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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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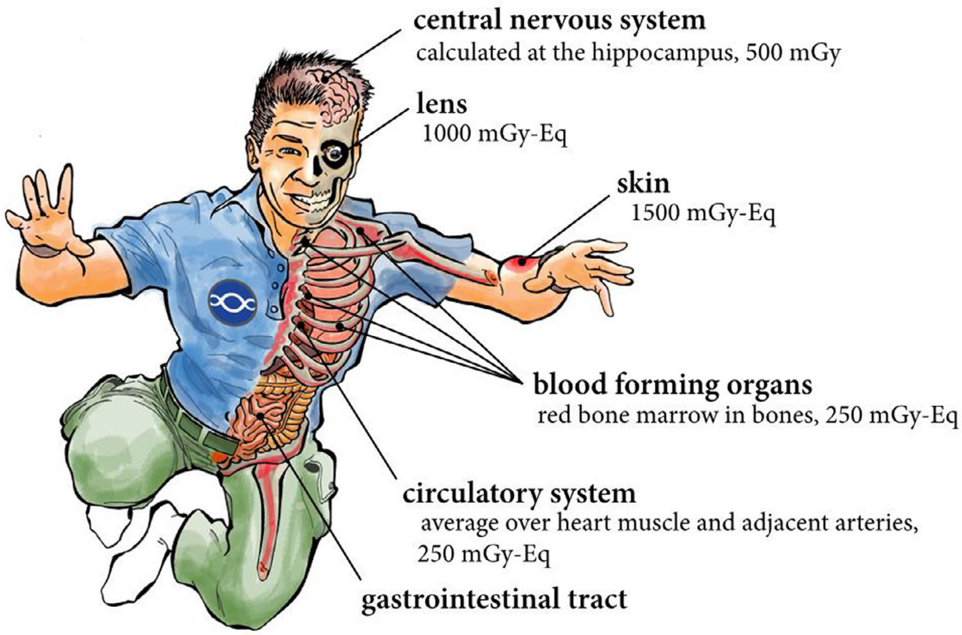

Fig. 1. Tissues and organs subject to short-term non-cancer effects related to space radiation exposure. 30-day exposure limits as currently set by NASA (2018) for low Earth orbit missions are indicated in the figure. Limits are expressed in Gy-Eq (physical dose in Gy multiplied by a RBE factor), exception 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 will be exposed to doses higher than threshold doses for short-term non-cancer limits in a realistic mission scenario, if not in case of occurrence of a large SPE. Solar protons, even when the exposure level is below dose limits for acute effects, also contribute to an increased risk of long-term health consequences, hence to an increased REID. To calculate the REID, predictions on the space radiation environment during the mission are therefore necessary: knowledge of the solar cycle phase is important, as solar events are more frequent during solar maximum, when, on the contrary, GCR fluxes are lower. A compromise has to be struck, to guarantee the lowest possible exposure levels. This is obviously dependent on available countermeasures for radiation shielding and on habitat design. If the increase in risk due to a large SPE is calculated considering only a thick habitat exposure scenario, the REID could be underestimated for missions including activities in low-shielded areas, and the risk of the onset of acute effects would be neglected.

Taken all together, these considerations lead to the conclusion that strategies complementary to habitat shielding need to be explored in view of future spaceflights beyond low Earth orbit. Personal radiation shielding through *e.g.* wearable systems is a promising strategy (Wilson et al., 2006; Waterman et al., 2016; Vuolo and Baiocco, 2017): a radiation-shielding spacesuit could offer protection to most radiosensitive organs in case of occurrence of a solar particle event. Emergency scenarios include *e.g.*: (i) the need to exit the radiation shelter and to operate in lower-shielded areas of the habitat when the event is still in progress; (ii) being caught by (or alerted for) the SPE when operating in a new thin class of spacecraft, similar to that afforded by a rover on a planetary surface; (iii) again, being caught by (or alerted for) the SPE during extra-vehicular activities, with the need of re-entering the habitat, waiting in the intermediate low-shielded hatch module for pressurization and therefore not being able to immediately get to the radiation shelter. In all these cases, the availability of personal shielding system could prevent the onset of acute radiation effects. At the same time, the increase in the risk of long-term consequences would be smaller. If a shielding spacesuit can be designed as comfortable enough to be worn most of the time, it could offer additional protection from the inner radiation environment generated by GCRs impacting on the habitat walls in nominal conditions. Similarly conceived sleeping bags could provide additional protection during astronauts' sleep period. In developing devices for personal radiation shielding, optimization in the use of available resources and multi-functionality should be the main drivers. Water and organic wastes offer great potential for use for personal shielding. For their elemental composition of lighter elements, they offer high electronic stopping power for incoming radiation at equal mass with respect to heavier materials. The cross sections for nuclear interactions and generation of secondary particles from the primary radiation field is also lower. Water is an essential resource in present and future space habitats. Wastes are a renewable resource, constantly produced on-board. Multi-functionality would imply that such radiation shielding devices could *e.g.* be designed acting at the same time as storage elements. Water and liquid wastes could be used to fill flexible elements, suitable for the design of a radiation shielding spacesuit.

In the framework of a feasibility study funded by the European Space Agency (ESA) on innovative radiation shielding approaches in space, we recently proposed a conceptual design of spacesuit models for intra-vehicular-activities in the space habitat, made of water elements with simplified geometries (Vuolo and Baiocco, 2017). We performed three-dimensional (3D) Monte Carlo simulations with GRAS (Geant4 Radiation Analysis for Space) /Geant4 (GEometry ANd Tracking) (Agostinelli et al., 2003; Santin et al., 2005) for an anthropomorphic phantom wearing the proposed spacesuit models in a low-shielded space habitat, and exposed to solar protons with an average energy distribution as given by the ESP (emission of solar protons) model (Xapsos et al., 1999, 2000). We demonstrated that when the phantom is wearing the radiation protection spacesuits, whose protection elements have a thickness in the range from 2 to 6 cm depending on their position on the body, a dose reduction higher than 50% to BFO can be achieved. Detailed results of this study have been previously published (Vuolo and Baiocco, 2017).

