MSP CONFERENCE ON RADIATION MITIGATION ON MARS

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Abstract

As we venture towards realizing a sustained way of human presence on Mars, the challenge of mitigating radiation exposure becomes a vital part of making this a reality. The conference aims to go over a diverse range of strategies that will combine into a multi-pronged system that will protect humans on Mars from exposure to this radiation. Topics to be covered include the usage of natural elements for shielding, such as the martian regolith and subsurface structures, as well as ways to manipulate these materials for our use. Additionally, we will go over ways of personalized protection measures, such as wearable technologies and medication that will help reduce the levels of radiation. By addressing the multifaceted challenge of reducing the radiation levels on Mars for future human explorers, we believe we can contribute to sustainable exploration and habituation on Mars.

EDITORIAL INTRODUCTION

Mars provides a unique opportunity for scientific exploration, climate-wise it is the most similar to Earth and the most likely candidate out of the planets of our solar system to be explored by humans. A majority of scientific focus lies behind the question of possible life forms existing on Mars; something which the current robotic fleet on Mars is not able to detect with current equipment [1]. This would require the need for manned exploration but in the vast expanse of space, we are not protected by an atmosphere or magnetosphere like on Earth. On a mission to Mars, an astronaut may face radiation levels up to 700 times higher than those experienced on our home planet [2]. These levels of radiation are referred to as "space radiation" and are universally acknowledged as a significant health hazard for astronauts [3]. Space radiation emanates from two primary sources: solar radiation, characterized by a continuous release of solar particles from the sun, including periodic surges following significant events like solar flares and coronal mass ejections; and galactic cosmic rays (GCRs), high-energy particles accelerated to nearly the speed of light, entering our solar system from distant stars within the Milky Way or even other galaxies, predominantly composed of protons. These cosmic rays also encompass heavier elements, ranging from helium to the most substantial ones. These more energetic particles can split apart atoms within the material they encounter, such as the metal walls of a spacecraft, habitat, vehicle and most importantly in the astronaut's body [4].

Astronauts exposed to long-term radiation experience a myriad of health effects. In our scenario astronauts would have to endure a minimum of 2 Earth years until Earth-Mars periapsis - the point at which Mars and Earth are closest, which occurs around every 780 days [5]. Though exposure over a duration of time is considered less harmful than an equivalent dose during shorter periods the health implications are still numerous [6]. DNA is readily damaged by radiation, increasing chances of genetic mutations from as little as 0.01 Grays (Gy) [7]. Exposure of cells to doses as low as 0.1 Gy causes major inhibition in cell proliferation [8]; in humans, this causes significant damage to high proliferating cells such as epithelial cells that line the stomach and intestines [7].

In delving deeper into the challenges posed by space radiation on manned missions to Mars, it follows the literature review examining existing research and insights. This section aims to provide a comprehensive understanding of the scientific landscape, shedding light on how we can mitigate the risk of space radiation on Mars to ensure manned mission success, by implementing a sustainable multi-pronged approach.

LITERATURE REVIEW

The research is structured around distinct protective strategies; however, it adheres to a unified set of criteria.

Sustainability

Sustainability in manned Mars missions encompasses a broad spectrum of challenges, which are crucial for the safety of the astronauts and long-term success. A sustainable approach to the exploration of Mars involves efficient usage of local resources, independence for Earth supplies, energy generation, etc. This is particularly important considering the vast distance between Earth and Mars, making resupply missions costly and time-consuming.

One of the primary considerations about living a sustainable life on Mars is the consideration of what to bring from Earth, given the limited space available in a spacecraft. This decision process involves the consideration of all the necessities for initial establishment and survival, alongside tools and equipment essential for in-situ resource utilization (ISRU) [9]. ISRU strategies are key for sustainability on Mars, as they focus on using Martian resources for multiple needs.

In 1979 The United Nations (Office for Outer Space Affairs) published a report named: "Agreement Governing the Activities of States on the Moon and Other Celestial Bodies." that highlights the importance of international cooperation in space exploration [10]. The agreement covers issues like property rights, Resource usage and the impact of space activities on the space environments. It focuses mostly on the moon but its principles are as relevant to Mars missions.

ALARA - The Safety of the Astronauts

Radiation protection management is always governed by the ALARA principle “As Low as Reasonably Achievable”. ALARA allows for flexibility by acknowledging that people working in radiological fields will experience radiation that is non-zero even though sufficient protection is applied [11]. Legal guidelines for exposure for radiological workers on Earth do exist at 0.05 Gy per year. NASA has also set age and sex-dependent guidelines for the recommended maximum dose that low-earth orbit astronauts face at 0.5 Gy per year [12]. Lifetime exposure to radiation is also taken into consideration with a NASA recommended universal career-long radiation dose limit of 0.6 Gy and ESA of 1 Gy. This dose limit corresponds to a 5% risk of cancer mortality [13]. As of 2021, only NASA has a process for granting a waiver to an astronaut that would allow them to exceed the career limit. Though a minimum stay would expose astronauts to a cumulative 0.4 to 0.2 Gy which is below the recommended limits one must consider radiation from transit to and from Mars and possible solar events which drastically change possible radiation. Solar radiation is also not constant. Coronal Mass Ejections (CME) are a large contributor to Solar Energetic Particles (SEP) [14], this can increase the daily radiation at the Martian surface by 20% [15].

Location

Location plays a major role in the amount of radiation that makes it to Mars’ surface. Varying between 0.2 and 0.1 Gy per earth year on Mars’ surface [16]. This trait intrinsically in tandem with Mars’ elevation dichotomy sets a general trend that radiation is greater in the southern hemisphere due to its increased elevation and thus lower pressure reducing already limited atmospheric shielding [17]. Similar trends exist on the intensity of cosmic rays [16]. Mars’ weak atmosphere also limits the planet’s ability to retain heat, this causes a wide variability in daily temperature [18]. Mars undergoes multiple cycles such as Water, Dust and Atmosphere that follow Martian seasons. The atmosphere undergoes seasonal changes, in martian winter 30% of atmospheric carbon dioxide condenses into polar ice caps, causing atmospheric pressure loss around Mars [18].

