MISSION TO MARS: RADIATION SAFETY OR RADIATION DISASTER? SPACE TRANSIT AND MARS RADIATION EXPOSURE RISKS – THE POTENTIAL SHIELDING EFFECT OF AN INTRAVEHICULAR GRAPHENE SPACE SUIT AND A STORM SHELTER DURING SPACE TRAVEL

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ABSTRACT

Aim

The purpose of this research was to employ radiobiological as well as physics principles to investigate materials for an intravehicular spacesuit and a “storm shelter” that might minimize radiation exposure to astronauts during a mission to Mars.

Methods

NASA’s OLTARIS space radiation modelling tool was used to investigate thirty-two potential shielding materials. Radiation exposure was estimated during a return transit to Mars of 360 days duration. We assessed each shielding material by its ability to decrease effective radiation dose received by a computerized phantom during the constant galactic cosmic radiation (GCR) and a single solar particle event (SPE). For the “storm shelter” a large liquid fuel tank was modelled adjacent to the phantom during a SPE.

Results

At standard conditions, graphene appeared to be a promising shielding material when comparing other materials including polyethylene and lithium. The shielding efficacy became comparable to polyethylene but inferior to lithium when materials were normalised to 10g/cm2, 20g/cm2 and 30g/cm2. The graphene around the phantom reduced effective dose from GCR compared with an unshielded transit by 34% (162mSv/yr vs 213.3mSv/yr). A “storm shelter” using a liquid fuel tank was positioned to create a barrier adjacent to the astronauts. The liquid barrier reduced effective dose by 98.8% (44mSv vs 3614mSv). Other mitigation strategies were deduced and divided into launch, transit and habitation considerations.

Conclusion

A graphene based intravehicular suit could decrease astronaut exposure to harmful radiation during transit to Mars. A storm shelter using fuel as a barrier also decreased radiation dose during a solar particle event.

INTRODUCTION

The risks associated with radiation exposure to astronauts on a mission to Mars must be understood prior to embarking on deep space missions beyond the protection of the Earth’s magnetosphere. Twenty four humans have ventured beyond the magnetosphere, and only briefly during the Apollo missions to the moon. The National Aeronautics and Space Administration's (NASA) Human Research Program identifies space radiation exposure as having a high likelihood of significant biological consequences for astronauts on a deep space mission.

There are two main types of radiation that pose a risk to astronauts who venture beyond the protective shield of the Earth's magnetosphere. Galactic cosmic radiation (GCR) and solar particle events (SPE) from the sun. (1). GCR contains mostly protons but a small amount of difficult to shield high atomic number energetic particles (HZE) which originate beyond our solar system from supernova explosions, neutron stars or pulsars (2). SPEs are occasional mass ejections of protons on a background of a steady stream of protons and electrons. These events are easier to shield than HZE and are proportional to sunspot activity with five recorded during the transit of the Mars Curiosity Rover (3). SPEs expand in size as they propagate away from the sun and can further accelerate particles creating shock waves.

HZE particles are difficult to shield particularly due to their relativistic velocity and ability to penetrate all current shielding materials. Thick dense shielding materials are impractical for launch, and increase exposure due to secondary radiation generation that 'showers' astronauts with subatomic particles. (4). These interactions add to the complexity of the intravehicular radiation environment for astronauts.

Highly hydrogenated substances with low atomic numbers appear optimal passive shielding materials against GCR (5). Studies have shown that polyethylene is a more effective shield than aluminium in the cosmic radiation environment. (6). Hydrogen is effective in breaking up the energetic ions into smaller less damaging fragments with fewer and slower secondary radiation. (7,8). Favourable materials would limit the generation of secondary neutrons as these particles can lead to significant biological damage. Active shielding mechanisms such as on-board magnetic shields could be created but are currently too large and require immense amounts of energy.

There are fundamental differences in the way types of radiation deposit dose. Photons can deposit dose in a dispersed manner with resultant electrons having a low linear energy transfer (LET). HZE particles encountered in space can travel in straight directions densely ionising along the way and due to high charge have a high LET. Although HZE particles account for a very small fraction of the GCR flux, when weighed by their respective LET and quality factors they account for a substantial fraction of dose equivalent to the astronaut (8).