Based on the results of this feasibility study, we undertook the technical design and manufacturing of a first prototype of a water-filled radiation protection garment for use in a pressurized space habitat. The PERSEO project—PErsonal Radiation Shielding for intErplanetary missiOns—was selected and funded by the Italian Space Agency (ASI) following an Announcement of Opportunity for experiments to be carried out on board the International Space Station (ISS) in the frame of the Italian scientific utilisation of the ISS. PERSEO led to the realization of the garment prototype and to its test on ISS by an ESA astronaut, during Expedition 52/53 - mission VITA (*Vitalità, Innovazione, Tecnologia e Abilità*). Purpose of this work is to report on the achievements of the PERSEO project, reflecting all steps from the conception of the experiment to actual hardware production and on-board operations, taking account of all requirements for use in the ISS. In the following we describe the solutions adopted for the garment prototype, the results of preliminary ground verification tests of requirements for use and the planning and the outcome of the experimental session on board the ISS. We finally discuss how this project represents a significant breakthrough in radiation shielding in space. At the same time, this work is intended to provide criteria and guidelines to be followed for the implementation of an experiment on board the ISS - at present, the best and only platform for testing new systems in view of future manned deep-space exploration missions.

2. Results

2.1. Preliminary Monte Carlo validation of the personal shielding strategy

Results presented in our previous study (Vuolo and Baiocco, 2017) served as starting point for the design of the PERSEO demonstrator described in this work. In view of the manufacturing of the garment prototype within given limitations and to be compliant with all requirements for use on board the ISS (see later for a detailed discussion), we opted for a maximum-simplicity design: we proposed a garment model protecting only the torso of the subject, with no elements protecting arms and legs as in previous conceptual models (Vuolo and Baiocco, 2017). As indicator of the shielding performance, we choose dose reduction to BFO. A selective shielding strategy is fully justified, considering the distribution of red bone marrow in different bone structures in the human skeletal system: the spine (upper, thoracic and lumbar spine down to the sacrum), the cage (ribs, sternum, clavicles and scapulae) and the pelvis (which is at least partially protected in the proposed solution) have the highest weights in terms of red bone marrow mass to bone mass, and together account for approximately 80% of the total red bone marrow mass in the body (ICRP, 2009). Protection is also offered to the gastrointestinal tract and to the cardiovascular system with this choice, while only partial protection is offered to the skin, and no protection to head and lenses.

The number of protection elements was reduced to a minimum of four: two protecting the astronaut's front and two protecting his/her back. The impact of this choice in terms of hazard category for the use of water on board the ISS is discussed later in this work. We proposed a thickness of 7 cm for all four protection elements, higher than that for elements in the same positions (4–6 cm) in previous models. A single thickness for all elements was also the most practical choice in view of the successive manufacturing and test campaign. The setup adopted for 3D calculations is shown in Fig. 2. We followed the same approach as in our previous work (Vuolo and Baiocco, 2017): we tailored the lateral dimensions of the four protection elements to the GRAS mathematical phantom (Fig. 2a), and we performed GRAS/Geant4 (Agostinelli et al., 2003; Santin et al., 2005) calculations of dose reduction (in Gy-Eq) to BFO when the phantom is protected by such elements (Fig. 2b) in

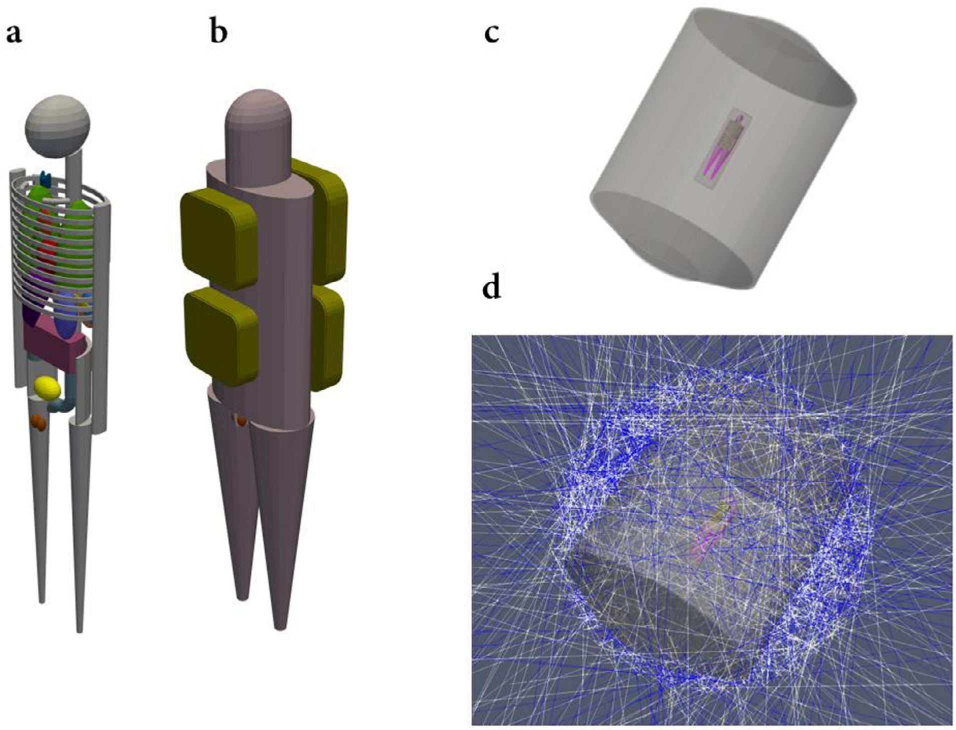

Fig. 2. 3D GRAS/Geant4 simulation setups for preliminary validation of the shielding effectiveness of the PERSEO garment. (a) GRAS/Geant4 mathematical phantom with internal organ distribution and skeletal system. (b) Phantom with positioning of protection elements around the torso. (c) Phantom wearing protection elements in the Al module. (d) Example of proton events generated isotropically from a spherical surface source around the Al module.

pressurized space habitat with average wall thickness of 1.5, 5 and 10 cm Al (Fig. 2c) (also with different phantom orientations), and the habitat is immersed in an isotropic radiation environment of solar protons (Fig. 2d) with an energy distribution given by the ESP model (Xapsos et al., 1999,2000). For a more realistic description of protection elements, a 2.5 mm layer of polyurethane (PU) has been added as containing layer of water elements. As a function of increasing habitat thickness, a decreasing but always significant garment effectiveness in terms of BFO dose reduction (from 42% to 31%) is achieved when the phantom is protected by water-filled elements (as well as, obviously, decreasing absolute dose values). More details can be found in the Material and Methods section of this work. These results served as preliminary validation of the shielding strategy potentially offered by the PERSEO demonstrator. They are not of general validity, and they depend on several specific factors, as later detailed in the Discussion section.