Sending a manned mission to Mars holds immense scientific promise and potential for advancing our understanding of the Red Planet and the broader field of space exploration. A majority of scientific focus lies behind the question of possible life forms existing on Mars; something which the current robot-fleet on Mars is not equipped with and has developed sensitive enough instruments for [1]. While robotic missions have provided valuable data, human exploration offers unique advantages, such as real-time decision-making and the ability to conduct intricate scientific experiments on-site. A manned mission to Mars would allow scientists to directly study Martian geology, atmospheric conditions, and potential traces of past or present life. Moreover, the physiological effects of extended space travel and habitation on the human body can be thoroughly investigated, providing crucial insights for future long-duration missions, such as those to more distant destinations like the outer planets or their moons. Additionally, the development of sustainable habitats on Mars could serve as a stepping stone for human colonization and the establishment of a permanent human presence beyond Earth.

HOW CAN WE MODIFY CURRENT THERAPIES TO ENHANCE RADIORESISTANCE IN HUMANS ON MARS?

M. Castellano, A. Kolaksazova, N. van Wesel

Abstract

This paper investigates potential medical strategies to address the diverse challenges presented by space radiation exposure on the human body, including tissue degeneration, central nervous system impairment, and cardiovascular damage. By framing our inquiry around the research question "How can we adapt existing therapies to enhance radioresistance in humans during Mars missions?", we aim to offer insights into mitigating the physiological impacts of radiation exposure in space. Through a thorough examination of McLaughlin et al.’s research, which proposed medications with potential radioprotective properties, we identify statins, n-acetylcysteine, and pentoxifylline as promising candidates for astronauts due to their synergistic, protective, and prophylactic attributes. They would be administered through a patch pump similar to the ones currently used in diabetes treatment.
While much of these proposals are still speculative, technological advancements will render many components of this more feasible and sustainable further down the line.

Introduction

In considering Mars habitation, space radiation poses a unique challenge with higher-energy sources than Earth’s gamma-rays and X-rays.
As detailed in recent scientific literature, the consequences of exposure to space radiation extend far beyond the well-known risks of radiation sickness and cancer [19]. The different types of radiation present in space, including solar cosmic radiation (SCR) and galactic cosmic radiation (GCR), possess unique characteristics compared to the radiation encountered on Earth [19]. This paper aims to explore potential medical solutions for the various challenges posed by space radiation on the human body, notably tissue degeneration, damage to the central nervous system, cardiovascular issues, immune system abnormalities and heightened risk of cancer. All of these symptoms are derived from the molecular impact of space radiation, which causes double stranded DNA breaks, cell cycle arrest or apoptosis. The amount of risks underscores the urgent need for comprehensive mitigation strategies to ensure the success of manned missions to Mars. The existing uncertainties surrounding the effects of space

radiation on the human body form the backdrop for our research question: "How can we modify current therapies to enhance radioresistance in humans on Mars?".

There many organs and systems that get affected by the exposure to the radioactive and microgravity environment of spaceflight as well as the lowered gravity environment of Mars compared to Earths'.

Galactic cosmic radiation (GCR), with its high energy nuclei component, poses a significant threat to the central nervous system, potentially leading to alterations in cognitive abilities, motor functions, and behavioral changes. The interaction between ionizing radiation and the microgravity conditions of space flight further complicates our understanding of the cognitive impairments that astronauts may face [20].

Prolonged exposure to lowered and microgravity also affects the cardiovascular system, inducing conditions such as tachycardia, baroreflex dysfunction, and sympathovagal imbalance. These cardiovascular disturbances increase the risk of fatal arrhythmias (abnormal heartbeat). Additionally, the impact of cosmic radiation on the immune system adds another layer of complexity. Abnormalities in immune system functioning, observed since the 1970s, may lead to increased infection rates, acute and chronic inflammation, and potentially carcinogenesis [20].

Many of these physiological alterations affect the absorption, distribution, metabolism and excretion (ADME) of drugs [21].

In the space environment, changes in stomach and intestine activity due to space motion sickness (SMS) can affect how oral drugs are absorbed. In microgravity, stomach emptying slows down and becomes less predictable because there's no gravity effect on what's eaten. Also, the speed and predictability of drug dissolution in the small intestine are affected. Chronic low oxygen levels during spaceflight can change how enzymes and transport systems work in the intestine, affecting drug absorption. Changes in gut bacteria, differences in liver blood flow, and shifts in first-pass liver metabolism also add to variations in drug absorption and availability [21].

The lower gravity environment present in space, compared to Earth's, brings about significant changes in the body that affect how drugs are distributed and move through the body. Fluid moves from the lower to upper body, reducing blood volume and changing cardiovascular factors. Less body water leads to higher drug concentrations in the blood. Changes in blood proteins and blood cell indices, like red blood cell mass and erythropoietin levels, can impact drug binding and availability [21].

Problems like endothelial dysfunction and disruption of the blood-brain barrier due to ongoing inflammation and redox imbalance might also affect how drugs move and their harmful effects. Loss of bone and muscle mass in space can potentially affect how drugs bind and store in tissues. However, there aren't many direct studies on these issues in space [21].

Moreover, the lack of gravity affects how the transport system and endothelium, crucial for drug absorption and distribution in body tissues, function. The loss of muscle mass and reduced tissue blood flow can also influence how drugs spread and are stored in tissues. Nonetheless, there's a lack of direct studies specifically addressing these effects in the space environment [21].

