Modelling human exposure to space radiation with different shielding: the FLUKA code coupled with anthropomorphic phantoms

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Abstract. Astronauts’ exposure to the various components of the space radiation field is of great concern for long-term missions, especially for those in deep space such as a possible travel to Mars. Simulations based on radiation transport/interaction codes coupled with anthropomorphic model phantoms can be of great help in view of risk evaluation and shielding optimisation, which is therefore a crucial issue. The FLUKA Monte Carlo code can be coupled with two types of anthropomorphic phantom (a mathematical model and a "voxel" model) to calculate organ-averaged absorbed dose, dose equivalent and "biological" dose under different shielding conditions. Herein the "biological dose" is represented by the average number of "Complex Lesions" (CLs) per cell in a given organ. CLs are clustered DNA breaks previously calculated by means of event-by-event track structure simulations at the nm level and integrated on-line into FLUKA, which adopts a condensed-history approach; such lesions have been shown to play a fundamental role in chromosome aberration induction, which in turn can be correlated with carcinogenesis. Examples of calculation results will be presented relative to Galactic Cosmic Rays, as well as to the August 1972 Solar Particle Event. The contributions from primary ions and secondary particles will be shown separately, thus allowing quantification of the role played by nuclear reactions occurring in the shield and in the human body itself. As expected, the SPE doses decrease dramatically with increasing the Al shielding thickness; nuclear reaction products, essentially due to target fragmentation, are of minor importance. A 10 g/cm\textsuperscript{2} Al shelter resulted to be sufficient to respect the 30-day limits for deterministic effects recommended for missions in Low Earth Orbit. In contrast with the results obtained for SPEs, the calculated GCR doses are almost independent of the Al shield thickness, and the GCR doses to internal organs are not significantly lower than the skin doses. Furthermore, nuclear interactions play a much larger role for GCR than for SPE doses.

1. Introduction
At least two astronauts are always present onboard the International Space Station (ISS), which orbits at about 400 km above the Earth surface with 51.6° inclination. Furthermore, it is in NASA’s plans to go back to the Moon and to send a manned mission to Mars within the first half of our century. After the beginning of space human exploration, it was soon recognized that space radiation can represent a serious hazard for the crew members. Indeed space radiation can induce both stochastic effects, for which there is essentially no threshold dose and the induction probability increases with dose, and deterministic effects, which are characterized by effect-specific thresholds and become more and more severe with increasing doses. The most important stochastic effect is cancer, which can show latency periods of more than 10 years; also exposure of the Central Nervous System (CNS) might lead to serious effects, although less is known on the radiation effects to CNS with respect to radiation-induced carcinogenesis. Typical examples of deterministic effects are skin burns and cataracts, although recent studies on cataract incidence among astronauts suggest that the threshold for this effect might be lower than expected, or there might be no threshold at all.

Astronauts are therefore classified as radiation workers, and limits have been established by the American National Council on Radiation Protection (NCRP) for missions in Low-Earth Orbit (LEO), i.e. within the protection of the geomagnetic field [1]. Concerning missions in deep space, no limits have been established yet due to the still poor knowledge of the action of heavy ions; LEO limits should be taken as guidelines. In Table 1 we report the 10-years career stochastic limits, which are age- and gender-specific, recommended by NCRP on the basis of a 3% excess lifetime risk of cancer mortality. The limits, expressed in Sieverts (Sv), refer to doses weighted by radiation quality factors and tissue weighting factors. Table 2 reports the recommended limits to prevent deterministic effects to specific tissues or organs at risk (skin, eye lenses and red bone marrow) following LEO missions of different duration. The limits are expressed in Gy-Eq (Gray-Equivalent), i.e. the dose in Gy is multiplied by the radiation Relative Biological Effectiveness (RBE) at inducing a specific (deterministic) effect. Concerning exposure of bone marrow during the entire career, stochastic effects are more important than deterministic effects, therefore stochastic limits apply.

