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A water-filled garment to protect astronauts during interplanetary missions tested on board the ISS

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ABSTRACT

As manned spaceflights beyond low Earth orbit are in the agenda of Space Agencies, the concerns related to space radiation exposure of the crew are still without conclusive solutions. The risk of long-term detrimental health effects needs to be kept below acceptable limits, and emergency countermeasures must be planned to avoid the short-term consequences of exposure to high particle fluxes during hardly predictable solar events. Space habitat shielding cannot be the ultimate solution: the increasing complexity of future missions will require astronauts to protect themselves in low-shielded areas, *e.g.* during emergency operations. Personal radiation shielding is promising, particularly if using available resources for multi-functional shielding devices. In this work we report on all steps from the conception, design, manufacturing, to the final test on board the International Space Station (ISS) of the first prototype of a water-filled garment for emergency radiation shielding against solar particle events. The garment has a good shielding potential and comfort level. On-board water is used for filling and then recycled without waste. The successful outcome of this experiment represents an important breakthrough in space radiation shielding, opening to the development of similarly conceived devices and their use in interplanetary missions as the one to Mars.

1. Introduction

Space radiation is one of the key limiting factors for manned missions in deep space (Chancellor et al., 2014). In planning the route for interplanetary missions, NASA (National Aeronautics and Space Administration) relies on the continuous development of new technologies and countermeasures to ensure the safety of the crew of new generation spacecraft in their future journeys, as the one to Mars (Durante, 2014;

Abbreviations: 3D, three Dimensional; ASI, Italian Space Agency; BFO, blood forming organs; EQM, engineering qualification model; ERB, earth radiation belt; ESA, European Space Agency; ESP, emission of solar protons; FM, flight model; GCRs, galactic cosmic rays; GDML, geometry description markup language; GEANT, GEometry ANd Tracking; GRAS, Geant4 radiation analysis for space; ICRP, International Commission on Radiological Protection; ISS, International Space Station; JSC, Johnson Space Center; LEO, low earth orbit; LLDPE, linear low-density polyethylene; NASA, National Aeronautics and Space Administration; NVR, non-volatile residue; PAHs, polycyclic aromatic hydrocarbons; PP, polypropylene; PU, polyurethane; PWD, potable water dispenser; QBBC, Geant4 QBBC hadronic model; QD, quick disconnect; RBE, relative biological effectiveness; RBM, red bone marrow; REID, risk of exposure-induced death; SPE(s), solar particle event(s); SPENVIS, SPace ENVironment Information System; VITA, *vitalità, innovazione, tecnologia e abilità*; VOCs, volatile organic compounds; WPA, water processor assembly; WRS, water recovery system; WWT, water waste tank

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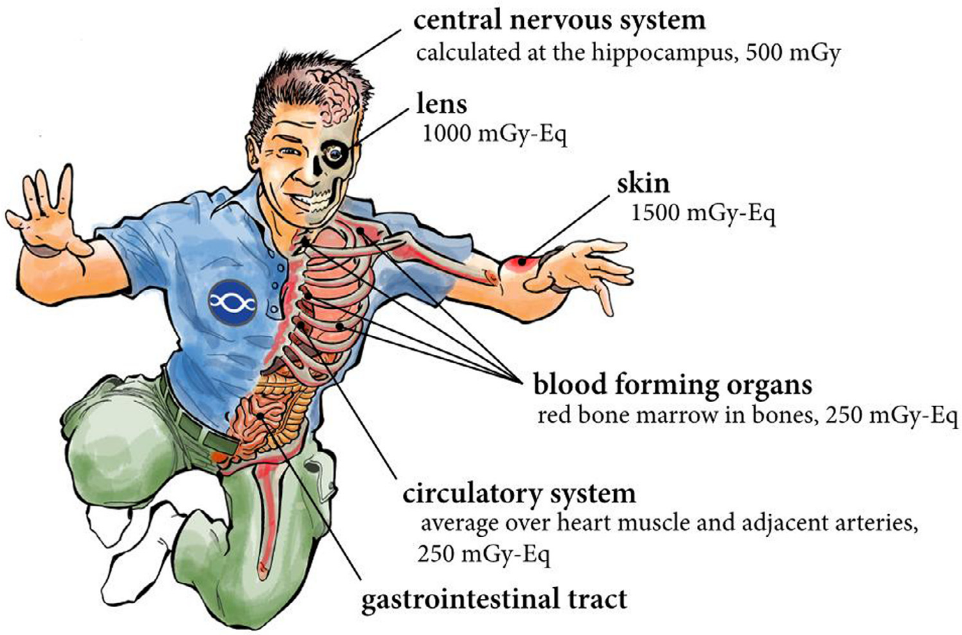

Fig. 1. Tissues and organs subject to short-term non-cancer effects related to space radiation exposure. 30-day exposure limits as currently set by NASA (2018) for low Earth orbit missions are indicated in the figure. Limits are expressed in Gy-Eq (physical dose in Gy multiplied by a RBE factor), exception made for the central nervous system, for which the RBE for non-cancer effects is largely unknown. For solar protons, the recommended RBE is 1.5. RBE values for neutrons (energy dependent) and heavy ions are also given by NASA (2018). Illustration by M. Baiocco.

