the chance that the high LET particles traversing through the cytoplasm of the cells is much higher than through the nuclei, the contribution of targeted cytoplasmic irradiation to induction of genomic instability and other chromosomal damages induced by

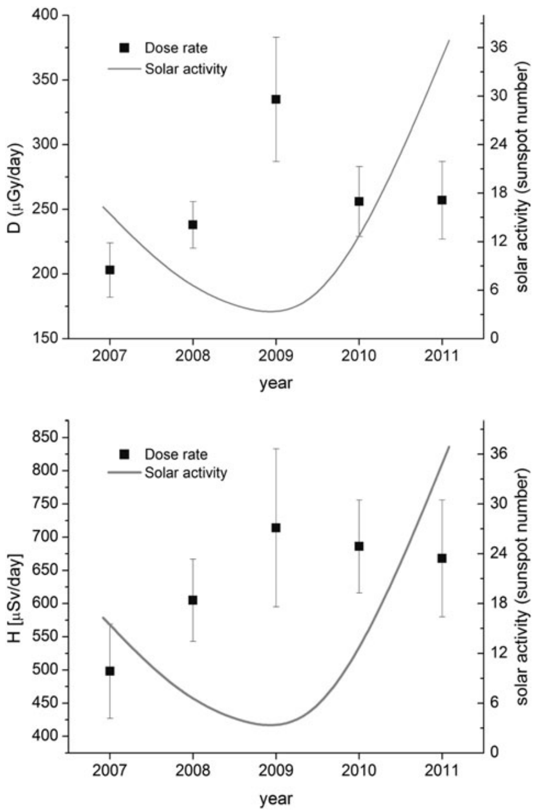

Figure 5. To the left, the average daily absorbed doses, measured with CR39 and TLD inside the MTR-R phantom[38], during 2007–2011 can be seen. In the same figure, the solar activity, given as sunspot numbers, is shown. To the right, the corresponding average daily dose equivalents are shown together with the sunspot numbers.

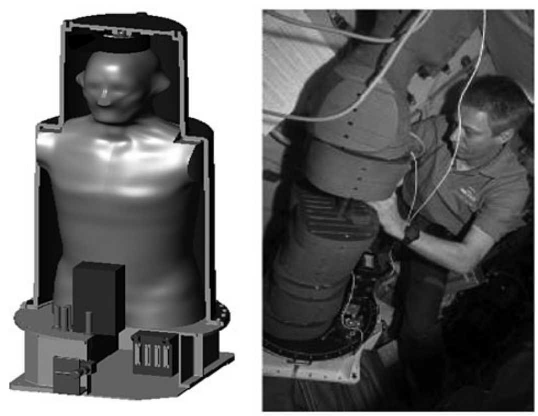

Figure 6. MTR phantom that has been located inside and outside the service module, and in the Kibo module of the ISS during 2004–2011.

Table 2. Effective dose measured with MTR-R.

	Dose, mSv d^{-1} (QF = 2.6)		
	Crew quarter	Piers-1 module	MIM-2
$D_{\text{mean-surface}}$	0.55	0.69	0.99
$D_{\text{mean-tissue}}$	0.45	0.56	0.87
D_{eff}	from 0.47 to 0.49	from 0.59 to 0.62	from 0.88 to 0.92

the highly densely ionising radiation is still quite unknown. It is, however, well known that the cellular membranes are particularly sensitive to the effects of radiation-induced oxidative damage, and that lipid peroxidation can alter membrane structure and function. The bystander and cell-to-cell communication, as well as genomic instability, inflammatory response, adaptive response etc., will also contribute to the risk when exposed to high LET particles. In addition, there are partly unknown synergistic effects, which must be studied in more details to decrease the uncertainty of the radiation risk coefficients.

