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Why Human Enhancement is Necessary for Successful Human Deep-space Missions

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While humans have made enormous progress in the exploration and exploitation of Earth, exploration of outer space remains beyond current human capabilities. The principal challenges lie in current space technology and engineering which includes the protection of astronauts from the hazards of working and living in the space environment. These challenges may lead to a paradoxical situation where progress in space technology and the ability to ensure acceptable risk/benefit for human space exploration becomes dissociated and the rate of scientific discovery declines. In this paper, we discuss the predominant challenges of the space environment for human health and argue that development and deployment of a human enhancement policy, initially confined to astronauts – for the purpose of future human space programmes is a rational solution to these challenges.

KEYWORDS Mission to Mars, space environment, space radiation, microgravity, human enhancement, gene editing, ethical issues

1. Introduction

The space environment is a hostile environment for human beings. Humans have evolved over the last several millions of years in a stable terrestrial environment with constant gravity. As there is no genetic memory for eukaryotic life responding to changes in gravity, the physiology and psychology of humans is adapted to the geophysical conditions of the Earth. Human cardiovascular and musculoskeletal systems and all biological systems including perception (Vico and Hargens 2018)

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are designed to operate in Earth gravity, denoted as 1 *g*. The geophysical properties of Earth made evolution of life possible and natural selection drove the evolution of living forms, including humans, to adapt to Earth geophysics. It would seem a reasonable assumption that under conditions of gravity greater than or less than 1 *g*, living forms would evolve alternate organizations of cardiovascular systems, which could provide appropriate blood pressure to sustain life. Likewise, under different rates of exposure to space radiation, such as when Earth did not have a magnetic field at the very beginning of its history, or during a temporary degradation of the magnetosphere which occurred about 565 million years ago (Bono *et al.* 2019), or a thick protective atmosphere about 2.7 billion years ago (Emspak 2016), a wide diversity of surface life would have been unlikely to evolve except in simple form. It is possible that only some extremophiles could evolve, which may reside under the planet's surface away from radiation exposure. Other factors important for the evolution of life, which distinguish Earth from other planets include temperature, atmospheric composition and access to water. In contrast to reduced or increased gravity and exposure to space radiation, humans have evolved in temperate climates in a breathable atmosphere and in the presence of water. While we can simulate some conditions needed for life, we cannot yet create artificial Earth-like gravity in space, or effectively protect humans against space radiation.

In this paper, we argue that human astronauts should be augmented for deep-space mission at the pre-launch stage in an alternative way from that offered by space agencies today. Current procedures include the inclusion of countermeasures such as diet, exercise, pharmaceuticals and anti-radiation shielding. Pharmaceutical efficacy may be limited to missions which are not longer than 2 years which may challenge a human mission to Mars which may last about 3 years. Astronaut augmentation may include a human enhancement programme based in part on genetic engineering, nanotechnology, robotics and cognitive science adaptation (Roco and Bainbridge 2003, Chien and Wagstaff 2017, Gao and Chien 2017). If we assume that the space environment may require enhancement of future astronauts, it is essential to ensure a clear rationale[1] for doing so as sending astronauts to such a hostile environment without consideration of appropriate countermeasures is unethical. Accepting that enhancement is a necessity, and assuming a favourable cost–benefit analysis, parameters such as invasiveness, reversibility or heritability must be considered. This will take into account long-term effects such as the risk of irreversibility of enhancements.

One major rate-limiting step in the concept of deep space exploration and colonization is protecting astronauts and future colonists from both short and long-term exposure to space radiation (Sion 2011; Chancellor *et al.* 2014, 2018; Cucinotta *et al.* 2014) and although we are aware of the complexity of other hazardous factors in space such as the effects of living and working in microgravity, and in isolated habitats, we will focus our attention on the effects of space radiation.

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[1] The issue of rationale for human missions to Mars and other human deep space missions is discussed in detail in Szocik (2019).

2. Rationale for human enhancement in space

Human enhancement implies that human functions and capacities are modulated, usually positively. However, in a dynamic system, enhancement may initiate new functions and capacities which are not a domain of the human species today. As such, human enhancement may be perceived as controversial. However, while some basic criteria should be satisfied such as safety and efficacy, there are good reasons to consider any opportunity to enhance human physical, psychological or even moral capacities.[2] First in places on Earth subjected to high radioactivity[3] or exposure to radiotherapy, which may cause behavioural and cognitive modifications (Newhauser *et al.* 2016), workers and patients are exposed to radiation for a limited time only. In space, exposure to a high radiation dose is constant. Moreover, even if astronauts are able to survive several year missions to Mars, their performance and effectivity may be expected to decline (Ade *et al.* 2017). Secondly, the return on investment (ROI) as determined by its mission success, and benefits to Society on Earth become questionable if astronauts are weak, ill and compete for survival in space. One solution may be the use of an automated or robotic crew though it is widely recognized that certain tasks are currently dependent upon human judgement in real time, which is irreplaceable by automation (Crawford 2012).