The heterogeneous cosmic radiation environment consists of a wide variety of ion species with a large range of energies. Simulation of this environment is being performed at the NASA Space Radiation Laboratory in order to perform radiobiological experiments. A study with simulated high energy protons and Fe ions induced mutations distinct from gamma-rays and resulted in in-vivo development of T-cell acute lymphoblastic leukaemia in mice (9). Interesting human data has emerged from NASA's "Twin Study" showing a change in telomere length, DNA methylation in immune cells along with cognitive and cardiovascular effects during prolonged human spaceflight (10). These changes may be due to radiation along with other confounding factors.

Synergistic factors exist in space that may increase damage caused by radiation. The addition of microgravity, environmental factors, isolation, emotional stress and nutrition may lead to increase cellular oxidative stress. For astronauts, this may result in inflammation, susceptibility to infection, poor healing and carcinogenesis. (Figure 1). Reactivation of Epstein-Barr, Varicella-Zoster and cytomegalovirus has been demonstrated in astronauts during short space flight being attributed to changes in immune state (11). Emotional stress on-board long confined space flights may play a role in cellular response to cosmic radiation. Increased DNA damage in peripheral blood lymphocytes has been observed following gamma irradiation in psychologically stressed subjects compared with control subjects (12)

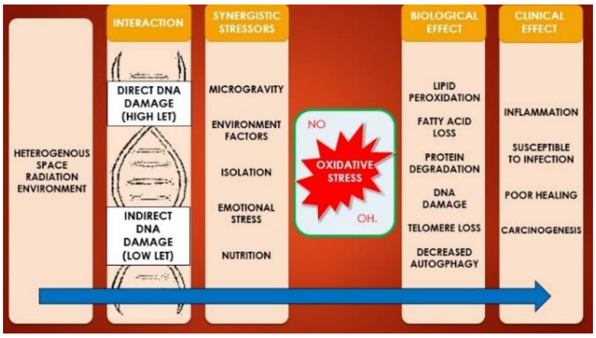


Figure 1 – Increased cellular oxidative stress during irradiation in the cosmic radiation environment.

An important environmental factor that may interact synergistically with cosmic radiation is sleep deprivation. The International Space Station (ISS) orbits the Earth at approximately 27,000 km/h with astronauts visualising 16 sunrises and 16 sunsets each day. This environment could negatively affect their circadian rhythm and sleep cycle. Cellular response to cosmic radiation may vary depending on the body's inherent circadian rhythm. There is a suggestion that night shift work is associated with decreased DNA repair (13). Several clinical studies have demonstrated distinct variations of toxicity experienced by patients dependent on whether they received radiotherapy in the morning or afternoon. Improved tumour cellular response has also been demonstrated when patients received radiotherapy in the afternoon (14).

Although radiation type and dose rates differ between therapeutic and cosmic radiation, there may be similar toxicities. Cataract formation, fatigue, neurocognitive impairment, vascular effects and malignant transformation are all potential effects from cosmic radiation. Skin burns, accelerated aging, sterility and germ line mutations may also occur (1).

AIM

The aim of this research was to employ knowledge of radiobiology, physics and interactions with matter to model strategies to mitigate the harmful effects of radiation exposure in deep space. Specifically, we investigated potential shielding material for an intravehicular suit that astronauts might wear during the lengthy transit to and from Mars in order to decrease effective dose caused by GCR. Our aim was to find a material that would increase fragmentation of the high atomic number particles into smaller less damaging secondary radiation and limit neutron generation. The materials investigated were light, practical, strong, non-flammable and non-toxic.

These included gases, polymers and elements of low atomic number. The strategies we suggest can be largely divided into launch and transit considerations, as well as habitation concepts.