The long-term risks for achieving cancer are of course a major concern for space missions, but there are many other degenerative cell, tissue and organ risks associated with an increased exposure to densely ionising radiation. The effects include cataracts, reduced immune system, heart and cardiovascular effects, just to mention some of them. Possible neurological and central nervous system (CNS) risks during space missions are altered cognitive function, including detriments in short-term memory, reduced motor function and behavioural changes, which may affect performance and human health. The late CNS risks might include neurological disorders such as premature aging, Alzheimer's disease or other dementia. If the space travellers will be exposed to intensive SEPs without adequate shielding, acute radiation syndrome can lead to a sudden death. Many more studies of short- and long-term biological effects of space radiation are therefore needed, as well as development of countermeasures, e.g. active and passive shielding, optimised nutrition and antioxidant protection etc. In the end, it is an ethical question how much risk is 'acceptable' when travelling in space.

REFERENCES

1. Protection, N. C. O. R. and Measurements. *Radiation Protection Guidance for Activities in Low-earth Orbit*. National Council on Radiation Protection and Measurements (2000) ISBN 9780929600659.
2. Benton, E. R. and Benton, E. *Space radiation dosimetry in low-Earth orbit and beyond*. Nucl. Instrum. Meth. B **184**, 255–294 (2001).
3. Protection, I. C. O. R. *ICRP Publication 60: 1990 Recommendations of the International Commission on Radiological Protection*. SAGE Publications (1991) ISBN 9780080411446.
4. Courades, J. M. *European legislation on protection against cosmic radiation*. Radiat. Prot. Dosim. **86**, 343–346 (1999).
5. Shurshakov, V., Petrov, V. M., Akatov, Y., Tolochek, R., Kartsev, I., Petrov, V. I., Polenov, B. and Lyagushin, V. *Study of dose distribution in a human body in Space Station compartments with the spherical tissue-equivalent phantom*. In: Proceedings of Fundamental Space Research, 21–28 September. Sunny Beach, Bulgaria, pp. 234–237 (2008).
6. Puchalska, M., Bilski, P., Berger, T., Hajek, M., Horwacik, T., Körner, C., Olko, P., Shurshakov, V. and Reitz, G. *NUNDO: a numerical model of a human torso phantom and its application to effective dose equivalent calculations for astronauts at the ISS*. Radiat. Environ. Biophys. **53**, 719–727 (2014).
7. Zeitlin, C. *et al. Measurements of energetic particle radiation in transit to mars on the mars science laboratory*. Science **340**, 1080–1084 (2013).
8. Commission, E. *Radiation protection 88: recommendations for the implementation of Title VII of the European Basic Safety Standards Directive (BSS) concerning significant increase in exposure due to natural radiation sources*. Office for the Official Publications of the European Communities (1997).
9. Frantisek, S., Ondrej, P. and Ivan, K. *Routine individual monitoring of aircraft crew exposure: Czech experience and results since 1998*. Radiat. Prot. Dosim. **125**, 416–420 (2007).
10. Malusek, A., Ploc, O., Kovar, I., Brabcova, K. and Spurny, F. *Routine Individual Monitoring of Aircraft Crew Exposure; Czech Experience and Results 1998–2008*. Radiat. Prot. Dosim. **144**, 684–687 (2011).
11. Ploc, O. and Spurny, F. *Further analysis of long-term measurements on board of Czech airlines aircraft*. Nucl. Instrum. Meth. A **580**, 671–674 (2007).
12. Ploc, O., Ambrozova, I., Kubancak, J., Kovar, I. and Dachev, T. P. *Publicly available database of measurements with the silicon spectrometer Liulin onboard aircraft*. Radiat. Meas. **58**, 107–112 (2013).
13. *The 2007 Recommendations of the International Commission on Radiological Protection. ICRP publication 103*. Ann. ICRP **37**, 1–332 (2007).
14. Mares, V., Maczka, T., Leuthold, G. and Ruhm, W. *Air crew dosimetry with a new version of EPCARD*. Radiat. Prot. Dosim. **136**, 262–266 (2009).
15. Sato, T. and Niita, K. *Analytical functions to predict cosmic-ray neutron spectra in the atmosphere*. Radiat. Res. **166**, 544–555 (2006).
16. Sato, T., Yasuda, H., Niita, K., Endo, A. and Sihver, L. *Development of PARMA: PHITS-based analytical radiation model in the atmosphere*. Radiat. Res. **170**, 244–259 (2008).
17. Ferrari, A., Pelliccioni, M. and Villari, R. *Evaluation of the influence of aircraft shielding on the aircrew exposure through an aircraft mathematical model*. Radiat. Prot. Dosim. **108**, 91–105 (2004).
18. Lindborg, L., Bartlett, D., Beck, P., McAulay, I., Schnuer, K., Schraube, H. and Spurny, F. *Cosmic radiation exposure of aircraft crew: Compilation of measured and calculated data*. Radiat. Prot. Dosim. **110**, 417–422 (2004).
19. Dachev, T., Dimitrov, P., Tomov, B., Matviichuk, Y., Spurny, F., Ploc, O., Brabcova, K. and Jadrnickova, I. *Liulin-type spectrometry-dosimetry instruments*. Radiat. Prot. Dosim. **144**, 675–679 (2011).
20. Ploc, O., Brabcova, K. P., Spurny, F., Malusek, A. and Dachev, T. *Use of energy deposition spectrometer Liulin for individual monitoring of aircrew*. Radiat. Prot. Dosim. **144**, 611–614 (2011).
21. Units, I. C. O. R., Measurements and Protection, I. C. O. R. *Reference Data for the Validation of Doses from Cosmic-radiation Exposure of Aircraft Crew*. Oxford University Press (2010).