In the following sections of this paper, we will delve into the current medications used for radiation exposure, the regulatory landscape, and the potential of radioresistant agents and genetic modifications as mitigation strategies. By unraveling the complexities of space radiation's impact on the human body, we strive to pave the way for innovative approaches to enhance radioresistance and ensure the success of future manned missions to Mars.

Description and Results

Current Regulations and Choosing the Most Promising Agents- Hitherto, for ISS missions, radiation protection in space has meant shielding and limiting mission length. At present, the attention of researchers is wandering toward Mars, leading to an increasing interest in biological and pharmacological solutions [22, 23].

There is only a small number of people who have traveled in space and even fewer who have participated in missions beyond Low Earth Orbit (LEO), making the epidemiological studies in the target population statistically inadequate, along with the lack of suitable facilities to replicate the space environment [24]. This prevents many medical drugs from being implemented in the treatment and prophylaxis of astronauts, despite being approved by the US Food and Drug Administration. Examples of such drugs are statins, nonsteroidal anti-inflammatory drugs (NSAIDs), angiotensin-converting enzyme inhibitors (ACEIs), angiotensin II receptor blockers (ARBs), metformin, fingolimod, N-acetylcysteine, and others, which have existent preclinical and clinical evidence in treating the previously mentioned complications associated with radiation exposure [25] (Fig. 1).

PHARMACEUTICAL OR CLASS	EVIDENCE AVAILABLE	POTENTIAL USES
Statins*	Extensive preclinical and clinical evidence	pulmonary fibrosis, gastrointestinal damage, neural protection
NSAIDS*	Extensive preclinical and clinical evidence	Pneumonitis, overall survival, prevention of metastasis
n-acetylcysteine	Extensive preclinical evidence	Wound healing, immune protection, dermatitis, liver protection, GI protection
ACEIs/ARBs*	Extensive preclinical and clinical evidence	Radiation mitigator only: pneumonitis, gastrointestinal damage, neural protection, nephropathy, hematopoiesis
Metformin	Limited preclinical evidence	Hearing, vasculature
Calcium channel blockers	Limited preclinical evidence	Vasculature, appetite
β-blockers	Limited clinical evidence	Overall survival, metastasis prevention
Fingolimod	Limited preclinical evidence	Neural protection, ovarian failure/infertility
Pentoxifylline	Limited clinical evidence	Pulmonary fibrosis, osteonecrosis, lymphedema

Figure 1: A Table Summary of the names, evidence available, and potential uses of the medicines proposed by McLaughlin [24]

With the current regulations on the acceptance of pharmacological agents without extensive clinical trials, it is difficult to proceed planning for a manned Mars expedition. The European Medicines Agency states that deviation from standards should only be considered when completely unavoidable and should be justified. The justification in our case would be the lack of machinery that can replicate the complex Martian environment, as well as the lack of human subjects that have previously been exposed to such radiation. EMA also mentions with regard to clinical trials with very small population 1) less conventional and/or less commonly seen methodological approaches may be acceptable if they help to improve the interpretability of the study results, and 2) a compromise can be made if randomized controlled trials are not feasible and only case series (with external control groups) or even only anecdotal case reports are available [26]. If new guidelines are to be developed and proposed, and the above-mentioned medicines are to be further tested, they have a great potential in being functional.

That is why we performed an in-depth inspection of McLaughlin et al.'s paper and decided to narrow down the list to limit dangerous chemical interactions between them. That was done keeping in mind that the subjects would be uptaking multiple different agents to ensure the protection of vital organs and bodily systems. Here we describe why some of the medicines proposed were rejected by us:

NSAIDs, used as radiation mitigators in murines, have vague effects that could contribute to the overall survival, but that is counteracted by the side effects, which include but are not limited to decreased gastric mucus production, thus gastritis (inflammation of the stomach lining), and analgesic nephropathy (deterioration of kidney function). Being aware that decreased renal function is particularly worrisome in the astronaut population, the use of NSAIDs was dismissed by us, along with ACEIs and ARBs for that same reason [24].

Instead statins were further considered, as they also protect the respiratory organs, prevent metastasis (the spread of cancer cells to other tissues), and additionally protect from gastrointestinal and neural damage [24].

Calcium-channel blockers were repudiated for the shortfall of benefits and the possibility of only using them as prophylactics. The latter also stood for β-blockers, which also had considerable side effects related to hypotension, which would be a concern in the astronauts when transitioning between different gravitational states, causing excess neurosensory stress [24].

Fingolimod, a neural and pain modulator, was rejected due to its possible adversity of exacerbated immunosuppression in space, despite the evidence for fertility protection in female astronauts [24].

By contrast, pentoxifylline, similarly a neural and pain modulator, which appears to be a promising agent for a lung, bone, and motion protector, was taken into account. The attainable combination with vitamin E, backed up its case.

For the treatment of immunosuppression, we decided on n-acetylcysteine, which is also a free radical scavenger that can elude double-strand DNA breaks [24]. That review reduced the list to 4 agents - statins, NAC, and pentoxifylline. Further research confirmed that the interactions between them were not hazardous, but rather synergistic [27–31].

Administration of Medicines- In the pursuit of establishing a sustainable research base on Mars, we searched for a mean to administer medicine with which astronauts would not need medical expertise or assistance, as would be in the case of IVs. With them uptake is maximised which is not always the case with oral intake, however in consideration we disclosed it highly important that risks of infection and complications were minimal. So instead we propose patch pump technologies be put to use. These wearable devices, commonly employed for conditions such as diabetes, provide a practical and continuous means of delivering controlled doses of medication. Drawing inspiration from existing systems like the Omnipod, we explored the potential utilization of patch pumps for enhancing the adaptability of humans to the Martian environment.