The lack of investment in human enhancement to support extended periods of space travel and a dearth in our knowledge support the use of pharmaceutical intervention over travel periods of long duration could lead to a divergence between the execution of human and robotic space missions. Without human enhancement it is possible that exploration of space by human astronauts will remain limited to low Earth orbit and possibly lunar expeditions and as a consequence of limited investment, robotic space exploration may become an alternative for limited science activities without endangering human life. If the costs of human enhancement are greater than the costs of developing robotic technology, then one may also make a cost–benefit argument in favour of a robotic space programme. In contrast, advocates of human presence in space which provides dexterity and intelligence superior to that of automated systems regard enhancement as a necessity and recommend development of human enhancement programmes, as a unique effective countermeasure.

Substantial and radical biological human enhancement proposes interventions which are invasive, irreversible and heritable (in the case of germline gene editing) and which may radically change human 'nature' like, for instance, in the case of hypothetical moral bioenhancement. In 1960 it was proposed that 'altering man's bodily functions to meet the requirements of extraterrestrial environments would be more logical than providing an earthly environment for him in space' (Clynes and Kline 1960). They introduced the term 'cyborg' expressing the idea

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[2] It is worth considering an interesting idea of moral enhancement by biomedical means considered by Julian Savulescu and colleagues. The key essence of biomedical moral enhancement is that we can increase human morality and improve our moral biases by biomedical intervention (Savulescu and Persson 2019).

[3] Air travel and underground working (mines, water supply) are significant radiation environments. In fact air crew are the most occupationally exposed group of workers. So there are legal requirements to monitor their radiation exposure. Some of the research groups looking at astronaut radiation exposure also work on aircrew exposure.

of human modification by available technologies. Their idea has not previously been explored by scientists working in space programmes in a systematic and in depth manner and even enhancement technologies discussed in regard to Earth are limited and somewhat restricted in thinking. Very recently proposed ideas for further development include, among others, human machine interface (brain-computer interface/BCI) and relationship or embodied cybernetic systems (Alicea 2018).

Our philosophy of human enhancement assumes that it will be by exception and only when the mission demands it, such as exploration voyages of longer than a two-year duration, or semi-permanent or permanent planetary colonization. Enhancement would require informed consent of adult astronauts who should be informed about all predictable effects of this procedure according to the current state of the art. For gene editing, we consider only an opportunity for gene editing of somatic cells and in some cases, genetic modification of somatic cells may potentially increase human resistance to long-term exposure to space radiation, and possibly cope with some hazardous effects of microgravity and reduced gravity. One option which could be considered, at least in theory, is inter-species human enhancement which includes application of genes of other, non-human animal species which may confer greater resistance to space radiation. The question arises as to whether non-gene editing procedures may be ever confer the same putative benefit afforded by gene editing. Because somatic gene editing/therapy is not heritable, it may be assumed that somatic gene editing could be treated as a morally and legally permissible procedure which is desirable for humanity *per se*, for instance due to its beneficial effects such as modifying serious disease. Here we do not consider gene editing of germline cells which is both highly controversial ethically, not necessary and logistically impossible for application to a crew pre-launch. Germline gene editing of future astronauts would require specific social engineering programmes in which society/mission planners decide which embryos should be selected to become deep-space astronauts of the future. Although not scientifically possible today, the possibility cannot be excluded given that human settlers will need to be able to reproduce in space.

Human enhancement in space is treated akin to therapeutic intervention rather than as an act of pure enhancement and if one wants to apply this to space, this may be regarded as a classical therapy-enhancement distinction. However, therapy-enhancement distinction is broadly criticized due to the problematic, unclear and flexible borders between what is therapeutic and what is for enhancement. Despite this critique, and accepting that the relevance of terminology such as therapy and enhancement depends on current environmental and ecological conditions and intended purpose, we will take for granted that any enhancement applied to astronauts will be aimed at increasing resistance and adaptivity to hazardous space factors, and will be a new type of therapeutic intervention. As designer human enhancement procedures in space may become a necessity, it may receive special, medical, ethical and regulatory consideration when compared with enhancement procedures on Earth which may be considered as unnecessary, extravagant and redundant procedures when applied to healthy individuals.

