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Review article

Space radiation protection: Destination Mars

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ABSTRACT

National space agencies are planning a human mission to Mars in the XXI century. Space radiation is generally acknowledged as a potential showstopper for this mission for two reasons: a) high uncertainty on the risk of radiation-induced morbidity, and b) lack of simple countermeasures to reduce the exposure. The need for radiation exposure mitigation tools in a mission to Mars is supported by the recent measurements of the radiation field on the Mars Science Laboratory. Shielding is the simplest physical countermeasure, but the current materials provide poor reduction of the dose deposited by high-energy cosmic rays. Accelerator-based tests of new materials can be used to assess additional protection in the spacecraft. Active shielding is very promising, but as yet not applicable in practical cases. Several studies are developing technologies based on superconducting magnetic fields in space. Reducing the transit time to Mars is arguably the best solution but novel nuclear thermal-electric propulsion systems also seem to be far from practical realization. It is likely that the first mission to Mars will employ a combination of these options to reduce radiation exposure.

1. Introduction

The risks of the space travel have been comprehensively summarized in the NASA Bioastronautics Roadmap, now updated in the Human Research Roadmap (NASA, 2005), and current gaps in knowledge also identified. Risks were rated from 1 (risk of serious health effects, and mission could be impossible without mitigation) to 3 (suspected health consequences with limited impact on the mission design). The risks can be summarized into three broad categories:

1. Physiological problems caused by microgravity (or reduced gravity)
2. Psychological and medical problems caused by isolation
3. Acute and late risks caused by exposure to radiation

The physiological changes due to weightlessness have been extensively studied, especially during long-term missions on space stations (International Space Station, ISS, and, previously, Mir) in low-Earth-orbit (LEO). Bone loss, kidney stone formation, skeletal muscle mass reduction, cardiovascular alterations, impaired sensory-motor capabilities, immune system dysfunctions are among the consequences of prolonged stays in microgravity. The risks are very well characterized, and several countermeasures are available. None of these risks are rated 1 in the Bioastronautics roadmap.

Isolation may lead to serious neurobehavioral problems caused by poor psychosocial adaptation. Several ground platforms are used to study these problems and develop countermeasures, such as the Concordia base in Antarctica and the Mars500 isolation experiments currently under way in Russia. Isolation also brings the problem of autonomous medical care (AMC), i.e. the capability to handle sickness or accidents in complete isolation. This is clearly a risk category 1 for the mission to Mars. Countermeasures for AMC risks are mostly technological, i.e. rely on the development of portable medical equipment and telemedicine.

Finally, there are the risks related to exposure to space radiation. Because of the complex nature of the space radiation environment (Durante and Cucinotta, 2011), both acute (i.e. short-term risk of radiation sickness) and late (e.g. cancer) effects are possible. Acute radiation syndrome (ARS) can be caused by intense solar particle events (SPE) with crews unable to reach adequate shielding. Late radiation morbidity is associated with the chronic exposure to galactic cosmic radiation (GCR), which is substantially different both qualitatively and quantitatively from the Earth's radiation natural background. Because of the qualitative difference in the radiation spectrum (γ-, β- and α-rays on Earth; protons and heavy ions in space), terrestrial data cannot be extrapolated to space radiation exposure scenarios. Therefore, the uncertainty in radiation risk estimates is very high, especially for

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Table 1
GCR dose in different mission scenarios based on the recent MSL measurements (Zeitlin et al., 2013; Hassler et al., 2014). Inspiration Mars is a 501 flyby mission. Mars sortie assumes a 30-days stay on the planet, and Mars base 500 days. Both those design reference missions (Tito et al., 2013) assume a 180 cruise to/from Mars.

	GCR dose rate (mGy/day)	GCR dose-equivalent rate (mSv/day)	Inspiration Mars (Sv)	Mars sortie (Sv)	Mars base (Sv)
MSL cruise (Zeitlin et al., 2013)	0.46	1.84	0.92	0.7	0.98
MSL on Mars (Hassler et al., 2014)	0.21	0.64			

carcinogenesis, central nervous system (CNS) damage, and late cardiovascular damage. Early estimates of the uncertainty on space radiation cancer mortality risk ranged from 400% to 1500%, with more precise estimates showing uncertainties at the 95% confidence level of 4-fold times the point projection (Durante and Cucinotta, 2008). Moreover, countermeasures are not readily available. A fundamental tenet of radiation protection is that there are three means to reduce exposure to ionizing radiation: increasing the distance from the radiation source, reducing the exposure time, and by shielding. Distance is not an issue in space, GCR being isotropic. Time in space should be increased rather than decreased according to the plans of exploration and colonization, although reduction of the transit time to the planet, where heavy shielding can be more easily achieved, may contribute to reducing radiation exposure (Durante and Bruno, 2010).

2. The Mars mission

The manned mission to Mars is considered the main goal of human exploration by all national space agencies, whose combined efforts are discussed in the International Space Exploration Coordination Group (ISECG) (ISECG, 2013). The ISECG roadmap considers a stepwise approach to Mars colonization, including asteroids and lunar missions.