Zeitlin et al., 2013). Astronauts in deep space, far from the Earth's magnetic field, need to be protected from the continuous flux of galactic cosmic rays (GCRs) and from solar particles (mainly protons) ejected into interplanetary space during hardly predictable solar particle events (SPEs). The exposure to the space radiation environment increases the risk of long-term detrimental health effects that can manifest in the course of the astronaut's life, years after the completion of a successful mission and return to Earth. In addition to this concern, accidental exposure to the high flux of particles during a solar event can also lead to the onset of immediate or short-term health effects, that can be so severe to impair mission success and eventually endanger the astronaut's life.

At present, radiation shielding in space mainly relies on the so-called *passive shielding* approach (Durante and Cucinotta, 2011), *i.e.* space habitats are designed with thick walls that can stop part of the incoming particles, depending on their energy. While losing energy penetrating through the habitat walls up to their possible stopping, primary particles induce nuclear reactions, generating lower energy secondary particles including neutrons (Norbury et al., 2016). Astronauts in the habitat are therefore exposed to the risk related to this internal mixed radiation environment. When adopting a *passive shielding* strategy in the design of spacecraft for interplanetary missions the issue of limitation of mass at launch from Earth needs to be taken into account, and solutions including vehicle assembling in orbit might be possible. When a space habitat is designed for a planetary surface instead, the use of planetary material can be envisaged. On-board resources as wastes, food or water supplies also offer good potential for habitat shielding, *e.g.* when used to build additional walls inside the habitat (Sato et al., 2011; Kodaira et al., 2014). Due to limitations on available mass and volume however, shielding the whole habitat with a uniform thickness of material and for the whole duration of the mission might be practically unfeasible. A compromise is to design shelters in the habitat, *i.e.* areas with increased wall thickness. This is necessary in particular to mitigate the risk of exposure to solar events, as the crew can be advised to take shelter in such areas as soon as signals of incoming solar particles or their precursors are detected. Depending on the specific habitat, shelters can be designed as areas where astronauts can spend most of their time (*e.g.* crew quarters), or as micro-shelters, in which they need to be confined during the event worst hours (Walker et al., 2013). In view of an increasing complexity for the operational scenario of future missions, it is highly probable that the direct intervention of the crew for emergency operations outside a shelter might become necessary during the solar event, or that members of the crew might be caught by high solar particle fluxes in a low-shielded area of the habitat, without being able to reach the shelter in due time.

In planning future deep-space manned spaceflights, NASA resorts to sophisticated models to predict cumulative dose levels absorbed by the crew (Cucinotta et al., 2013 2012). Dose levels are given in sievert (Sv) and obtained by conversion of the physical dose in gray (Gy) applying biological weights to distinguish different types of radiation based on their biological effectiveness (*i.e.* on their spatial pattern of energy deposition) and to account for the radiosensitivity of different tissues or organs. Finally, this information needs to be translated into an associated prediction of risk. The risk of exposure-induced death (REID) can be adopted, defined as the risk of occurrence of a cancer with lethal consequences in the course of the astronaut's life, that can be attributed to his/her exposure to the space radiation environment. The REID for crew members of a space mission is considered acceptable only below a threshold of 3% with 95% confidence level. In addition to such limitation, also short-term non-cancer effects induced by radiation need to be prevented (Wu et al., 2010; Parihar et al., 2015). this is currently done by NASA setting thresholds on permissible doses to specific tissues and organs at risk, over a period ranging from 30 days to 1 year, and over the astronaut's career (NASA, 2018). Such dose limits are generally given in Gy-Eq, *i.e.* the physical dose in Gy is multiplied by a relative biological effectiveness (RBE) factor, which is agreed upon mainly on the basis of radiobiological knowledge and depends again on the different qualities of radiation (particle type and energy) (Wilson et al., 2002). At present, dose limits for short-term non-cancer effects are given for blood forming organs (BFO), skin, circulatory system, lens and central nervous system (CNS), although only for missions near low Earth orbit (LEO), and no regulations for interplanetary missions still exists. In Fig. 1 we summarize existing dose limits for tissues/organs subject to short-term non-cancer effects. Among tissues and organs at risk, the importance of protecting the BFO is well recognized: the lethality of an acute radiation exposure can be mainly attributed to the failure of the hematopoietic system, while spontaneous regeneration of the bone marrow is possible if the system is not too heavily damaged.

Given the characteristics of the space radiation environment (in particular the low flux of GCRs) and the shielding conditions we can expect for a future interplanetary journey, it is unlikely that the crew