3. Space environment and hazardous factors in space

As Mars is the most probable destination for the first human interplanetary mission, we will focus our attention on this planet. In contrast to Earth, Mars does not have a global magnetic field. Its atmosphere is 100 times thinner than the atmosphere on Earth (Flores-McLaughlin 2017) and for this reason, the Martian surface is freely bombarded by galactic cosmic radiation (GCR).

Another challenge for astronauts is experiencing microgravity during the interplanetary journey and in living under reduced gravity on Mars, which is 0.38 *g*. Other deleterious factors in space include psychological discomfort, and possible toxic air composition in spacecraft and on the surface of Mars (Moreno-Villanueva *et al.* 2017).

The health hazards of living and working in space have been documented by many (eg Braddock 2017a, 2018a, Vico and Hargens 2018), and no place on Earth can fully replicate an equivalent environment in space. Hazards include: effects of altered gravity such as 'lack of gravitational loading and hydrostatic pressure, lack of convection, buoyancy and sedimentation;' in-flight and long-term impact of radiation; specific space habitat including 'distance from Earth, 90 min day and night cycles, acoustic noise (60 dBA), reduced and closed space, isolation, lack of natural light and surroundings, modest increased ambient CO_2;' conditions of life in space like 'limited privacy, floating, disturbances in sleep, hygiene, performance pressures;' possible effects caused by EVA like 'high vacuum, extremes of temperature, meteoroids, space debris, ionospheric plasma, hand and shoulder injuries' (Vico and Hargens 2018). The most dangerous occupations on Earth do not include the risk of being killed by a meteorite or space debris. Military pilots, for instance, are exposed to transient high g forces and other extreme physical parameters, which are not comparable with the launch of a space rocket or managing permanent microgravity in space.

One important scientific issue is the difference between short high exposures and long low exposures to radiation, which apply to space missions within and beyond the protective effects of the Van Allen belts outside of the solar system. The low dose may well have less impact as the human body has some ability to repair radiation damage. It is likely that short high doses will carry a greater level of risk and it is essential that astronauts shelter or are protected from events which generate short high doses such as solar particle events (SPE) (Hu 2017). Long, low exposures might be mitigated against if DNA repair mechanisms can be enhanced and the NASA roadmap for conferring radioresistance proposes some strategies, based in part upon identification of radioresistance factors from extremophiles (Cortese *et al.* 2018). The assessments ESA made 10–15 years ago noted that without a major advance in radiation protection (e.g. much better shielding, reduced travel time) astronauts may survive a mission to Mars and back to Earth but cannot go further into the solar system or beyond it. Space missions also cause a substantial loss of bone mineral density and the deleterious impact of microgravity may be augmented by space radiation (Vico and Hargens 2018), and vice versa (Moreno-Villanueva *et al.* 2017).

NASA has identified five hazards for astronaut health in space which include space radiation, isolation, distance from Earth, micro- and reduced gravity and hostile environment in general (NASA 2018c). The NASA Human Research Roadmap illustrates well the hazardous effects of space radiation on health such as the potential diseases of central nervous system, impairment of the immune system, acute tissue atrophy elevated risk of developing cancer.

Astronauts face greater for long interplanetary journey. Some astronauts have spent one year in space, such as Scott Kelly and Mikhail Kornienko in 2015/2016 and longer such as, 437 days spent by Valeri Polyakov at the Mir space station mission in 1994/1995. However, the durations of these missions are well within the minimal time for a round trip mission to Mars, which is estimated to last 3 years.

After the risk of cancer, circulatory disease is the next greatest challenge to health during a mission to Mars (Cucinotta *et al.* 2013). In addition to the effects of radiation, the cardiovascular system affected by altered gravity, diet, permanent confinement and social stress. Countermeasures include physical exercise, diet and radiation shielding (Hughson *et al.* 2018). No methods for substantial enhancement are applied or recommended.

Despite this, the study of early NASA astronauts shows that there is no higher risk of cancer or cardiovascular disease when compared with a non-astronaut cohort (Elgart *et al.* 2018). Another study on astronauts and cosmonauts confirms these results and shows that these groups have lower chances for death caused by natural diseases than the general population (Reynolds and Day 2018). However, in animal studies with mice, a higher risk of developing lung and colorectal cancer was demonstrated after exposition to heavy ion and SPE exposure (Kim *et al.* 2014). Future space missions beyond low earth orbit (LEO) will generate new data and personal experiences of astronauts exposed to higher space radiation than experienced from previous space missions Elgart *et al.* (2018) and Chancellor *et al.* (2018).