2.2. Prototype design and planning of the on-board session: preliminary considerations

The PERSEO technological demonstrator had to be realized in compliance with: (i) guidelines for approval by medical boards for use by a human subject during the experimental session on board the ISS; (ii) safety requirements for use on board the ISS, as established by NASA; (iii) given limitations in terms of resources made available to the Italian Space Agency (ASI) in the framework of ASI-NASA agreements, namely payload mass at launch, payload volume in the launch configuration, crew time for operations on board. For the success of the experiment, we established minimum requirements in terms of the garment design and the session execution: (i) the prototype had to offer sufficient protection against solar protons in the space habitat, *e.g.* a desired water thickness on most radiosensitive organs had to be reached, as established by radiation transport simulations with an anthropomorphic phantom; (ii) during the experimental session on board the ISS, the garment had to be filled with on-board water; (iii) the garment had to be worn by the astronaut for a given time frame, while performing simple activities; (iv) water had to be drained back in the on-board water recovery system, without water waste; (v) the astronaut's opinion concerning the practicality and ease to use of the system and the garment wearability had to be collected.

The main safety hazard identified related to the execution of the experiment was the leakage of water. Possible hazard causes were identified as: (i) improper design, workmanship and assembly, including material selection; (ii) inability to withstand mission loads, as crew-induced loads during use; (iii) overfill during the filling with on-board water. For all hazard causes, appropriate controls with verification methods needed to be put in place during the development of the prototype and for the testing of the manufactured models.

As the hazard category associated to the use of water on board the ISS varies with the water amount, the decision was taken to distribute water in different detachable bags embedded in a sleeveless garment. A design with four bags was agreed upon, two protecting the astronaut's front and two protecting his/her back. This design solution was also optimal in terms of mobility, leaving the astronaut's torso free to bend at the belly height, as in the posture typically assumed under microgravity conditions. Bags were designed to be all interconnected by internal circuitry, but equipped with valves: this solution allowed at the same time: (i) to minimize crew operations, as only one bag needs to be interfaced with on-board water dispenser (and draining) systems and then distribute water to the remaining bags; (ii) to isolate the amount of water in each bag, thus mitigating the risk of a massive water leakage and keeping the hazard category lower. For the bag dimensions: (i) the bag thickness was set based on preliminary calculations of dose reduction, as discussed before; (ii) the bag lateral dimensions were tailored to anthropometric measurements of the subject selected to carry on the experiment, to cover the largest portion of the torso surface and offer protection to radiosensitive organs.

To prevent leakage, both while filling and because of rupture when filled, bags needed to be manufactured and tested to resist the maximum pressure at the filling interface and possible crew-induced loads, with the application of appropriate safety margins. On-board systems available for filling and draining of the garment were identified by NASA. For the filling, we were required to use a specific port of the Potable Water Dispenser (PWD, Aux Port), delivering iodinated water. Material compatibility with iodinated water needed to be verified too. To prevent overfilling, telemetry was suggested: from the selected dispenser port, the garment can be filled with a pre-set water quantity, and the dispenser can be isolated via ground controls when such target quantity is reached. For the draining, we were required to use a fluid transfer pump system conveying water into the Water Processor Assembly (WPA) Waste Water Tank (WWT). We further needed to be compliant with cleanliness requirements established by NASA, to avoid possible back-contamination of the water reservoir through the filling interface, as the release into the water of particles that cannot be later eliminated by on-board Water Recovery System (WRS). No concern for microbial growth exists instead, as the water is finally drained into the waste water tank.

Materials were selected based on criteria of compatibility with the space habitat, and lighter materials were to be preferred, both for ease of manufacturing and to stay within given limits on the payload mass at launch. A further requirement was given on the payload volume in the launch configuration: the overall volume needed again to be within given limits, but also to fit to one of few options on standard shapes for commonly adopted cargo transport bags. A folding solution for the garment was proposed to be compliant with these requirements.

Finally, the documentation produced to obtain the approval from medical boards included a consent form that needed to be signed by the subject. The subject was informed that assessing the potential discomforts felt while wearing the PERSEO garment was the main objective of the wearability test on board the ISS, and feedbacks in this sense were to be collected via a dedicated multiple-choice questionnaire. Possible risks identified for the subject while wearing the water filled garment included:

(i) the increase of the astronaut's inertial mass, which requires the astronaut to learn how to regulate his/her movements in microgravity conditions. A sufficient time had to be established for the wearability test, so that the subject becomes aware of the increased mass and learns how to move, as *e.g.* decelerate. No exercise or strenuous activity, neither activities that require agility have to be performed while wearing the garment;

(ii) a possible slight cold/warm perception (even though the astronaut's body is not in direct contact with the garment). On-board water is at a lower temperature with respect to the astronaut's body temperature, so the astronaut might experience a feeling of cold. Later during the test, on the contrary, a slight overheating might be possible, in that the astronaut will be carrying the additional mass of the water wrapped on his body.

As a further risk mitigation method, the garment needed to be manufactured in such a way that, in the improbable case any discomfort becoming unbearable, the astronaut can quickly get rid of it.

2.3. The garment prototype: manufacturing and ground verification tests

The PERSEO demonstrator is a sleeveless garment with four embedded water bags. The dimensions of the garment and of the bags were tailored to anthropometric measurements of the subject selected to carry on the experimental session. The thickness of the four bags was fixed to 7 cm. The four bags are as follows:

1. a *collector bag*, protecting the astronaut's lower back with a surface of a 37×37 cm^2, with 4 pipes interfaced with it. Water is flowing into the collector bag from the on-board dispenser and then is distributed to the each of the other bags through three pipes. Water allowance for the *collector bag* is 7.5 l;
2. one *back bag*, protecting the astronaut's upper back, with a single pipe connecting it to the *collector bag*. The *back bag* is identical to the *collector bag*, exception made for connections;
3. two identical *front bags*, protecting the astronaut's abdomen and chest with a surface of 25×25 cm^2, each connected with the *collector bag* through a single pipe. Water allowance for each of the *front bags* is 3.9 l.

The lengths of the pipes have been set to allow the bags to be placed at the chosen positions around the astronaut's torso, by appropriate rotation of the *front bags* when donning the garment. Valves have been inserted at each bag's inlet/outlet, resulting in two valves per pipe on all pipes going from the *collector bag* to the *back bag* and to the *front bags*. A single valve has been inserted on the pipe going from the *collector bag* to on-board water dispenser and transfer pump, before the 3/8-inch male quick disconnect (QD) connector indicated and provided by NASA as suitable interface for the filling and draining. We selected commercially available polypropylene (PP) valves, highly chemical resistant and suitable for vacuum operations (bags are vacuumed in the launch configuration) and linear low-density polyethylene (LLDPE) 3/8-inch pipes.