The mechanisms employed by patch pumps are crucial for efficient medication delivery. Among the various types – mechanical, motor-driven, and microprocessor-controlled – the microprocessor-controlled mechanism stands out as the most efficient and sustainable. This technology allows for programmable dosing and remote adjustments from Earth, reducing the reliance on manual intervention by Martian settlers.

The Omnipod offers several advantages. As a tubeless system, it eliminates movement restrictions by delivering medication directly to the body without the need for external or internal tubes. This feature is particularly advantageous in the challenging Martian environment, where the lack of tubes mitigates risks associated with clogging or disconnections. Equipped with a personal health monitor, the Omnipod enables automatic administration based on real-time health metrics, aligning with the goal of minimizing manual intervention for settlers.

The administration process of the Omnipod involves priming the pod, attaching it to the body, and deploying a stainless steel needle that allows for the rapid entry and exit of a soft cannula that provides continuous medication delivery. While initially designed for insulin delivery, the continuous and basal nature of the administration aligns with the requirements for radioresistant medications on Mars.

In short, the patch pump technology presents a promising solution for administering the chosen radioresistant medications on Mars.

Conclusion

Developing sustainable solutions to this challenging feat which relies heavily on speculation and on information which is not yet available because this work is the brink of new knowledge and possibilities makes it difficult to come to definitive conclusions. Nevertheless, based off the extensive literature reviews performed and research throughout the course of this investigation we have begun to paint a clearer picture of what the internal protection against radiation could look like on a manned mission to Mars, providing a basis for future research that could be endless as we begin to transcend the more difficult biological questions and as the timeline gets shorter for the reality of a manned mission to Mars. This work is incredibly important as innovative and creative ideas are what will allow researchers to best equip astronauts on their missions with a real chance at survival so that we can explore space research beyond just a mere idea. Internal mitigation strategies are incredibly important as they protect the body from its own natural mechanisms and consider an entirely different realm of conditions which are very different to those on Earth, as such having a whole new field of work that is yet to be understood.

First and foremost, to prevent space associations from having to make compromises with medicines that can affect the health of astronauts negatively if left untested, new regulatory systems would have to be put in place. They need to encourage less common methodological practices and allow meta-analyses to be used as valid evidence, at least until the population of people that have gone beyond LEO has increased.

As we begin to scratch the surface of possible internal strategies, there are many limitations that need to be addressed by advancements in technology and potential innovations. The need for refillable cartridges to decrease the amount of materials that would need to be brought from Earth, and more long-lasting cartridges will need to be addressed in order to maintain sustainability. Although current pod lifespans may be limited to three days and to 200 units of medicine, ongoing developments aim to extend these limitations, making them more suitable for the prolonged stay of Mars settlers.

Internal mitigation strategies are incredibly important, but at the moment will not be efficient enough in providing total protection against the galactic cosmic rays and space radiation which is much stronger than anything experienced on Earth. It must work symbiotically with external mitigation strategies and epidermal strategies in order to have as many layers of protection as possible to give astronauts the best chance at survival.

RADIATION RESILIENCE: BREAKTHROUGHS IN EPIDERMAL PROTECTION FOR MARS MISSIONS

M. Pareja Boto, M. Doukovska, A. Lynch

Summary

The study reviews ongoing research efforts in epidermal protection, by focusing on Selenomelanin, Cladosporium sphaerospermum, and boron nitride nanotubes (BNNTs).

Selenomelanin, a selenium-enriched biomaterial, shows potential in shielding against radiation on Mars. Cladosporium sphaerospermum, a fungus capable of radiosynthesis, uses melanin to grow and convert gamma rays into chemical energy, providing probable protection against cosmic rays.

Boron nitride nanotubes (BNNTs) are explored for spacesuit technology. They serve as a structural framework into which hydrogen can be incorporated and stored, which enhances protection against solar particle events and cosmic radiation.

Our findings contribute to understanding novel strategies for safeguarding human skin from Martian radiation exposure. Ultimately, our research provides valuable insights into the development of advanced protective measures crucial for human exploration and habitation on Mars.

Introduction

Space radiation poses a significant and hazardous threat to human health, primarily through the direct impact of solar energetic particles (SEP) and galactic cosmic radiation (GCR). The interaction of highly charged particles from SEP and GCR with molecules results in damage [32]. Moreover, when GCR and SEP interact with the skin, they lead to the production of secondary radiation, particularly damaging neurons, which have been associated with an increased risk of radiogenic cancers [33]. It is crucial to note that when cells are exposed to this secondary radiation, they undergo damage, yet remain capable of reproduction, resulting in mutations that can have long-term consequences [34]. Recognizing the outermost layer of the skin, the epidermis, as a natural protective barrier against various external factors, including on-Earth radiation, emphasizes the need for specialized measures to protect this layer. In the context of space exploration, preserving the integrity of the epidermis becomes critical to prevent potential damage caused by space radiation. Epidermal protection, as a concept, involves the development and implementation of effective measures or materials specifically designed to shield the skin from the harmful effects of space radiation. In light of these considerations, this research explores innovative solutions and strategies aiming to contribute to the development of robust protective measures for astronauts during space missions.

Description

We first reviewed the ongoing research and efforts in epidermal protection for astronauts against space radiation. Significant research delved into Selenomelanin, Cladosporium sphaerospermum and boron nitride nanotubes (BNNTs).

Selenomelanin and Cladosporium sphaerospermum- Melanins are vital polymers found in living organisms such as animals, plants, fungi and bacteria. Five varieties of melanin have not been fully structurally understood yet: eumelanin, neuromelanin, pyomelanin, allomelanin and pheomelanin. Some researchers have found that pheomelanin has enhanced absorption capabilities for X-rays, although allomelanin and eumelanin have been thoroughly researched before. It is believed that there is a new biomaterial in nature which is a mimic of pheomelanin. Instead of containing sulfur, this material is enhanced with selenium. Since selenium is heavier than sulfur and its absorption capabilities are stronger due to the X-ray absorption being proportional to the fourth power of the atomic number, scientists believe that this type of melanin, called selenomelanin, will provide better protection against radiation on Mars [35].