**Table 1 Stochastic limits referring to a 10-year career for LEO missions**

| age at exposure | sex | maximum dose (Sv) |
|----------------|-----|------------------|
| 25             | M   | 0.7              |
|                | F   | 0.4              |
| 35             | M   | 1.0              |
|                | F   | 0.6              |
| 45             | M   | 1.5              |
|                | F   | 0.9              |
| 55             | M   | 3.0              |
|                | F   | 1.7              |

**Table 2 Deterministic limits for LEO missions of different duration**

| Exposure time | Skin (Gy-Eq) | Eye (Gy-Eq) | Bone Marrow (Gy-Eq) |
|---------------|--------------|-------------|---------------------|
| 1 month       | 1.5          | 1.0         | 0.25                |
| 1 year        | 3.0          | 2.0         | 0.50                |
| career        | 6.0          | 4.0         | stochastic limit    |

The exposure to space radiation can pose serious threats to astronauts’ health especially for long-term missions such as those onboard ISS, which often imply staying periods of a few months, or a possible travel to Mars. A trip to the “Red Planet”, at least with the currently available technology, would last about two years, including a permanence of some months on the planet surface waiting for
a favorable trajectory to come back. While the planet itself and its atmosphere would provide a (slight) protection from space radiation, during the travel the crew members would be continuously exposed to Galactic Cosmic Rays originating outside our Solar System, probably following supernovae explosions. The GCR energy spectrum, which shows a peak at 1 GeV/n, consists of energetic protons, Helium ions and heavier ions - including Carbon and Iron - with maximum fluxes of about 4 particles cm$^{-1}$ s$^{-1}$, corresponding to dose rates of more than 1 mSv/day. In terms of flux, protons represent the largest component (87%); He ions contribute for about 12%, whereas the contribution of particles with higher charge and energy ("HZE particles") to the GCR flux is only 1%. However, due to their high charge and thus their high Linear Energy Transfer (LET), the contribution of HZE particles in terms of dose is far larger. The radiation exposure scenario is further complicated by the possible occurrence of one or more Solar Particle Events (SPE), which consists of charged particles - mainly protons - accelerated into the interplanetary space following mass ejections from the Sun corona. The energies of solar particles are relatively low, since the main part of the spectra is below 200 MeV/n. However, intense SPEs can reach fluence values of more than $10^{10}$ particles/cm$^2$ delivered in a few days or even hours, that would imply human body doses of the order of some Gy. In particular the August 1972 event was estimated to be potentially lethal for a human crew on the Moon surface without appropriate shielding [2]. Solar Particle Events are occasional and almost unpredictable, although they are correlated with the number of sunspots. The probability of having an intense SPE is regulated by the Sun activity, which is characterized by periods of minima and maxima on the basis of an 11-year cycle. However, planning a mission at solar minimum might not be a solution, since the SPE probability would be minimum, but the GCR flux would be maximum. Indeed the Sun magnetic field, which shows its highest intensity when the Sun is in a period of maximum activity, partially protects the solar system with respect to cosmic rays. Therefore GCR fluxes are higher at solar minimum than at solar maximum.

Reliable risk estimations and shielding optimization studies are mandatory in the field of manned space missions. However, the quantification of space radiation risk is still affected by large uncertainties, which have been estimated to be a factor between 4 and 6 [3]. A strong source of uncertainty is our poor knowledge of the action of heavy ions, not only in terms of their biological effects but also in terms of nuclear interactions occurring in the spacecraft walls and shielding, which generally consist of Aluminum, and in the human body itself. Such interactions modulate the composition and energy spectrum of the primary radiation fields. In this framework, models and computer codes which simulate ion transport and interaction including projectile and target fragmentation can be of great help. Examples of codes developed by other groups and applied to space radiation related problems are HZETRN [4], SHIELD-HIT [5] and PHITS [6]. While HZETRN is an analytical code, the others adopt a Monte Carlo approach.