22. Spurný, F. and Dachev, T. *Measurements on Board an Aircraft during an Intense Solar Flare, Grond Level Event 60, on April 15, 2001 (Letter to the Editor)*. Radiat. Prot. Dosim. **95**, 273–275 (2001).
23. Smirennyi, L. N. *Study of spatial distribution of tissue doses with the aid of a phantom-mannequin*. In: Proceedings of the Third International Congress of Protection Association, Washington, NY, September 9–14 (1973).
24. Konradi, A., Atwell, W., Badhwar, G. D., Cash, B. L. and Hardy, K. A. *Low Earth orbit radiation-dose distribution in a phantom head*. Nucl. Tracks Radiat. Meas. **20**, 49–54 (1992).
25. Berger, T., Hajek, M., Schoner, W., Fugger, M., Vana, N., Akatov, Y., Shurshakov, V., Arkhangelsky, V. and Kartashov, D. *Application of the high-temperature ratio method for evaluation of the depth distribution of dose equivalent in a water-filled phantom on board Space Station Mir*. Radiat. Prot. Dosim. **100**, 503–506 (2002).
26. Berger, T., Hajek, M., Schoner, W., Fugger, M., Vana, N., Noll, M., Ebner, R., Akatov, Y., Shurshakov, V. and Arkhangelsky, V. *Measurement of the depth distribution of average LET and absorbed dose inside a water-filled phantom on board space station MIR*. Phys. Med. **17**, 128–130 (2001).
27. Berger, T., Hajek, M., Summerer, L., Vana, N., Akatov, Y., Shurshakov, V. and Arkhangelsky, V. *Austrian dose measurements onboard space station MIR and the International Space Station - overview and comparison*. Adv. Space Res. **34**, 1414–1419 (2004).
28. Yasuda, H., Badhwar, G. D., Komiyama, T. and Fujitaka, K. *Effective dose equivalent on the ninth Shuttle–Mir mission (STS-91)*. Radiat. Res. **154**, 705–713 (2000).
29. Badhwar, G. D., Atwell, W., Badavi, F. F., Yang, T. C. and Cleghorn, T. F. *Space radiation absorbed dose distribution in a human phantom*. Radiat. Res. **157**, 76–91 (2002).
30. Cucinotta, F. A., Kim, M. H., Willingham, V. and George, K. A. *Physical and biological organ dosimetry analysis for international space station astronauts*. Radiat. Res. **170**, 127–138 (2008).
31. Yasuda, H. *Effective dose measured with a life size human phantom in a low Earth orbit mission*. J. Radiat. Res. **50**, 89–96 (2009).
32. Kireeva, S. A., Benghin, V. V., Kolomensky, A. V. and Petrov, V. M. *Phantom—dosimeter for estimating effective dose onboard International Space Station*. Acta Astronaut. **60**, 547–553 (2007).
33. Semkova, J. *et al*. *Radiation measurements inside a human phantom aboard the International Space Station using Liulin-5 charged particle telescope*. Adv. Space Res. **45**, 858–865 (2010).
34. Machrafi, R. *et al*. *Neutron dose study with bubble detectors aboard the International Space Station as part of the Matroshka-R experiment*. Radiat. Prot. Dosim. **133**, 200–207 (2009).