Moreover, researchers discovered a fungus, called Cladosporium sphaerospermum, that "feeds" on radiation to grow and turns the gamma rays and X-rays into chemical energy. This is very similar to how plants perform photosynthesis. Scientists call this specific process radiosynthesis. The secret behind these capabilities and benefits for human missions to Mars lies within the high amounts of melanin in this fungus. The melanin plays a crucial part in producing energy and protecting the astronauts against the hazardous cosmic rays.

Boron nitride nanotubes (BNNTs)- Previous investigations into hydrogen's chemical properties highlight its effective shielding properties, primarily attributed to its high charge-to-mass ratio. Hydrogen demonstrates efficiency in stopping protons from solar particle events and breaking apart heavy ions in galactic cosmic radiation. Moreover, hydrogen slows down secondary neutrons formed during matter interactions with cosmic rays or solar particles. However, hydrogen lacks structural integrity on its own, necessitating the construction of a supportive framework. Recognizing the substantial neutron absorption capabilities of boron and nitrogen, both surpassing carbon, there is an emphasis on integrating them with hydrogen to enhance secondary protection. The collaborative efforts of NASA Langley Research Center (LaRC), Jefferson Sciences Association (JSA), and National Institute of Aerospace (NIA) have recently resulted in the synthesis of long, highly crystalline boron nitride nanotubes (BNNT) using an innovative pressure/vapor condensation method [33] As seen in Fig. 2, these BNNTs are nanotubes where hydrogen can be incorporated and stored.

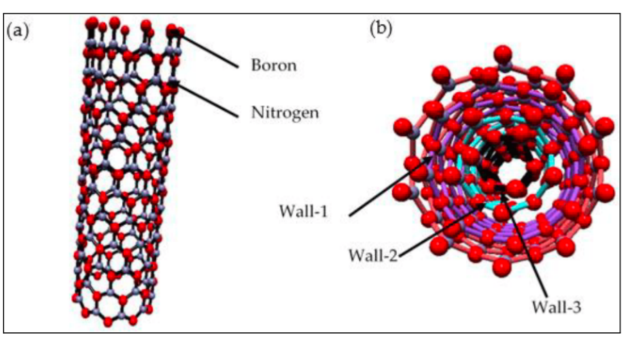

Figure 2: Illustration of (a) BNNTs (red—boron, blue—nitrogen); (b) multiwalled BNNTs [36]

Results

Selenomelanin synthesis- Gianneschi's team at Northwestern University conducted an experiment to synthesize the new biomaterial - melanin enriched with selenium and investigate how it performs under radiation. One of the main experiments they did was to explore what effect selenomelanin nanoparticles (SeNP) have against radiation on neonatal human epidermal keratinocytes (NHEK). The team focused on G2/M phase cell cycle arrest. This is the phase in the cell cycle where the cells prepare for division. If the G2/M phase population increases, then that suggests that there is a delay in cell division, which could be due to cellular stress or damage, caused by the X-ray exposure.

The experiment involved exposing NHEK cells to X-rays and monitoring the ones that are treated with synthetic melanin nanoparticles and the ones that are not. The untreated ones showed a significant increase in the G2/M phase population from 15% to 46%. Gianneschi's team treated the exposed NHEK cells with three types of synthetic melanin nanoparticles and observed that out of all of them only the SeNPs were able to prevent G2/M arrest. This is why they treated the cells with the SeNPs and then exposed them to different doses of X-ray radiation (0, 2, 4, or 6 Gy). Even after being exposed to 6 Gy X-ray radiation, the G2/M phase population remained at 17%, which was identical to the one in non-X-ray treated cells. These results show that SeNPs can protect the human skin against radiation exposure.

After these exceptional results, the scientists also believe that this biomaterial can be made and used as a type of melanin-based sunscreen or as a protective film to shield different materials from radiation as well [37]. They found out that this selenomelanin can be bio-synthesized which means that if fed with the proper nutrients, live cells may be able to produce it and the biomaterial would still retain its protective properties [37].

Moreover, a separate team is researching samples of the fungus Cladosporium sphaerospermum on the International Space Station and how it performs under radiation. They exposed petri dishes with and without the fungus to cosmic radiation. The results showed that the ones containing the fungus cut the radiation levels by 2%. Another experiment that they did was to investigate the attenuation properties and the ionizing events of the fungus. What the team discovered was that approximately 8.6% of the accumulated biomass of the fungus was estimated to be made up of melanin. Melanin is known for its high attenuation capacity at 150 megaelectronvolts, which makes it very effective for shielding against ionizing radiation. By combining the biomass of the fungus or melanin with Mars regolith, the researchers hope to create a material that provides improved protection against ionizing radiation. There have been discussions for the use of melanin in these materials for textiles and advanced manufacturing technologies as well.