METHODS

Access was granted from NASA to utilise the On-line Tool for the Assessment of Radiation in Space (OLTARIS) galactic cosmic radiation simulator. The simulator used HZETRN2005 and NUCFRG2 research codes for transport and physics. We researched the composition of 32 materials with particular interest in those with a low atomic number, high hydrogen content and low neutron production. These included gases such as hydrogen, low atomic number elements including carbon and polymers such as polyethylene. Materials were specified by their chemical composition, density and thickness. These materials were initially simulated as a 3mm thick sphere at their standard condition surrounding the computerised phantom to assess realistic suit material. A sphere configuration was chosen given the isotropic nature of GCR exposure. Materials were then converted to 10g/cm2, 20g/cm2 and 30g/cm2. A 6mm thick sphere of graphene 30g/cm2 was modelled around the phantom within a sphere of aluminium 20g/cm2 to represent the spacecraft hull. A 360 day return transit to Mars was simulated during a cycle of maximum sun activity (solar maximum), a cycle of minimum sun activity (solar minimum) as well as a solar particle event. This time was chosen to represent an average journey to and from Mars to solely investigate radiation exposure during transit. A 100cm thick liquid fuel cell was modelled adjacent to the phantom to represent a "storm shelter" that could be retreated to in the event of an SPE. The OLTARIS environment conditions were based on data received during the transit of the Mars Curiosity Rover and modelled on a computerised male anatomical phantom. Whole body and individual organ effective doses were calculated per day and per year for each of the shielding materials utilising tissue weighting factors. We also theorised other strategies that could be employed to limit the dose of radiation to astronauts, particularly during launch, transit and habitation.

RESULTS

Graphene intravehicular suit during transit

At standard conditions, gases such as oxygen and carbon dioxide performed poorly as shielding materials against GCR. Intermediate performing materials included polymers such as polyethylene and polycarbonate. Optimal shielding materials included boron, graphene and beryllium. Beryllium was considered impractical due to its highly flammable nature (Figure 2). When shielding materials were compared at 10g/cm2, 20g/cm2 and 30g/cm2 graphene and polyethylene were comparable in their shielding ability. Lithium performed favourably, although construction of an intravehicular suit using this material may be challenging.

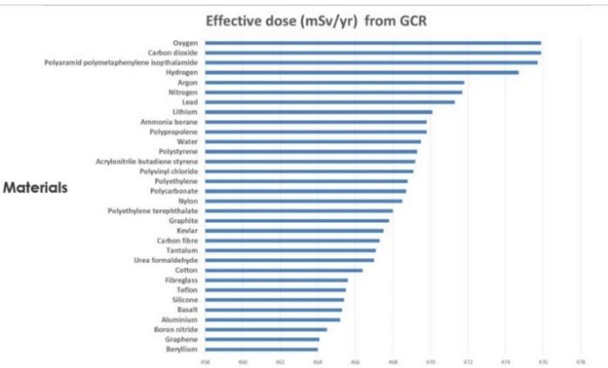


Figure 2 – Effective dose received during Mars transit with varying materials at natural densities.

Graphene consists of a hexagonal network of carbon atoms and has many favourable attributes including immense strength, flexibility, heat conductivity and it could be made into fibres to create a material suitable to be worn during transit. There was an effective dose reduction when the graphene material was simulated around the phantom within the spacecraft (162mSv/yr) compared with spacecraft shielding alone (213.3mSv/yr).

Liquid Fuel Tank Bunker Simulation during a SPE

A solar particle event was simulated during a transit to Mars. A storm shelter that astronauts could retreat to where they would be situated behind a fuel cell filled with liquid was modelled. This storm shelter design significantly reduced effective dose during a solar particle event from 3614mSv to 44mSv resulting in an effective dose reduction by 98.8%. An unshielded exposure could result in a 50% chance of death at 3-6 weeks post exposure following severe prodromal and haematological symptoms.

Behind the liquid fuel tank effective dose was significantly reduced for individual organs including the skin, heart, lens, testes and brain. Without this shelter the simulation predicted during a solar particle event astronauts may experience a skin dose of 14.5Gy, testicular dose of 3Gy, heart dose of 8Gy, brain dose of 1.6Gy and lens dose of 7.5Gy. These radiation doses could have clinically significant effects for the individual organs. This is provided death is avoided from an acute radiation syndrome. All of these doses without the storm shelter are in excess of the 1 year exposure limits set by the National Aeronautics and Space Administration (NASA). Behind the liquid barrier dose to all organs was below 0.01Gy (Table. 1).