35. Hallil, A. *et al*. *Mosfet Dosimetry Mission inside the Iss as Part of the Matroshka-R Experiment*. Radiat. Prot. Dosim. **138**, 295–309 (2010).
36. Jadrnickova, I., Brabcova, K., Mrazova, Z., Spurny, E., Shurshakov, V. A., Kartsev, I. S. and Tolochek, R. V. *Dose characteristics and LET spectra on and inside the spherical phantom onboard of ISS*. Radiat. Meas. **45**, 1536–1540 (2010).
37. Semkova, J *et al*. *Cosmic radiation dose rate, flux, LET spectrum and quality factor obtained with Liulin-5 experiment aboard the International Space Station*. In: Proceedings of Fundamental Space Research, 21–28 September, Sunny Beach, Bulgaria, pp. 229–233 (2008).
38. Ambrozova, I., Brabcova, K., Spurny, F., Shurshakov, V. A., Kartsev, I. S. and Tolochek, R. V. *Monitoring on board spacecraft by means of passive detectors*. Radiat. Prot. Dosim. **144**, 605–610 (2011).
39. Gustafsson, K., Sihver, L., Mancusi, D., Sato, T., Reitz, G. and Berger, T. *PHITS simulations of the Matroshka experiment*. Adv. Space Res. **46**, 1266–1272 (2010).
40. Reitz, G. *Reducing radiation risk in space: The MATROSHKA project*. ESA Bull. (2010).
41. Sihver, L., Sato, T., Puchalska, M. and Reitz, G. *Simulations of the MATROSHKA experiment at the international space station using PHITS*. Radiat. Environ. Biophys. **49**, 351–357 (2010).
42. Puchalska, M., Sihver, L., Sato, T., Berger, T. and Reitz, G. *Simulations of MATROSHKA experiment outside the ISS using PHITS*. Adv. Space Res. **50**, 489–495 (2012).
43. Reitz, G. *et al*. *Astronaut's organ doses inferred from measurements in a human phantom outside the international space station*. Radiat. Res. **171**, 225–235 (2009).
44. R, B. *Radiation hazards to astronauts*. TU V Media (2009).
45. Zhou, D., Semones, E., O'Sullivan, D., Zapp, N., Weyland, M., Reitz, G., Berger, T. and Benton, E. R. *Radiation measured for MATROSHKA-1 experiment with passive dosimeters*. Acta Astronaut. **66**, 301–308 (2010).
46. Dettmann, J. and Reitz, G. *MATROSHKA: measuring radiation hazards for spacewalkers*. On Station **1–4**, 13–20 (2003).
47. Reitz, G. and Berger, T. *The MATROSHKA facility–dose determination during an EVA*. Radiat. Prot. Dosim. **120**, 442–445 (2006).
48. Dettmann, J., Reitz, G. and Gianfiglio, G. *MATROSHKA—The first ESA external payload on the International Space Station*. Acta Astronaut. **60**, 17–23 (2007).
49. Koliskova, Z., Sihver, L., Ambrozova, I., Sato, T., Spurny, F. and Shurshakov, V. A. *Simulations of absorbed dose on the phantom surface of MATROSHKA-R experiment at the ISS*. Adv. Space Res. **49**, 230–236 (2012).
50. Berger, T., Bilski, P., Hajek, M., Puchalska, M. and Reitz, G. *The MATROSHKA Experiment: Results and Comparison from Extravehicular Activity (MTR-1) and Intravehicular Activity (MTR-2A/2B) Exposure*. Radiat. Res. **180**, 622–637 (2013).