BNNTs and spacesuit technology- Theoretically, the BNNT could undergo processing to create structural BNNT, exhibiting thermal stability up to 800°C in air, suitable for use in load-bearing structures [33] . Furthermore, they have extraordinary strength and high temperature stability. At Rice University, a team led by professors Matteo Pasquali and Angel Martí found that BNNTs assemble themselves into liquid crystals under the right conditions. They then developed a process to extrude liquid crystals of boron nitride nanotubes into fibers. The fibers could be useful for aerospace

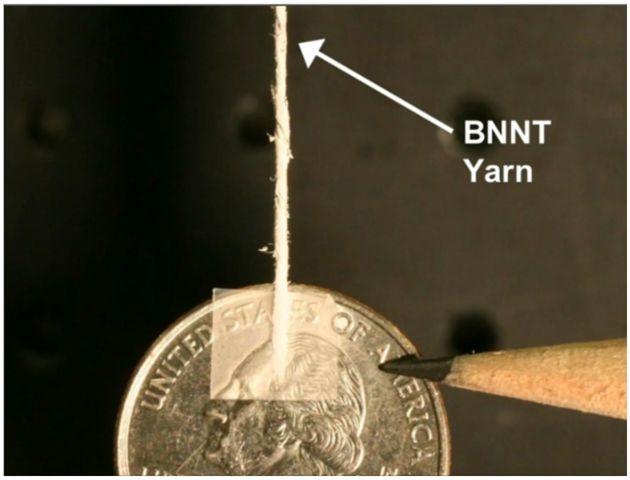

Figure 3: A piece of the boron-nitride nanotube yarn [38]

and electronics applications and as energy-efficient materials [39]. They have indeed developed yarn, as portrayed in Fig. 3, made out of BNNTs which could be used for the spacesuits.

Conclusion

In conclusion, exploring innovative solutions has led to the discovery of selenomelanin which shields against X-rays, along with the unique capabilities of Cladosporium sphaerospermum, and the development of BNNTs as a promising effective epidermal shield against space radiation. As we delve into the potential applications that range from wearables to aerospace vehicles, it becomes clear that a multifaceted approach holds the key to mitigating the challenges for manned missions to Mars. A combination of effective internal, epidermal and external protection will be the only solution to the challenge posed by radiation. The utilization of Cladosporium sphaerospermum as a potential shielding agent for aerospace vehicles and constructions warrants further exploration and consideration. A comprehensive study is imperative to ascertain the quantity required for effective shielding, coupled with an analysis of the growth time required to achieve the desired protective layers. Furthermore, beyond its shielding properties, integrating Cladosporium sphaerospermum into spacesuit design presents an intriguing idea. Such an approach could potentially leverage radiation exposure not only for shielding purposes but also as a means to generate electricity. Due to radiosynthesis, this fungus can generate energy which could be harvested and used for various purposes, including sustaining essential life-support systems within the spacesuit, as is oxygen maintenance. Further investigation into external protection will follow.

INNOVATIVE STRATEGIES FOR EXTERNAL RADIATION PROTECTION AND SUSTAINABLE HABITATS ON MARS

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Summary

Innovative usage of the Martian environment and its resources is required in order to shield and protect future terrestrial life from radiation. A strong external barrier is a necessary component in providing radiation mitigation; the usage of winding underground lava tubes, ancient impact craters and Chernobyl radiotrophic fungus all provide different angles in this query. Though on-site research is limited since there is no established safe martian base yet; this paper provides many possible future research alternatives in order to create a safe research environment, with an emphasis on options for the first Martian settlers.

Introduction

Ensuring external protection against radiation is a critical imperative for the progress of human exploration, particularly in new frontiers such as Mars. As highlighted by Walsh et al. (2019), the prolonged exposure to elevated radiation levels on Mars poses a substantial threat to astronaut well-being, especially considering the envisaged duration of manned missions exceeding two years. Consequently, an effective external radiation shielding strategy becomes indispensable for the mission's success. The challenge is compounded by the need for shielding solutions that are both enduring and cost-effective, considering the significant cost associated with transporting every kilogram to Mars [40].
This paper advocates for the incorporation of in-situ resource utilization (ISRU) as a fundamental aspect of external radiation protection on Mars. Our proposed framework comprises two primary components: habitat and location. The habitat, where astronauts will predominantly reside, demands a design that optimizes both volume and weight efficiency. Given the logistical complexities and cost considerations, leveraging local resources through ISRU becomes imperative.
The selection of a suitable location emerges as a critical factor for the success and safety of the initial manned mission, given the substantial variability in radiation levels across Martian terrains [16]. Astronauts, constrained in their exploration range during the early phases of the mission, will heavily rely on the chosen location for protection against radiation. Thus, careful consideration and fulfillment of multiple criteria are imperative in the strategic selection of the mission's location. This paper aims to delineate and propose effective strategies for addressing these multifaceted challenges in achieving robust external radiation protection on Mars.

Description

Location- Identifying a site with the lowest radiation and highest average annual atmospheric pressure could serve as an initial step in mitigating radiation risks. The Hellas Planitia (Fig. 4) is an impact crater in the southern hemisphere of 2299.16 km in diameter [41] and up to 8000 km in depth [42] it is recognized as possibly the deepest point on Mars. This causes the Hellas Planitia to experience the highest average pressure of around 1/100th of an atm or 1.2 103 Pa [43]. The Hellas Planitia is provided with a unique climate which proves cooler than the surrounding planes. It presents the possibility of the existence of liquid water, though inconsistent as daily temperature as it reaches below 273K, the range still allows for liquid water to exist within the basin [44]. The triple point of water is 277.15K at 812.7 Pa [45] as such given a higher than average temperature it would be possible for water to exist in liquid form in the Hellas Planitia. Spectral analysis indicates elevation concentration of gypsum ($CaSO_4 \cdot 2H_2O$) which co-occurs with halite ($NaCl$) and specific sulfates in the Planitia [46]. Further analysis of