In this paper we present examples of space radiation dose calculations carried out with FLUKA, a Monte Carlo code that can deal with transport and interaction of radiation of different types and energies, including nucleus-nucleus interactions down to $\sim$100 MeV/n [7,8]. To allow for dose calculation in the various tissues and organs of the human body, the code has been coupled with two anthropomorphic phantoms, a mathematical and a "voxel" model. Since quantities such as dose and LET are average values, they cannot fully take into account the stochastic features of energy deposition by ionizing radiation. Therefore, besides organ-averaged absorbed dose and dose equivalent (the latter obtained multiplying the dose by the radiation quality factors indicated in the ICRP report no. 60 [9]), we also calculated "biological doses". The quantity that we call "biological dose" is represented by the average number of "Complex Lesions" (CLs) per cell in a given organ or tissue, where Complex Lesions are clustered breaks of the DNA double helix. Their yields per Gy and per cell, which depend on the radiation quality, have been previously calculated by means of "event-by-event" radiation track structure simulations at the nm level [10] and subsequently integrated on-line into FLUKA, which adopts a condensed-history approach. Such lesions have been shown to play an important role in the processes underlying cell killing [11] and chromosome aberration induction [12,13], which in turn can lead to cell conversion to malignancy. In the following sections, we will describe in detail the concept of integration, the features of the phantoms and the irradiation
conditions. Section 4 will be devoted to the presentation of result examples, whereas in the last section we will provide some discussion and comments about possible future developments of this work.

2. The integration concept: from event-by-event to condensed history codes

As mentioned above, the dose is not sufficient to fully characterize the radiation effects in biological targets, especially if one takes into account that the DNA linear dimensions are of the order of the nm \[14\]. Such effects can be well described by the so-called “event-by-event” track structure codes, which simulate each single energy deposition (essentially atomic/molecular excitations and ionizations) at the nm level. Event-by-event codes can be successfully applied up to the cellular level, i.e. at the \( \mu \)m scale. Examples of applications of such codes to the simulation of DNA damage, cell death and chromosome aberrations can be found in refs. [10-13]. However, the "event-by-event" approach cannot be applied to the case of tissues and organs since it would require unacceptable computing time. A possible solution consists of integrating data (either from event-by-event simulations or from radiobiology experiments) into condensed-history codes like FLUKA. To this aim, each energy deposition calculated by FLUKA for a given radiation type and energy has been associated to the corresponding yield of induced “Complex Lesions” (CLs) per cell. For light ions, the average number of \( \text{CL} \cdot \text{Gy}^{-1} \cdot \text{cell}^{-1} \) has been found to increase with the radiation LET up to a maximum in correspondence of about 100 keV/\( \mu \)m \[10\]. Furthermore, protons have shown a higher effectiveness with respect to He ions of the same LET, reflecting the track structure features of these particles: for a fixed LET value, protons have lower velocity, implying that secondary electrons produced by protons have lower energy and therefore higher level of clustering at the nm scale. This makes protons more effective than He ions of the same LET in terms of production of clustered DNA damage.

3. The phantoms: main features, shielding and irradiation

In view of applications in radiation protection, as well as in radiotherapy, FLUKA has been coupled with two anthropomorphic phantoms, i.e. a mathematical model based on combinatorial geometry and a “voxel” model constructed starting from whole-body CT data. The mathematical model is a hermaphroditic phantom derived from "ADAM", a male model originally developed at the GSF Institute in Munich, Germany, and subsequently translated in terms of FLUKA geometry after addition of the female organs and separation between red bone marrow and bone surface \[15\]. The height is 180 cm, the mass 70.65 kg. The second phantom is a voxel model called GOLEM, also developed at GSF \[16\]. GOLEM derives from a whole-body CT examination of a leukemia patient who was a 38-year-old male, 176 cm in height and 68.9 kg in weight. The segmentation process (220 slices, each consisting of 256x256 pixels) resulted in a particularly realistic model of an adult male person described by more than 2.2x10\(^6\) voxels, each voxel being a cube element of 2x2x8 mm\(^3\). Coupling of GOLEM with FLUKA and further separation of bone marrow regions according to the proportion of red and yellow marrow resulted into 287 different FLUKA regions.