The bags were manufactured in Coretech® (Saint-Gobain). As a safety requirement to prevent water leakage, they needed to be designed to resist a differential pressure of 24 psig (1.6 atm differential pressure) at the filling interface without leakage or rupture. To this aim, they were designed with an internal reinforcement system, with additional Corethech® layers, and a high-frequency welding procedure has been adopted for the manufacturing. In Fig. 3a we show a drawing of a bag with single inlet/outlet positioning. Before manufacturing, structural analysis with LS-DYNA (LS-DYNA, 2017) has been carried out to predict the bag response to the application of a range of differential pressure values, up to the maximal value. As an example of LS-DYNA results, we show in Fig. 3b the heat-map of the material Von Mises stress (in Pa) following the application of a differential pressure of 24 psig to a single bag model. The maximal predicted stress for the bag material is of about 9 MPa, below the reference allowable limit of 30 MPa given for Coretech®. Two bag qualification models with the same dimensions of the *collector/back* bags were realized and tested before manufacturing bags to be embedded in the garment, both with a single inlet/outlet connection. Garment bags were then manufactured and tested once integrated in the final configuration. The test campaign demonstrated that single qualification bags and the whole system (four integrated bags with circuitry as in the garment) are able to resist high differential pressure at the filling interface without leakage or rupture. The system was successfully tested for endurance to vacuum after the application of the differential pressure. Interested readers are referred to the Material and Methods for technical details on test procedures.

The dispenser system indicated for use by NASA delivers iodinated water. Tests were therefore necessary to verify the compatibility of Coretech® with iodinated water: simplified immersion tests were carried out, and material samples were exposed to water with a nominal Iodine concentration of 6 mg/l, for either 10 or 30 days. It was observed that Coretech® is responsible for quick total Iodine absorption: residual Iodine concentration was not quantifiable after ten days for water with sample in immersion, while a ~50% reduction with respect to initial concentration was measured for water with no sample at the same timepoint. No release of hazardous substances of any kind (both volatile organic compounds and polycyclic aromatic hydrocarbons, for all parameters subject to water primary drinking regulations) was measured at any of the time-points. A tensile test before and after immersion was also carried out, at the same two time-points, to verify if Iodine absorption has an impact on the material resistance to stresses leading to breakage. Samples with welded joints of different sizes were used: to manufacture the bags, we then used welded joints of the size for which no difference in the break strength was observed, when comparing samples that were immersed iodinated water to reference dry ones. Concerning cleanliness requirements on the system before filling, bags in the integrated configuration underwent a series of soaking and rinsing steps, finally verifying compliance on particulate counts in size-classes and the absence of non-volatile residue. For the interested reader, technical details on material compatibility with iodinated water and cleanliness requirements are given in the Material and Methods

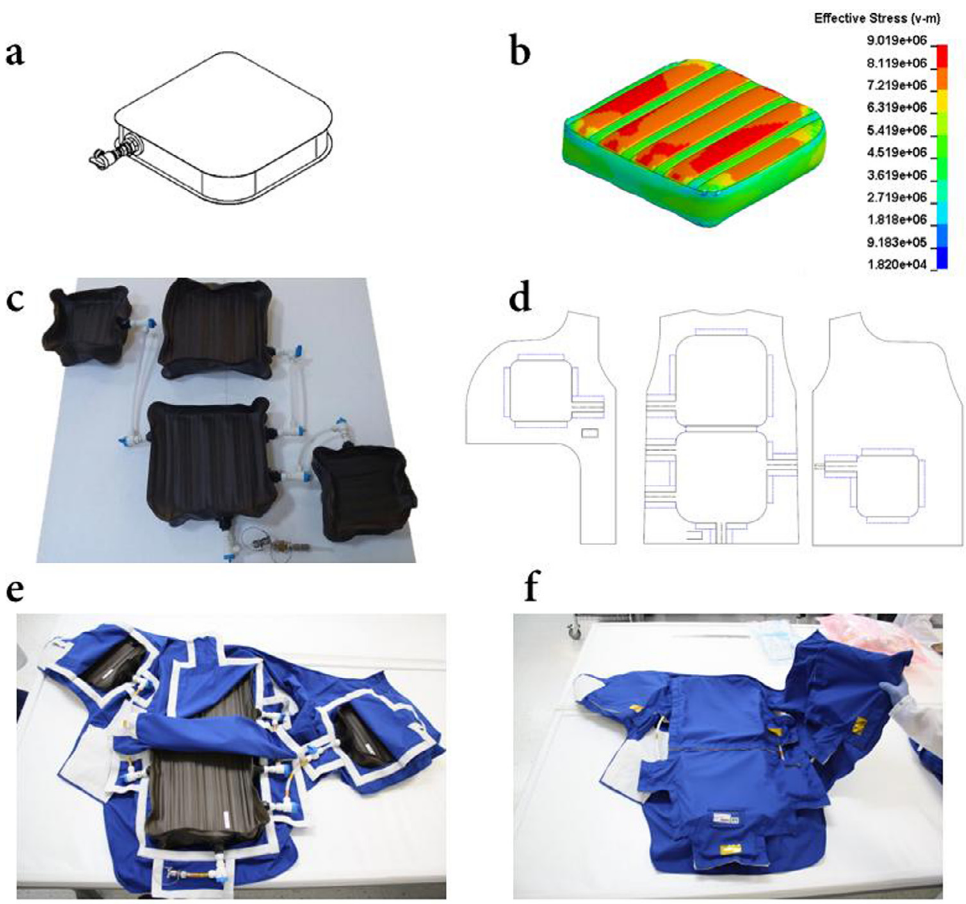

Fig. 3. Development of the PERSEO garment prototype. (a) Technical drawing of one of the Coretech® bags (*back bag*) embedded in the PERSEO garment, isometric view. (b) Results of LS-DYNA calculations for the application of a differential pressure of 24 psig to a single bag model, Von Mises material stress in Pa in color scale. (c) Interconnected Coretech® water bags with circuitry, vacuum condition and all valves closed (pipes, valves and QD connector are visible). (d) Technical drawing of the Nomex® garment, with pouches for the bags. (e) View of the inner side of the garment, open velcro flaps showing water bags. (f) View of the inner side of the garment, closed pouches, labeling visible. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

section.