NASA's "Design Reference" Mars mission (Drake et al., 2010) analyzes different scenarios, with a typical figure of about 180 days for the cruise duration (each way) and 30 (Mars sortie) to 500 (Mars base) days on the planet. In April 2013, Dennis Tito proposed Inspiration Mars, a manned mission planned for 2018. One male and one female astronaut will travel in a free-return (flyby) 501-days interplanetary flight starting in January 2018 (or 2031) to exploit the favorable reduced distance of the Earth–Mars trajectories (Tito et al., 2013). Inspiration Mars has relatively simple mission architecture and would exploit rockets with conventional technologies, such as the recently developed Falcon Heavy (53 tons to LEO, 10 tons to Mars) by SpaceX.

The measurements of the Radiation Assessment Detector (RAD) instrument on the Mars Science Laboratory (MSL) during the cruise to Mars (Zeitlin et al., 2013) and on the planet's surface (Hassler et al., 2014) can be used to estimate the dose in different Mars mission scenarios (Table 1). Measurements were accumulated around the 2012–2013 solar maximum activity. Even though the mission was around the solar maximum period, SPE only contributed 5% to the total dose during the journey (Zeitlin et al., 2013), perhaps because the present solar maximum is relatively weak. During solar minimum the solar magnetic field is reduced and the GCR equivalent dose rate can be up to two times higher (Durante and Cucinotta, 2011). However, the actual dose rate within the spacecraft will depend on the shielding. Therefore, in our exercise, we used the MSL measurement in all mission scenarios. It is interesting to see that most of the dose is incurred during cruise phase (Table 1). The dose on the planet can be further reduced using bases with heavy shielding, exploiting in situ planetary materials.

Estimates of the dose in Table 1 can be converted into estimated excess relative cancer risk (ERR) coefficients. ERR for cancer death risk can be derived from the latest Report 14 (Ozasa et al., 2012) of the Radiation Effects Research Foundation (RERF). Lifetime absolute excess cancer risk (%) is given by the product of the ERR and the background cancer death risk. Background site- and gender-specific mortality for cancer is derived from the most recent statistics in the USA population (Siegel et al., 2013). Cancer risk coefficients in the mission to Mars should be scaled compared to the A-bomb survivor data to account for radiation quality and low dose-rate exposure. Radiation quality is already included in the MSL measurement, which provided a mean quality factor of 3.82 in deep space (Zeitlin et al., 2013) and 3.05 on Mars (Hassler et al., 2014). For the dose- and dose-rate effectiveness factor (DDREF) the current uncertainty is very high (Durante and Cucinotta, 2008). According to the most recent BEIRVII report (National Research Council, 2006), in this exercise a DDREF = 1.5 is used to scale the ERR from the Report 14 (Ozasa et al., 2012) to the space environment (Table 2).

Table 2
Excess relative risk (ERR) and lifetime excess mortality risk (%) for the male and female astronauts at 30 years of age at the time of the Inspiration Mars mission.

	ERR		Background mortality in USA (%)	Excess risk (%)	
	Male	Female		Male	Female
All solid cancers	0.166	0.249	22	3.802	7.285
Noncancer diseases	0.080		71	5.592	

Cancer is not the only late risk attributable to cosmic ray exposure. Noncancer effects, e.g. CNS and cardiovascular diseases, may also impact astronauts' health, and the uncertainty on these radiation-induced effects is even higher than for cancer (Durante and Cucinotta, 2008). RERF data demonstrate an increase in noncancer death risk in A-bomb survivors, largely driven by cardiovascular and pulmonary morbidity (Ozasa et al., 2012). A comparison of radiogenic cancer and noncancer risks in the Inspiration Mars (Tito et al., 2013) scenarios is provided in Table 2. Absolute mortality for cancer and noncancer diseases refers to the general US population (Siegel et al., 2013). ERR for noncancer mortality was estimated using the linear dose model, in which city, sex, age at exposure, and attained age were included in the background rates, but not allowing radiation effect modification by those factors (Ozasa et al., 2012). These ERR are compared to those for solid cancers at 30 years of age. We used the same DDREF for cancer and noncancer diseases. Females have a higher cancer risk than males, mostly driven by the breast cancer ERR. The results in Table 2 suggest that the risk for Inspiration Mars would exceed the 3% excess cancer risk originally used by NASA for career limits of astronauts in LEO (NASA, 2005). New NASA radiation standards limit astronaut exposures to a 3% risk of exposure induced death (REID) at the upper 95% confidence interval (CI) of the risk estimate (NASA, 2007). Using the NASA model for the REID, Cucinotta et al. (2013) recently estimated the combined REID for cancer and circulatory diseases and related uncertainties for different Mars mission scenarios. The REID calculations show that the 3% limit at 95% CI would be exceeded for both Mars conjunction and opposition missions (Cucinotta et al., 2013).

The MSL measurements (Zeitlin et al., 2013; Hassler et al., 2014) and corresponding health risk estimates (Cucinotta et al., 2013) clearly point to radiation as a major health hazard for the Mars mission. Reduction of the risk uncertainty can only be achieved by extensive research programs, especially ground-based