Both phantoms can be inserted into a shielding structure of variable shape and dimensions, thickness and material. As in previous studies \[17,18\], an Al cylindrical shell was used to obtain the results presented herein. The values considered for the shell thickness were 1 and 2 g/cm\(^2\) (nominal spacesuit and lightly-shielded spacecraft), 5 g/cm\(^2\) (heavily-shielded spacecraft) and 10 g/cm\(^2\) (storm shelter where the astronauts should take refuge in the case of an intense SPE). In some simulations a 0.3 g/cm\(^2\) thickness (light spacesuit) was considered as well. The space between the shielding box and the phantom was filled with air, and the phantom was irradiated isotropically. As suggested in other works \[19\], the integral proton fluence data of the August 1972 Solar Particle Event were represented by an exponential function of the form \( \Phi = 6.6x10^8 \exp\left[-\left(E-100\right)/30\right] \), where \( \Phi \) is the number of protons-cm\(^{-2}\) with energy > E and E is expressed in MeV. The GCR spectra were taken from the model of Badhwar and O’Neill \[20\], with solar modulation parameters \( \varphi = 465 \text{ MV} \) for solar minimum and \( \varphi = 1440 \text{ MV} \) for solar maximum. All ions with atomic number in the range 1-28 were considered.
4. Representative Results: August 1972 SPE and solar minimum Galactic Cosmic Rays

Table 3 shows the three considered dose types (absorbed dose, dose equivalent and "biological" dose) calculated for skin following exposure to the August 1972 SPE proton spectrum. For each shield thickness, the dose due to secondary particles produced by nuclear reactions is reported in parenthesis.

| Al shield [g/cm²] | Absorbed Dose [Gy] | Dose Equivalent [Sv] | "Biological" Dose [CL/cell] |
|-------------------|---------------------|----------------------|-----------------------------|
| 1                 | 8.2 (0.15)          | 13.3 (0.92)          | 4.83 (0.42)                 |
| 2                 | 4.7 (0.11)          | 7.2 (0.62)           | 2.68 (0.28)                 |
| 5                 | 1.5 (0.05)          | 2.2 (0.27)           | 0.84 (0.12)                 |
| 10                | 0.4 (0.02)          | 0.6 (0.12)           | 0.23 (0.05)                 |

As expected, all dose types decrease dramatically by increasing the shielding. Although the role of nuclear reaction products is not negligible, primary protons play a major role. With respect to skin, larger relative contributions of nuclear reaction products were found for internal organs (e.g. 30% to the liver dose equivalent behind 10 g·cm⁻²). The relative contribution of nuclear reaction products increases with increasing the shield thickness (e.g. from 1.8% to 5% for the absorbed dose, from 6.9% to 20% for the dose equivalent and from 8.7% to 22% for the "biological" dose). This can be explained by the fact that since the primary particles are protons, nuclear interactions mainly consist of target fragmentation, which leads to the production of slow heavy particles with are characterized by high LET and therefore high effectiveness.

The results obtained in terms of "biological dose" (average number of CLs per cell) can be interpreted on the basis of our model of chromosome aberration induction [12,13], which is based on the hypothesis that two CLs in the same cell can give rise to a chromosome aberration if they are induced sufficiently close. According to this model, a yield of 4.8 CL/cell (that is what we found for skin behind 1 g/cm² Al) implies that each exposed cell has about a 0.3 probability to be affected by a translocation, which is an important aberration type because it is correlated with cell conversion to malignancy. However, such considerations need to be taken with some caution since the present version of the model is specific for acute irradiation, whereas the typical duration of a SPE is of the order of some hours or days.

Concerning eye lenses and red bone marrow, which together with skin are the reference organs for radiation protection relatively to deterministic effects, the dose equivalents calculated with the mathematical phantom were 6.89 Sv (eye) and 1.8 Sv (bone marrow) behind 1 g/cm² Al and 0.56 Sv (eye) and 0.25 Sv (bone marrow) for 10 g/cm² Al. Slightly different values (lower for skin and eye, higher for bone marrow) were found with the voxel phantom, mainly due to differences in the organ description (e.g. skin thickness and bone marrow distribution).