In Fig. 3c the four garment bags are shown in the integrated configuration with complete circuitry, including the QD connector to interface with ISS systems: the whole system is vacuumed, and interconnecting valves are closed. A Nomex® sleeveless garment was designed, tailored to the subject anthropometric measurements and with pouches to accommodate bags with their valves and interconnecting pipes. A technical drawing of the garment is shown in Fig. 3d. Nomex® was selected as a space-qualified flame-resistant material, fabric with an areal thickness of 190 g/m^2 was used. All pouches can be opened via Velcro flaps to allow for operations with the QD connector and opening/closing the valves, and for visual inspection once the bags with circuitry are embedded in the garment, as it is shown in Fig. 3e. In Fig. 3f, the garment is shown with embedded vacuumed bags and circuitry, and all flaps are closed, as in the launch configuration.

Fig. 4a and b shows the flight model of the PERSEO garment worn during the pre-flight inspection at Johnson Space Center (JSC), Houston. To meet the requirements of regular standard shapes for payloads at launch, the garment with embedded bags was designed to be folded as shown in Fig. 4c and stowed in a Nomex® transport bag with easy Velcro opening, manufactured on purpose (Fig. 4d). The overall volume of the payload in the final configuration (garment folded in the bag) is ∼ 75 l, with dimensions of 60 × 50 × 25 cm. The final mass of the garment, with embedded vacuumed bags, circuitry and QD connector is ∼ 4 kg.

2.4. The planning of the experimental session on board the ISS

The experimental session on board the ISS was planned in three consecutive phases, referred to hereafter as *filling, wearability test* and *draining*. Operations were planned to be video-recorded. Crew procedures were issued by NASA, prepared with the support of the team of developers, containing detailed instructions on all steps of the experimental session. A summary in layman's terms of operations to be executed by the astronaut in each phase is given below:

- *filling*
  - retrieve the transport bag and unfold the garment;
  - inspect the payload, checking in particular that all garment bags are still vacuumed;
  - open all interconnecting valves and connect the garment to the PWD Auxiliary port for filling;
  - start the fill and fill the garment with 22 l of water. The amount of water is set to be below the maximal water allowance of the garment (22.8 l), and the transfer is monitored via telemetry so that the flow is stopped when the target quantity is reached. During the filling (with a nominal flow of 0.8 l/min from the PWD Aux port), the crew monitors the filling with regular checks. The duration of the filling is ultimately depending on PWD conditions at the beginning of the session;
  - disconnect the garment after filling is complete, and close all valves, so that no water flow among bags is allowed;
  - inspect for any possible leak, and get ready for the wearability test;
- *wearability test*
  - don the garment;
  - the garment is worn filled for about 30 min: during this time, the astronaut performs nominal tasks, first learning to move around with the increased inertial mass, takes pictures and is asked to fill a questionnaire with feedbacks on the comfort of the garment;
  - doff the garment and get ready for the draining;
- *draining*

Fig. 4. PERSEO garment prototype inspection and configuration for launch. (a,b) Garment worn during pre-flight inspections at Johnson Space Center (JSC) – Houston, USA, before launch, front and lateral view. (c) Garment folded in the transport bag for the launch configuration. (d) Closed transport bag containing the garment.

- connect the garment to the WPA Waste Water Tank (WWT) and start the transfer pump;
- monitor the transfer (nominal flow of 0.56 l/min) with regular checks until bags are empty;
- disconnect the garment from the pump;
- dry wet connectors, if any, fold the garment and stow it back into the transport bag;
- complete the questionnaire for the overall evaluation of the session, including the draining.

2.5. The execution of the experimental session on board the ISS

On August 14, 2017, the PERSEO payload (*ad-hoc* manufactured transport bag containing the PERSEO garment) was successfully launched with the Dragon spacecraft within SpaceX twelfth commercial resupply services mission, from NASA Kennedy Space Center, Florida. Dragon was captured and successfully docked to the ISS two days later, on August 16.

The PERSEO session on board the ISS was scheduled and took place on November 7, 2017. The astronaut carried out on-board operations as planned, with no deviation from the procedures, and the scientific objectives of the experimental session have been fully achieved. Operations were followed real-time both from NASA mission control center and from the Italian team of developers. An overall description and evaluation of the session outcome is reported hereafter, also based on analysis of picture and video recording and on the feedback collected from the astronaut in the dedicated questionnaire.

Unfolding/folding of the garment, filling/draining operations and donning/doffing the garment have been judged extremely easy to perform. The filling time, depending on initial PWD pressure conditions, was of about 20 min. The garment was filled with a water amount in the range 20.7 – 21.5 l. The garment was worn for about 30 min. The draining time was of about 40 min. As far as the wearability test is concerned, volume and mass of the garment have been reported as only slightly limiting the freedom of movement, with a moderate influence on daily operations. According to the astronaut's feedback, more complex intra-vehicular operations would still be possible while wearing the garment, though with some difficulty. The garment itself was judged as very comfortable, the only discomfort being a feeling of cold, due to the temperature gradient between water in the bags and body temperature. Though the slightly lower water quantity with respect to target 22 l, no water movement inside the bags while wearing the garment has been reported. Finally, the garment has been judged as suitable to be worn also for longer periods, up to a maximum of one day.

In Fig. 5 we report a series of pictures taken during the experimental session: the garment is being filled in Fig. 5a, and the astronaut is wearing the garment and testing its comfort moving around in the ISS in Fig. 5b–d.

3. Discussion

Strategies complementary to habitat shielding need to be explored in view of future space exploration missions. Personal shielding with available resources as on-board water offers promising perspectives, both in terms of shielding performance, and in terms of optimization. Water-filled suits, selectively protecting astronauts' more radiosensitive organs as BFO, could allow crew members to quickly protect themselves in emergency scenarios during solar events. It is also interesting to notice that a water-filled garment may serve also as radiation protection tool from the Earth's radiation belt (ERB) protons in low Earth orbits, due to some similarity of the ERB proton spectra and that of solar