Organ	Dose Behind Liquid Barrier	Unshielded Dose	Clinical Effect
Skin	0.013Gy	14.5Gy	Pain Erythema
Testes	0.012Gy	3Gy	Azoospermia Infertility
Heart	0.012Gy	8Gy	Coronary Artery Disease Valvular Fibrosis
Brain	0.013Gy	1.6Gy	Nausea/ Vomiting Neurocognitive Effects
Lens	0.013Gy	7.5Gy	Cataract Formation

Table 1 – Comparison of dose received behind liquid fuel tank and unshielded dose along with potential clinical effects experienced by astronauts from an unshielded exposure from an SPE.

Strategies to reduce radiation exposure can be summarised into a theoretical "best and worst case scenario". Optimisation of launch, transit and habitation strategies could lower effective dose received by astronauts significantly (Table 2).

	Best Case Scenario	Worst Case Scenario
Crew Selection	No radiosensitive genes Resistant to sleep deprivation and psychological stress	General crew selection
Solar Cycle Launch Time	Solar maximum	Solar minimum
Propulsion System	Chemical, nuclear and electrical	Chemical
Intravehicular Suit	Graphene suit ~ 162mSv	No additional shielding ~ 213.3mSv
SPE Warning System	Solar flare telescope	No solar flare telescope
On-Board Storm Shelter During A SPE	Fuel tank barrier ~ 44mSV	No barrier ~ 3614mSv
Location On Mars For Habitation	Hella Planitia	Olympus Mons
Depth Below Surface For Habitation	3m below surface ~3mSv/yr	Surface ~300mSv/yr
Total Radiation Dose	~209mSv/yr	~4127.3mSv/yr

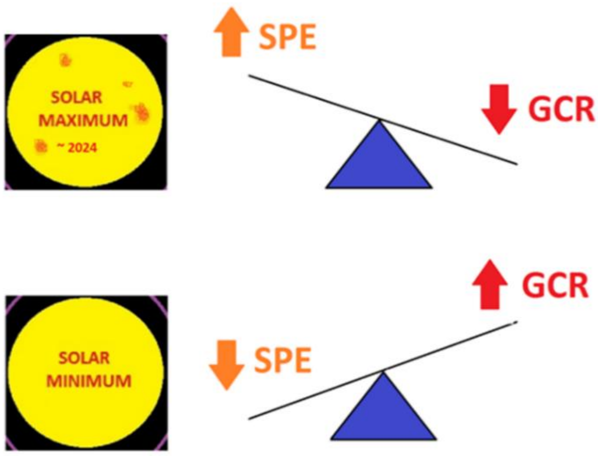
Table 2 - "Best and worst case scenario" incorporating potential launch, transit and habitation strategies.

DISCUSSION

Mars has been of scientific interest with questions regarding its formation, evolution and potential cessation of life. Factors that appear to facilitate survival of primitive organisms include water availability, favourable chemical environment, suitable energy source for metabolism and favourable physical conditions including temperature, pressure and limited radiation exposure (15). Given the drive and inevitability of a manned mission to Mars, solutions must be found to maximise the safety of astronauts.

Pre-Launch/Launch Considerations

The previous solar maximum was recorded in 2014 and the next has been estimated to occur around 2024. There is an increase in solar particle events during solar maximum but these are easier to shield compared with the high atomic number charged particles from the constant bath of galactic cosmic radiation. These considerations result in balancing dose contribution from GCR and SPE (Supplementary Data 1). Generally, current unmanned missions to Mars occur at two yearly intervals due to favourable orbital alignments.



Supplementary data 1: Balancing radiation dose from SPE and GCR during solar maximum and minimum. During solar maximum GCR is likely to contribute less radiation dose with an increase in frequency of SPE. During solar minimum there is likely increased dose due to GCR and less frequency of SPE.

Transit Considerations

Our hypothesis is that the low atomic number graphene material arranged in a hexagonal network is effective at fragmentation of the HZE particles into less damaging secondary radiation resulting in a lower effective dose to the astronaut comparable to other materials including polyethylene. Whilst lithium may be used as an effective structural shield, construction of an intravehicular suit with this material may be challenging. Graphene fibre production and incorporation into clothing is currently feasible. Therefore, graphene may be a more suitable material to be incorporated into an intravehicular spacesuit.

Research on-board the International Space Station has shown equivalence of Kevlar compared with polyethylene in terms of shielding ability against GCR. (6). The findings from our research reflect observations that graphite performs favourably as a shielding material against GCR on Mars.