Figure 1 shows the daily dose (in mGy/day) following exposure to a GCR solar minimum spectrum (modulation parameter $\phi=465$ MV) calculated with the mathematical phantom for the liver, taken as a representative internal organ, whereas figure 2 shows the quantity shown in figure 1 multiplied by the radiation quality factors indicated by ICRP [9], expressed in mSv/day. Also in this case, for each Al thickness value the contributions from primary ions and nuclear interaction products ("secondary hadrons" in the figures) were calculated separately. In contrast with SPE results, the GCR absorbed dose does not decrease by increasing the Al shielding, due to the high energy of primary ions. At larger shielding thickness one might even expect an increase, as suggested by a pilot study performed with mono energetic 500 MeV protons [17]. While the contribution of the primaries shows a (slight) decrease, the contribution from nuclear reaction products increases with increasing shielding. This trend (i.e. increase in secondaries and decrease in primaries) is emphasized for the dose equivalent. With respect to internal organs, the skin showed similar doses but higher dose equivalents, although the differences were not so dramatic as those found for SPEs. Similarly to what obtained for SPEs, for the skin the relative contribution from nuclear reaction products was smaller than for internal organs, due to nuclear interactions occurring in the human body.
Fig. 1 Liver-averaged daily dose (in mGy/day) following exposure to a solar minimum GCR spectrum behind an Al shield thickness with values in the range 0.3-5 g/cm$^2$.

Fig. 2 Liver-averaged daily dose-equivalent (in mSv/day) following exposure to a solar minimum GCR spectrum behind an Al shield thickness with values in the range 0.3-5 g/cm$^2$; radiation quality factors were taken from the ICRP publication no. 60 [9].

Annual effective doses for GCR exposure at solar minimum were calculated as well, obtaining values of about 0.5 Sv per year. According to these results, a hypothetical 2-years mission in deep space (typical duration of a possible mission to Mars) under solar minimum conditions would allow to respect the NCRP career limits for males who are at least 35-years-old (limit: $\geq 1$ Sv) and females of at least 45 (limit: $\geq 0.9$ Sv) [1]. Again, comparisons with these limits have to be considered with caution due to the differences between the radiation environment in deep space and that within theGeomagnetic field.

5. Discussion and conclusions
Examples of application of the FLUKA code to space radiation protection problems were provided, focusing on the contribution of nuclear interaction products to organ doses. More specifically, organ-averaged dose, dose equivalent and "biological dose" following a hypothetical exposure to the August
1972 Solar Particle Event and to Galactic Cosmic Rays under different shielding conditions were calculated with the FLUKA Monte Carlo code coupled with a mathematical and a voxel phantom.

Concerning Solar Particle Events, as expected the doses showed a dramatic decrease with increasing the Al shielding thickness, and nuclear interaction products (mainly deriving from target fragmentation) were found to play a minor role. According to these calculations, an Al storm shelter of 10 g/cm$^2$ Al would be sufficient to respect the NCRP limits for 30-days missions in Low Earth Orbit in case of a solar event similar to the August 1972 SPE, although comparisons with these limits have to be taken with caution because they refer to missions within the Geomagnetic field. In contrast with the SPE results, the GCR doses were found to be essentially independent of the Al shielding within the range 0.3-5 g/cm$^2$, due to the higher energies of the incoming particles. As expected, secondary particles produced by nuclear interactions in the shield or in the human body accounted for a significant fraction of the total dose especially at high shielding, where this contribution can be higher than that of primary particles.

As a natural development of this kind of studies, in a near future we plan to calculate separately the contributions of neutrons produced in the shielding and in the human body. As a further step, we plan to include the effects of the geomagnetic field, also in view of possible comparison and benchmarking against experimental data taken onboard the International Space Station. To this aim, we also plan to insert the phantoms in more realistic shielding structures, such as one or more specific modules of the ISS.

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