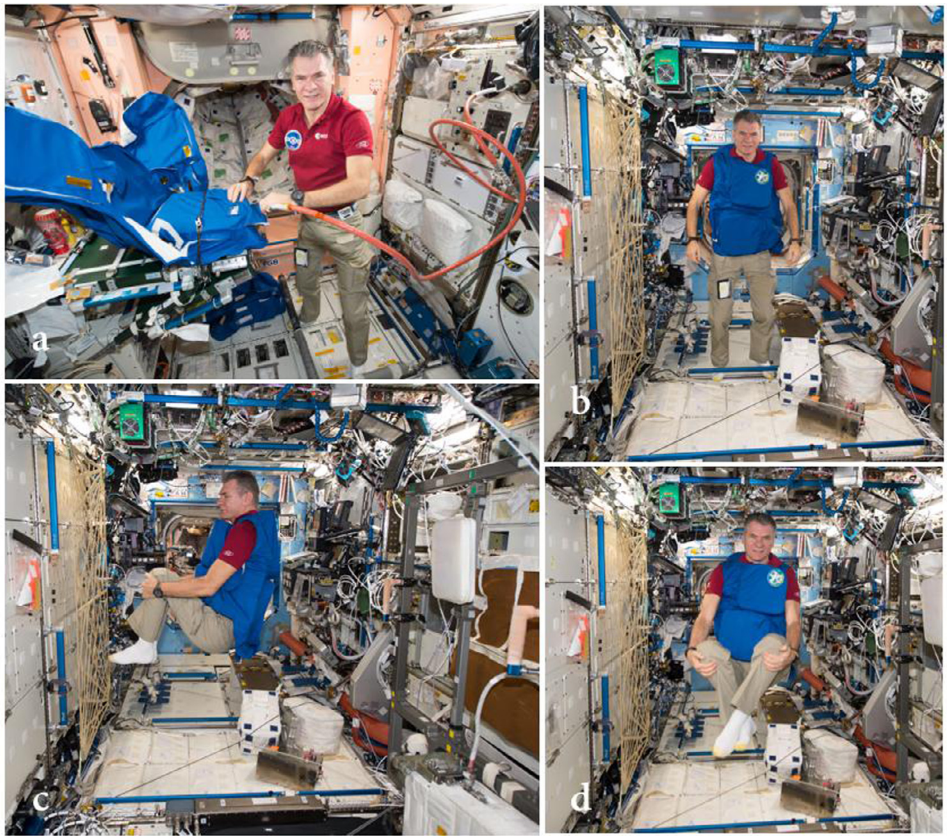

Fig. 5. Pictures of the experimental session on board the ISS. (a) Garment filling from PWD Aux port. (b– d) Wearability phase with test of comfort while the astronaut is moving in the habitat.

energetic protons. Emergency scenarios of SPE occurrence with astronauts obliged to operate in low-shielded conditions need to be considered for the correct evaluation of the risks associated to future deep-space journeys, as the one to Mars, both for long-term health effects, as quantified by the REID, or for the onset of short-term effects, in case exposure levels become higher than tissue/organ-dependent thresholds that still need to be established in future regulations for interplanetary missions.

The PERSEO garment we designed and manufactured is the first prototype of a personal shielding device of this kind to be successfully tested on board the ISS, in terms of: (i) practicality of filling the device with on-board water; (ii) comfort while wearing the garment in microgravity conditions; and (iii) practicality of draining back the water to re-insert it in the on-board water recovery cycle with no resource waste.

Preliminary 3D radiation transport calculations with GRAS/Geant-4, with a geometrical anthropomorphic phantom wearing a simplified version of the PERSEO garment in a low-shielded habitat immersed in an average SPE radiation environment, showed that a significant reduction (42 ± 3%) of the dose to BFO (measured in Gy-Eq) can be achieved thanks to this device. This result is only indicative and depends on many factors, as the chosen simplified phantom and definition of BFO, the average energy distribution considered for solar protons and the simplified definition of the space habitat. Together with results presented in our previous work (Vuolo and Baiocco, 2017), it is however intended to give a quantitative evaluation of a baseline BFO shielding effectiveness for a device of this kind (to be interpreted as an upper bound limit for the lowest considered shielding of 1.5 Al) and offers a preliminary validation of the proposed shielding strategy, still requiring a follow-up study with further analysis, *e.g.* with realistic SPE spectra (including the time evolution of the event), phantom and description of the impact of habitat shielding.

Concerning all other tissues and organs subject to short-term non-cancer effects, while the circulatory system (heart and adjacent arteries) and gastrointestinal tract also benefit from the protection offered by a similar garment, the skin is only partially protected and nearly all of the CNS and eye lenses exposure are not attenuated by the proposed personal shielding. Still, the approach of optimization based on dose reduction to BFO appears justified at this stage of development of the proposed personal shielding solution: as previously discussed, the lethality of an acute exposure can be mainly attributed to heavy damages to the hematopoietic system; at least in current standards set by NASA for LEO missions, dose thresholds for the skin, CNS and lenses are set to higher levels than that for BFO (though BFO benefits from higher shielding by body tissues); and, finally, the same approach has recently been included in recommendations to NASA for the design of SPE shelters for missions beyond LEO (Townsend et al., 2018) (though the shielding offered by a shelter is effective for all organs at the same time).

For a refined quantitative evaluation of the shielding effectiveness of the water-filled PERSEO garment, a series of measurements with radiation detectors as ALTEA/LIDAL (Narici et al., 2017; Rizzo et al., 2017) is currently being planned by project partners. Measurements could be planned on board the ISS, to quantify the reduction of dose due to a chosen water thickness related to the space radiation environment, or at accelerator facilities, with *e.g.* proton beams impinging on a human phantom wearing the PERSEO garment filled with water. This latter option would deliver significant information as dose to selected organs also as a function of the beam energy, to benchmark radiation transport calculations and later predicting the garment shielding effectiveness given the characteristics of any chosen SPE spectrum.

The PERSEO garment prototype described in this work was designed following a maximum-simplicity philosophy, and designed and manufactured in compliance with a wide variety of requirements, mainly coming from: (i) human factors for the involvement of a human subject; (ii) safety aspects for the use on board the ISS; and (iii) limitations in available resources in terms of mass and volume at launch, and budget constraints. Requirements as those related to the use of the filling and draining systems on board the ISS, as indicated by NASA, remain necessarily specific to this first prototype. As a major example, water containers have been designed to resist high differential pressure at the filling interface to mitigate the hazard of leakage when filling. If it is likely that a similar requirement will hold for future developments of any water-fillable radiation shielding garment, the specific maximum pressure value (24 psig) was derived from the operational design pressure of the ISS potable water dispenser indicated by NASA for the filling (after application of safety margins). Such a high value for the maximum pressure led to low-flexibility containers with regular shapes, which is necessarily impacting on the wearability of the garment. For future developments, technical solutions with flexible containers with more ergonomic shapes must be envisaged (including design accommodation for female astronauts), also given different technical characteristics for the filling interface. The shaping of water elements on the astronaut's body would lead to a certain gain in garment fitting and wearability, also preventing the displacement of protection elements on the torso that was sometimes observed during the test. The aspect of thermic isolation for water-filled elements must also be addressed, to avoid the minor discomfort experienced by the astronaut. The duration of the filling session was also dictated by water flow from the PWD: it is understood that a duration of the order of 20 min is not optimal in the scenario of an emergency use of the garment, though still in compliance with the recently formulated recommendation to NASA of a time interval shorter than 30 min from the SPE onset for the assembly of a protection system (Townsend et al., 2018). A different filling interface able to offer higher water flow should be considered for future developments, possibly with simultaneous fast filling of multiple garments. Another interesting perspective would be to ensure that long-term storage of potable water in newly developed radiation protection garments would not alter water quality. Technical solutions for innovative flexible materials to be used in space and able to maintain water potable are currently under development by project partners (Patent pending, 2018). Covering internal wetted surfaces of the garment with materials of this kind would deliver a multi-functional device, to be used both as radiation shielding garment and water storage device, and always ready to use in case of emergency during a SPE. Finally, always for future developments, the garment design should be complemented with increased skin protection and dedicated protection elements for head and eyes (as for instance with polymeric helmets and glasses), to prevent the onset of other possible in-flight detrimental health effects.