There are limitations in material input parameters of the OLTARIS simulator in that only chemical formula, density and thickness data can be added. Therefore, the exact arrangement of the carbon atoms could not be specified and hence the form of carbon is not certain. This limitation can be resolved by physically simulating graphene using a particle generator. We suggest that the graphene suit may be constructed similar to a wetsuit with elasticised fibres allowing mobility and comfort. These fibres may be incorporated into existing intravehicular suits which combat bone and muscle loss. In vivo experiments with graphene will provide further evidence for its shielding ability.

During an SPE we have suggested utilising a large liquid barrier adjacent to the astronauts such may be the case with a fuel tank. This will become depleted with time as the fuel is expended. When this occurs supplies and or waste products on board could be arranged into a thick barrier to attenuate the radiation from the astronauts. Although waste must also be minimised and recycled maximally to make a Mars mission feasible.

There needs to be sufficient warning for astronauts to seek shelter on-board during an SPE. A low energy particle eruption from the Sun may take hours to travel to a spacecraft on the way to Mars. A radio signal could be received 10 minutes after it being sent from Earth to warn astronauts of the radiation event. However, a high energy eruption may travel much faster limiting time for astronauts to seek shelter on-board. Space based observatories may obviate the need for a message to be sent from Earth to facilitate a more timely warning. The direction of an SPE can be uncertain as particles emitted from the Sun follow its magnetic field lines. An eruption from the Sun may not occur on the same side as the transit vehicle on a mission to Mars and therefore not pose a threat to astronaut safety given the direction of the event.

An aspect of the radiation “As Low As Reasonably Achievable“ (ALARA) principle that can be managed is limiting time of exposure during a deep space mission to minimise radiation dose to astronauts. Currently, chemical propulsion is the most commonly utilised system and will likely remain a significant component of future missions given the superior thrust compared with other systems. Electrostatic and electrothermal based systems are currently in operation but are less commonly utilised. Solar sails and thermal technology has been demonstrated with smaller spacecraft and satellites. Nuclear fusion systems and antimatter technology remain unproven but could be utilised in the future (16).

Biological damage from radiation may also be increased by altered circadian rhythm (17) and the prolonged effects of microgravity (18). Therefore, the damage caused by radiation during future space missions may be limited by enforcing a circadian rhythm and counteracting the effects of microgravity.

Whilst the cosmic radiation environment is complex, simulation has facilitated radiobiology studies (19). The carcinogenic risk from GCR exposure is uncertain given that the 5% increased risk of cancer induced death at 1Sv is based on photon data and therefore extrapolation from this data should be interpreted with caution.

The evidence for biological effects of cosmic irradiation consisting of high LET radiation has been demonstrated in animal studies (20, 21, 22, 9). It is accepted that there are uncertainties in predicting and extrapolating biological response to radiation exposure in humans, although the NASA “Twin Study” has provided significant biological effects from long term spaceflight (10) which may be in part related to radiation exposure.

Radiation countermeasures can include radioprotectors administered prior to exposure to reduce damage to organ systems. Radiation mitigators are administered after exposure to alter the biological effects of the radiation. Whilst there is some support for these agents in the low-LET setting their efficacy during high-LET solar particle irradiation is uncertain. (20)

Habitation Considerations

Location for settlement on Mars will be an important factor to consider. Higher radiation doses have been measured at higher altitudes and the depleted atmosphere will only provide a small amount of shielding from radiation. Even at the lowest geographic location at Hella Planitia 7km below the plains the yearly background radiation dose is 75x that on Earth. (Figure 3) A location underground would be a suitable option given that the yearly background dose of radiation received 3m below the Martian surface is equivalent to the yearly background radiation dose on the surface of Earth being approximately 3mSv/year. Martian regolith may also be used to create protective bunkers. Underground lava tubes created from now extinct volcanoes may provide a suitable habitat for future colonists. However, this will depend on their geographic location on Mars in terms of their usefulness.