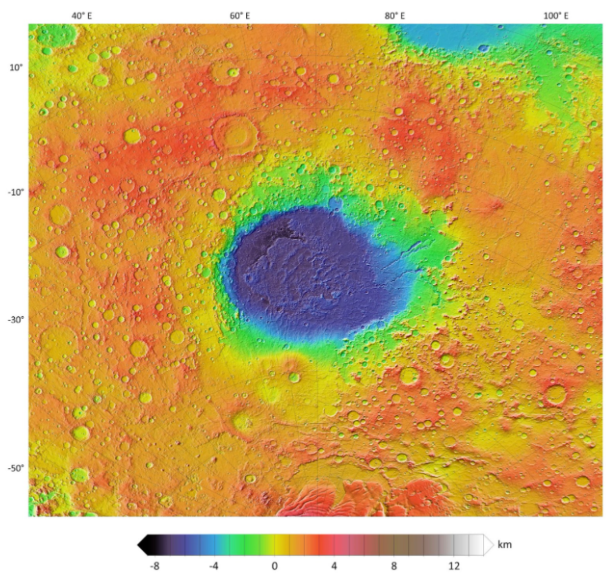

Figure 4: Topographic Map of Hellas Planitia [47]

Hellas Planitia indicates promising locations in the vicinity of Hadriacus Mons, an ancient low relief volcanic mountain along the northeastern edge of Hellas Planitia. A review of more than 1500 images from NASA's Mars Reconnaissance Orbiter has identified three candidate lava tubes for potential manned exploration and habitats [48].

Habitat

Regolith as a radiation shield- Embarking on the journey to establish human colonies on Mars requires innovative approaches to address the challenges posed by radiation exposure. Exploring the effectiveness of Martian regolith as a radiation shield is a key aspect of this endeavor [49]. Martian regolith composition primarily comprises weathered basalt, featuring salts like sulfates and perchlorates. Analyses reveal essential macro elements (C, H, O, N, P, S, K, Mg, Na, and Ca) and minor elements (Mn, Cr, Ni, Mo, Cu, Fe, and Zn) crucial for life within basaltic regolith soil. [50]. Research has delved into the efficacy of Martian regolith as a radiation shield, highlighting the potential of mixing water ice with regolith to create concrete for constructing radiation-resistant habitats [49]. Concurrently, experiments focusing on waterless concrete, achieved through varying regolith-to-sulfur ratios, have pinpointed an optimal composition of 70% regolith and 30% sulfur for superior strength and durability [51].

Models for a sustainable colonization underscore the use of Martian concrete, proposing structurally efficient forms, like MarZ-5, which reduce material and energy requirements by 50%, presenting a cost-effective approach to colonization [52]. By using all of the sulfur concrete's elastic tensile capacity, the quantity of material needed for construction can be reduced through the use of relative optimization [52]. Relative optimization can be utilized to enhance the suggested models' structural behavior and lower the quantity of material needed for construction [52]. Proposed models also exhibit elastic behavior under Martian loads, requiring less concrete and energy for construction [53].

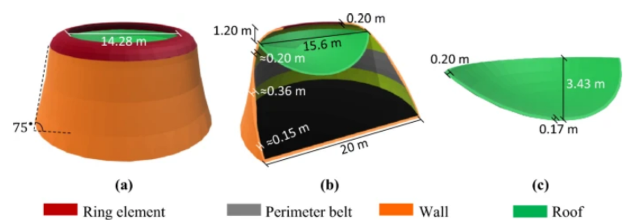

Figure 5: MarZ-5 Model [52]

Radiotrophic fungi- In the exploration of viable habitats on Mars, there's a growing interest in incorporating radiotrophic fungi, organisms known for their ability to thrive in environments rich in ionizing radiation. These fungi exhibit unique responses to radiation exposure, including enhanced growth and adaptability [54]. Recent studies have identified melanized fungal species, particularly those found in high-radiation environments like Chernobyl's reactor and space stations, showcasing their resilience [54]. On the International Space Station (ISS), various fungal species, including Aspergillus, Penicillium, and Saccharomyces, have been identified, with their presence hinting at the potential advantages of melanin (biological pigment absorbing radiation, with energy transduction and shielding properties) in extreme conditions. As long as there is enough humidity, these fungi may flourish in the ISS, despite being exposed to 4 cGy of ionizing radiation annually, which is not fungicidal [54].

In our exploration of sustainable solutions for Martian habitats, we are intrigued by the potential benefits of integrating radiotrophic fungi into the structure of surface habitats. Beyond the sustainable structural models, such as MarZ-5 [52], providing protection against Marsquakes and micrometeorite impacts, these fungi could contribute to radiation shielding on the surface of the habitats. Moreover, their unique ability to convert ionizing radiation into other forms of energy [54] introduces an exciting prospect for harnessing this radiation-rich environment as an alternative energy source to support and sustain Martian habitats. Further future research could potentially delve into the prospect of genetically engineering plants to become radiation resistant using the same mechanics of the melanin pigment behavior in radiotrophic fungi. Indigenous, fixed nitrogen in Martian rocks and sediments [55] have important ramifications for the growth of these genetically modified terrestrial plants.

Natural shielding on Mars- Surface habitats on Mars however confront significant challenges when considering the first base settlement, spurring exploration of alternative solutions. Specific Martian topographical features, such as buttes with shadows, have been identified as natural shelters offering radiation protection [56] Studies indicate that during certain periods, these geological formations can shield approximately 7.5% of neutral radiation (secondary particles such as neutrons), providing a valuable option for temporary refuge during emergencies or solar flares [56] This intrinsic shielding effect showcases the potential for utilizing Mars' natural landscape to enhance astronaut safety [56] Furthermore, insights from health threat assessments during manned missions to Mars underscore the crucial role of advanced materials, such as hydrogenated BNNT microtubules, integrated into spacecraft structures and spacesuits for enhanced radiation shielding [17].
In addition, a pioneering approach proposed by Technical University Delft (TUD) envisions subsurface habitats created by excavating into Martian regolith, providing natural shielding from radiation and stable temperatures crucial for thermal insulation [57]. These requirements are crucial for thermal insulation and survival of crew on Mars. Simultaneously, the process allows for in-situ resource utilization (ISRU) by extracting valuable materials [58]. An approach to this process is the design-to-robotic-production (D2RP) method, involving a swarm of autonomous robots excavating regolith mixed with cement for 3D-printing structures, presenting an innovative, self-sufficient approach to habitat construction [57]. The limitations of creating an electrostatic radiation shield are acknowledged, emphasizing the need for protective measures, such as constructing underground shelters in lava tubes for temporary and long-term habitation [17].