Concluding, all scientific objectives of the test of the prototype on board the ISS on November 7, 2017, have been fully achieved. The feedback of the astronaut, collected through the questionnaire, together with picture and video recording of the session, demonstrated that the impact of wearing a water-filled radiation shielding garment on freedom of movement to perform simple intra-vehicular operations is limited. The quality of design and manufacturing led to a first garment prototype that was judged as very comfortable to be worn, still with clear room for improvements. The possibility to use a device of this kind for personal radiation shielding during a time period ranging from a fraction of hour to a full day was demonstrated. Related to chosen filling/draining interfaces, the feasibility of filling a radiation shielding garment with on-board water and later drain it with no water waste has been verified.

The successful outcome of the PERSEO project represents an important breakthrough in the field of radiation shielding in space. The design, manufacturing and test of the first prototype of a water-filled garment on board the ISS offers in perspective a validation of a personal radiation shielding strategy, complementary to habitat shielding and to other possible innovative countermeasures to be developed, to ensure the safety of the crew for future human exploration of deep space.

4. Methods

4.1. 3D calculations of radiation transport with an anthropomorphic phantom

The approach followed for the preliminary validation of the shielding performance of the water-filled garment with Monte Carlo radiation transport simulations is the same as in our previous work (Vuolo and Baiocco, 2017). The energy spectrum used for the SPE environment was obtained using the ESP (Emission of Solar Protons) model on the ESA SPENVIS (SPace ENVironment Information System) website (SPENVIS, 2017), with a 90% confidence level for a 1 year mission without considering the Earth magnetic shielding (deep space exposure). Simulations were performed using GRASv3.3 (Santin et al., 2005) tool based on Geant v.4.9.6.p03 (Agostinelli et al., 2003), using the QBBC physics list (Ivantchenko et al., 2012). The simulation setup was built using GDML (Geometry Description Markup Language) (Chytracek et al., 2006). A simplified software reproduction of the garment bags has been implemented, with realistic material properties as chemical composition and density. The thickness was set to 7 cm for water elements, plus a 2.5 mm layer of polyurethane (PU) added as containing layer. Bags were positioned around the torso of the geometrical phantom available in GRAS. Lateral dimensions of the bags were scaled with respect to real dimensions for the garment prototype to be adapted to the phantom size. The phantom, with and without the protecting elements, has been positioned at the center of an Al module (2.25 m radius, 6 m length) intended to reproduce a simplified space habitat. Increasing average thickness values have been tested for the module walls: 1.5; 5 cm and 10 cm, specifically equal to the thickness of the lateral cylindrical surface (with thinner conical surfaces and thicker caps), to reproduce different shielding conditions starting from a very-low-shielding scenario. For a first evaluation on how the variation of the shielding thickness influences the dose reduction to sensitive organs, two different positions have been considered for the phantom inside the module: the phantom has been placed with the cranio-caudal axis parallel to the module axis, or rotated by 90°. The module was then immersed in an isotropic radiation environment generated by a spherical surface source emitting protons with the chosen energy spectrum. For both conditions (phantom with and without the garment) we calculated the dose in Gy-Eq delivered to phantom organs, including Blood Forming Organs (BFO). The dose in Gy-Eq is obtained from the physical dose in Gy multiplied by a RBE factor, established equal to 1.5 for non-cancer effects induced by protons (NASA, 2018) (thus with the underlying assumption that dose to target organs is mainly delivered by protons impinging on the astronaut's body). As no strict definition of BFO is possible with the geometrical phantom available in GRAS, the dose to BFO is obtained with a weighted sum of doses to bone structures present in the phantom, taking account of the proportion of red bone marrow (RBM) (actively producing blood cells) in different bones. RBM weights have been derived from ICRP (International Commission on Radiological Protection), Publication 110 (ICRP, 2009). The expression for the physical dose to BFO with RBM weights reads:

$$Dose_{\ BFO-rbm} = \frac{\sum rbm_{\rm i}\, D_{\rm i}}{\sum rbm_i} \tag{1}$$

where D_i is the dose to the i-th bone in Gy, the summation takes place over bone structures in the phantom (upper and lower spine; cage; pelvis; right and left leg/arm bones, scapulae and clavicles) and rbm_i weights are given in Table 1, together with RBM to bone mass ratio. As the phantom has a simplified skeletal system, different bones listed in ICRP 110 are grouped in corresponding phantom bone structures for the derivation of RBM weights: phantom lower spine includes thoracic

Table 1
Bone components in the GRAS anthropomorphic phantom and red bone marrow content. For each bone structure the red bone marrow mass rbm_i in kg is reported, together with the corresponding ratio (%) to the total $mass_i$ of the bone. rbm_i values are used in Eq. (1) for calculation of dose to the BFO and derived from ICRP 110[22].

Bone	rbm_i [kg]	rbm_i / $mass_i$ [%]
Upper spine	0.05	25.8
Lower spine	0.36	32.2
Pelvis	0.17	19.0
Leg bone (left/right)	0.01	0.3
Arm bone (left/right)	0.03	2.6
Scapula (left/right)	0.01	4.0
Clavicle (left/right)	0.00	4.7
Cage	0.21	23.6

and lumbar spine and sacrum in ICRP 110; phantom leg and arm bones are taking into account femora/humeri upper halves only, with relative weight from ICRP 110; phantom cage includes ribs and sternum in ICRP 110. After calculation of $Dose_{\ BFO-rbm}$ for the phantom in the module with and without the garment, the final indicator of the shielding performance in terms of dose reduction is given as:

$$Dose\ Red^{\ \%} = 100 \cdot \frac{Dose_{\text{Phantom in module}} - Dose_{\text{ Phantom with garment in module}}}{Dose_{\text{Phantom in module}}} \tag{2}$$