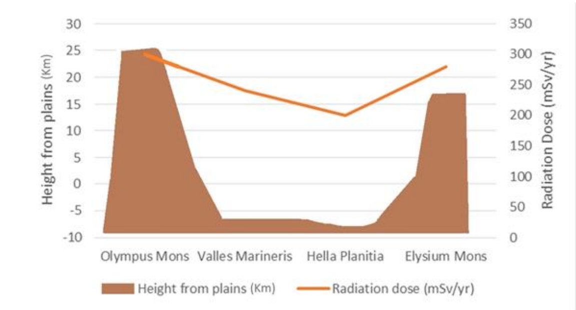


Figure 3 – Increased radiation doses at higher altitude on the surface of Mars.

Recommendations

Missions should take place during solar maximum due to increased solar magnetic field strength potentially limiting GCR exposure during transit (Figure 4).

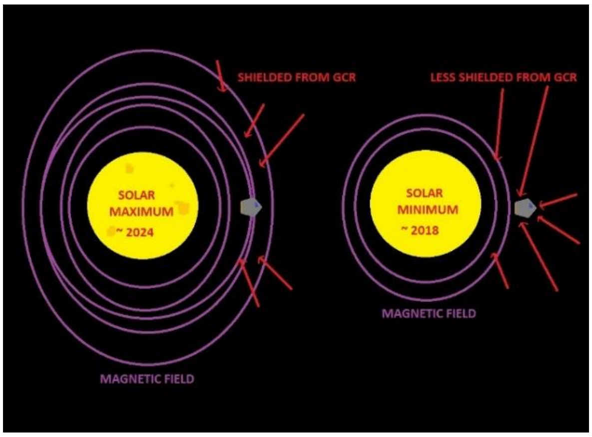


Figure 4 - Decreased effective dose received during transit due to increased solar magnetic field strength during solar maximum compared with solar minimum.

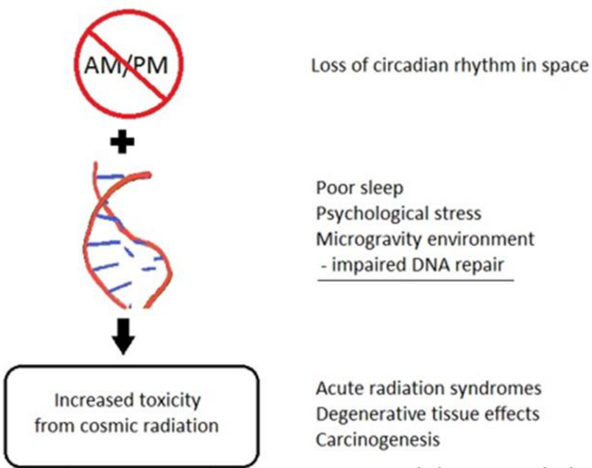
Astronauts could be excluded from deep space missions if they have radiosensitive gene expression or are vulnerable to psychological stress and sleep deprivation to limit the damaging effects of radiation exposure. Although genetic screening remains controversial.

Graphene based fibres may be able to incorporated into existing skin suits that combat the deleterious effects of microgravity on bone and muscle health thereby providing an added benefit of radiation shielding.

A solar flare telescope on-board may provide advanced warning of an impending SPE by visualising a flare prior to energetic particles being incident on the spacecraft. The amount of advanced warning would be dependent on the energy of the particles emitted and distance travelled, with higher energy particles taking minutes to reach the spacecraft and lower energy particles potentially taking hours.

Utilisation of a physics based approach rather than a solely mechanical approach to advanced propulsion systems will allow much faster transit speeds. This could be achieved by a combination of chemical systems as well as nuclear-thermal and electrical propulsion technology.

DNA damage repair in response to cosmic radiation may be improved if astronauts are able to sleep and maintain a circadian routine on-board the spacecraft. This could be facilitated by sleep scheduling and controlled light exposure times. (Supplementary Data 2).



Supplementary data 2 – Potential synergistic effect of loss of circadian rhythm with environmental factors resulting in increased toxicity from cosmic radiation.

We propose lower altitude locations for habitation as well as utilisation of underground structures such as lava tubes to facilitate shielding from radiation on Mars.

CONCLUSION

Incorporation of graphene fibres into an intravehicular space suit during transit may be a relatively simple way to decrease effective dose received by astronauts on deep space missions. The manufacture of a graphene fibre suit to be worn during transit is feasible as is optimising spacecraft design to include a shelter protected by a liquid fuel cell.

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