Lava Tubes- A more sustainable option for the first Martian settlers could potentially be lava tubes. These geological formations could serve as natural shelters, shielding human missions from radiation and environmental challenges [48], aligning with the sustainable approach to Martian colonization. Lava tubes are a promising location for any habitat on Mars because of the ideal features. Lava flows are an outburst of lava that moves during a non-explosive effusive eruption. While lava can be 100,000 times more viscous than water, these lava flows can flow for a large distance before abating and solidifying. Lava flows can occasionally result in lava tubes, natural subsurface caves, which appear when the exterior of rapid lava flows cool more rapidly and form a strong crust over the subsurface lava [48]. The lava flow ultimately drains out of the tube, leaving a conduit shaped void almost parallel to the ground and several meters under it. These lava tubes exist on Earth and Mars, and as martian gravity is 37% of that on earth, martian lava tubes are generally much larger than those found on earth. Promising lava tubes at Hadriacus Mons range from 600 to 900 meters long and from 300 to 600 meters wide. To ascertain the feasibility of using lava tubes to reduce crew radiation exposure on mars analog radiation experiments were conducted on Earth. While there is much less radiation on Earth, some still reaches the surface especially during solar events. The results showed a reduction from 0.471 μGy/hr to 0.083 μGy/hr [48]. This represents an average radiation reduction of 82% inside analog lava tubes. It is therefore possible to infer that the analog martian lava tubes at the southwest of Hadriacus Mons would also reduce radiation by 82% and accordingly reduce crew exposure from 342.46 μGy/day to 61.64 μGy/day.

Conclusion

It is crucial to emphasize using the materials present on Mars for habitat construction, as otherwise shipping materials to and from Earth and Mars would pose problems. Thankfully, there are many ways that we can be creative with Mars' topography and geology, such as the lava tubes inside of the Hellas Planitia. Once this first settlement has been set up, it will be much easier to continue research on the Martian climate, its natural minerals and geological characteristics. This will ultimately speed up the process for any further colonization projects, where a more extensive settlement will have to be built. Research will now have to continue on how to perfect the methods of mining regolith and other minerals, building habitats with autonomous robots, and 3D-printing using concrete made up with sulfur before we can make this first settlement a reality. Delving into the prospect of bioengineered radiotrophic terrestrial plants as another layer of external radiation protection could realize the vision of a surface city on Mars further down the line.

EDITORIAL CONCLUSION

This literature review has provided a comprehensive exploration of radiation protection strategies for Mars, encompassing internal, epidermal, and external dimensions. While significant advancements have been made in those domains, numerous opportunities for future exploration and refinement persist.
Internal radiation protection necessitates continued investigation into the long-term effects of pharmaceutical interventions. Rigorous clinical trials in simulated Martian environments are imperative to validate the efficacy and safety of identified compounds such as statins, n-acetylcysteine, and pentoxifylline. Understanding potential synergies and side effects arising from combining these medications will be pivotal for optimizing radioresistance during extended Mars missions.

The development and customization of advanced technologies for medication administration, including patch pump systems, represent an ongoing area of research. Future endeavors should focus on materials science, and advancements in cartridge technology to enhance the longevity, efficiency, and adaptability of drug delivery systems, tailored specifically to the challenges of Mars habitation.

Epidermal radiation protection demands further exploration into innovative materials and technologies. Bioengineered solutions that enhance the natural shielding properties of the skin, akin to the melanin-based mechanisms in radiotrophic fungi, hold promise. Additionally, advancements in wearable technologies that provide real-time monitoring of radiation exposure and offer adaptive shielding mechanisms should be a focus for future investigations.

External radiation protection, encompassing habitat design, shielding materials, and strategic location selection, constitutes another critical frontier. Sustainable colonization of Mars requires robust and enduring solutions. Further research is needed to optimize the use of Martian regolith in constructing habitats, as well as evaluating the efficacy of radiotrophic fungi as natural shields, and harnessing Mars' unique topographical features for enhanced protection.

Moreover, the regulatory landscape surrounding pharmaceutical and technological interventions in space missions requires attention. Advocating for flexible guidelines that consider the unique limitations of space exploration will be crucial for the successful implementation of novel therapeutic and protective strategies. Bridging the gap between evolving space medicine practices and regulatory frameworks is an avenue for both current and future stakeholders to explore.

Looking beyond the confines of interplanetary exploration, the technologies developed for Mars radiation protection-internal, epidermal, and external domains, can significantly contribute to sustainability challenges on Earth. Historical precedents, such as Teflon and Velcro, showcase how innovations driven by space exploration find diverse applications in terrestrial contexts. Similarly, breakthroughs in radiation protection have the potential to spill over into advancements benefiting healthcare, materials science, and environmental protection on Earth.

Mars, with its sustainability challenges, serves as a testing ground for innovative solutions that, once perfected, can be adapted to address challenges on Earth. The interdisciplinary nature of this research offers a unique opportunity for cross-cutting applications in various fields. As researchers continue to push the boundaries of space colonization, the knowledge gained and technologies developed not only advance our capabilities for interplanetary habitation but also hold the promise of positively impacting sustainability efforts on Earth.

In essence, this research lays the groundwork for the next phase of advancements in radiation protection for future Mars settlers. Continued collaborative efforts and interdisciplinary research will be pivotal in turning these possibilities into reality, ensuring the success of future missions and the broader applicability of the technologies developed.

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