For the simplified garment geometry implemented in this work, we obtained dose reduction values to BFO of (42 ± 3%) for the lowest-shielded condition (1.5 cm Al module), (34 ± 3%) and (31 ± 3%) for the higher habitat shielding (respectively, 5 and 10 cm Al module) when the phantom axis is parallel to the module axis. For the test position with the phantom rotated by 90°, dose reduction values differ at maximum by a few percent, with a variation that tends to decrease with increasing thickness, finally within error bars for the thickest-shielding cases. Statistical uncertainties on dose reduction values are obtained from propagation of uncertainties in primary dose quantities, and dictated by the statistics for incoming protons (up to several millions in 3D calculations). By construction, dose reduction results are independent on the specific fluence of the SPE event. As done in our previous work (Vuolo and Baiocco, 2017), a worst-hour model (OMERE, 2017) can be applied to obtain information on dose rate magnitude and corresponding dose rate reduction when the suit is worn. In our calculations, applying the same normalization as in our previous work (Vuolo and Baiocco, 2017), leading to a solar proton yield (integrated over the whole energy range) of 1.3 $10^{11}/cm^2/h$ for the worst-hour condition, dose-rate values to BFO are of 0.099, 0.035 and 0.014 Gy-Eq/h for the naked phantom in Al modules of thickness 1.5, 5 and 10 cm. If the 250 mGy-Eq limit to BFO is taken as a reference, and a constant dose rate equal to the worst-hour condition in the low-shielded scenario is assumed for the event, the dose limit would be reached in ∼2.5 h if the astronaut is not wearing any protection garment, or, considering the 42% dose reduction offered by the garment, in almost double of this time if the astronaut is wearing it. However, considerations of this kind are only intended to provide an indicative upper bound effectiveness for the PERSEO garment, as they are based on several simplifying assumptions (see the Discussion section).

4.2. Ground-tests of the garment bags for resistance to differential pressure

ARESCOMSO S.p.A. developed two single Coretech® (Saint-Gobain) bag qualification models and two identical models of the integrated system (4 interconnected Coretech® bags with circuitry): the engineering qualification model (EQM) and the flight model (FM), to be further integrated into the EQM and FM model of the PERSEO garment. To meet the requirement on resistance to high differential pressure (24 psig), preliminary simulations with LS-DYNA (LS-DYNA, 2017) have been carried out. A technical solution with an internal reinforcement system, always in Coretech®, has been proposed, and a high frequency welding procedures for Coretech® layers, with the size of welded joints set on the basis of break strength measurements after material immersion test in iodinated water (see later). For the EQM and FM, bags are interconnected through pipes, with low linear density polyethylene (LLDPE) hose 3/8-inch, polypropylene (PP) adaptors and speedfit valves and delrin tank adaptors designed and realized ad hoc. LLDPE and PP products are specifically designed for potable water high quality fluid systems. Water allowance for the integrated EQM and FM model is of 22.8 l. Ground verification tests of the resistance to differential pressure at the filling interface were conducted at ARESCOSMO S.p.A. premises in Turin, Italy. The EQM has been brought into vacuum and then filled with water until reaching a proof pressure of 16 psig. No leakage has occurred for more than 3 min applying this condition. Water flow has then been restarted and an ultimate pressure of 24 psig has been reached. No leakage has occurred for more than 3 min. As a result of the test, a water volume of 30 l has been inserted into the system, higher than the nominal water allowance of the system, due to the expansion of Coretech® bags. No permanent deformation has been found for the EQM, as well as no material failure, also on the line of high-frequency welding. The EQM has been successfully tested for endurance against vacuum after the stress test. The same test procedure has been followed for the FM, without applying the ultimate pressure. At the proof pressure of 16 psig, the amount of water inserted in the FM system was of 24.6 l. No permanent deformation has been found on the FM, as well as no material failure, also on the line of high-frequency welding. The FM has been successfully tested for endurance against vacuum after the stress test.

4.3. Verification of material compatibility with iodinated water

Tests of Coretech® compatibility with iodinated water have been conducted at SMAT S.p.A. premises in Turin, Italy. Immersion tests of Coretech® samples have been carried out in water with a nominal Iodine concentration of 6 mg/l. Purpose of the tests was to verify: (i) material absorption of Iodine in the aqueous solution and material release of hazardous substances; (ii) material degradation in terms of physical properties, verified with tensile tests before and after sample immersion. Two different exposure scenarios were considered for immersion tests, with duration of 10– 30 days.

For absorption and release tests, the following measurements were done for each sample: I concentration and all parameters related to drinking water regulation for volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs). Results are as follows:

- for the reference sample (no Coretech® immersed), reduction of I concentration with respect to initial concentration was of 54% after 10 days, and 64% after 30 days. In case of Coretech® immersion, no residual I concentration could be measured already after 10 days, indicating a quick I absorption from the material;
- for VOHs and PAHs, no release of hazardous substances was measured at any time.

For tensile tests, immersion tests of different groups of (20 × 2.5) cm^2 sample strips were carried out: samples without welded joints; samples done by two strips with welded joints of different increasing size. A statistical analysis (two-tailed *t*-test with significance level $\alpha = 0.05$) was carried out to evaluate the significance of measured differences in break strength before and after the immersion. For samples without welded joints, the break strength is affected by immersion in iodinated water at any time points, and all differences are significant. The size of welded joints used for manufacturing the bags was chosen as the one for which the break strength is not significantly affected by immersion in iodinated water, for all time-points.

4.4. Verification of cleanliness for wetted surfaces

Tests of the cleanliness level have been conducted at TAS-I and SMAT S.p.A. premises, Turin, Italy. Wet surfaces of the integrated system (water bags and circuitry) underwent a series of soaking and rinsing steps with high purity water, and were finally disinfected with solutions of Sodium Hypochlorite. Water rinse samples were analyzed for non-volatile residue (NVR) and particulate count. NVR was not determinable (class A). Particles were classified in size bins in µm. Particle counts per 0.1 m^2 were very low for all size bins, with only a particle per 0.1 m^2 with size greater than 200 µm (class 200). Final cleanliness level was 200A according to IEST-STD-CC1246D (IEST-STD-CC1246E, 2017) standard.

The authors declare no competing financial interest.

NASA Institutional Review Board (IRB), ESA Medical Board and the Ethical Committee for research conducted by the University of Pavia (Comitato Etico Area di Pavia, Fondazione I.R.C.C.S. Policlinico San Matteo) approved the experimental session of the project to be carried on by the selected human subject. All research was performed in accordance with relevant guidelines/regulations. Informed consent was obtained from the participant, consent for the use of identifying images was also obtained.

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