NASA's twin study reveals how the space environment changes global gene expression (Garrett-Bakelman *et al.* 2019). A 7% change in gene expression was measured for Scott Kelly after his one-year space mission at the ISS. His gene expression profile was compared with his twin brother Mark who remained on Earth. Although 93% of Scott's profile returned to normal after landing, the remaining 7% may implicate longer term changes in gene expression responsible for maintenance of the immune system, efficient DNA repair, bone metabolism and a response to hypoxia, and hypercapnia (Edwards and Abadie 2018).

In addition to the negative consequences for the space environment on human health, during a mission to Mars, unlike on Earth, astronauts will have limited access to medical treatment, and very limited access to professional care should emergency procedures need to be performed (Blue *et al.* 2019a). This circumstance may additionally reduce protection against radiogenic cancer (Aravindan *et al.* 2016) and is a considerable challenge for long term missions dependent upon Earth based medical resupply, given that all medications have a limited shelf-life and tolerance to temperature and radiation for example vitamin B-1 (Chuong *et al.* 2011) and some probiotics (Sakai *et al.* 2018) and this area has been recently reviewed (Blue *et al.* 2019b).

4. Space radiation

4.1. Characteristic of space radiation

Space radiation includes particles around the Earth's magnetosphere in Van Allen Belts, SPE[4] and galactic cosmic rays/radiation (GCR). GCR contains 1% of high-energy heavy ions (HZE particles), 90% of high energy protons and 9% of helium particles (Durante and Cucinotta 2008). Space radiation includes mostly protons and heavy ions and is qualitatively different from Earth radiation which comprises γ rays, β rays and α-rays. Space radiation, comprised of mostly high linear energy transfer (LET) particles causes greater health damages than radiation on Earth (Sion 2011). In addition to the killing effect of radiation and the potential for cell repair at low, longer exposures compared with high and shorter exposures, one additional factor is the impact of secondary radiation in spacecraft (Ohnishi *et al.* 2002). The Earth's inner radiation belt contains only ionizing protons because of the protective impact of magnetosphere and atmosphere and has not shown to be problematic when traversed quickly as with the Apollo missions. Without the magnetosphere, life on Earth would likely not exist on the surface and more probably exist in subsurface forms. The radiation received on the Martian surface includes GCR, SPE, secondary particles and albedo particles reflected from the regolith (Matthiä *et al.* 2017).

The exposure rate of radiation on Mars surface is difficult to measure precisely despite currently improved methodology (Wet and Townsend 2017). Space-based measurement registers only a part of neutron energy (Norbury *et al.* 2016, p. 48), and the main source of neutrons for astronauts on Mars expeditions will be secondary radiation. Isolated SPEs can produce more radiation and includes mostly low energy ions that can be effectively neutralized by shielding systems. Due to reduced solar activity in recent cycles, a higher impact of GCR is expected in the next series of solar cycles, which may reduce the number of safe days dedicated to interplanetary missions (Schwadron *et al.* 2018).

Exposure of astronauts to space radiation is between 50–2,000 mSv. 1 mSv is equivalent of three chest x-rays (NASA 2018a). The radiation dose received by an astronaut on the ISS is approximately ten times higher than the natural radiation dose on Earth (Blanchett and Abadie 2017c). In interplanetary missions, however, the exposure to GCR is estimated to be a further ten times higher than on the ISS (Krukowski *et al.* 2018). The daily radiation dose in space, 1.8 mSv, is comparable to the annual dose on Earth – between 1 and 3 mSv (Zeitlin *et al.* 2013) or 3.6 mSv (space radiation). 100 mSv of radiation absorbed by astronauts during 6 months on the ISS may cause an elevated risk of cancer on Earth (Chancellor *et al.* 2018). According to some estimations, the expected radiation dose during interplanetary journey is 1–2 mSv per day, while on Mars surface about 0.5–1 mSv per day (Chancellor *et al.* 2018). 500 days mission on Mars is equivalent to 180 days of journey to Mars and each day exceeds by approximately ten times the annual radiation worker limit (Flores-McLaughlin 2017). The estimated radiation dose received by an

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[4] SPE can arise from both flares and from fast coronal mass ejections. Flare-sourced SPE are shorted lived (up to 24 h) whilst those from fast CMEs may continue for several days.

astronaut during a three year mission to Mars is 1200 mSv (Space Radiation). NASA limits for LEO astronauts is 1000 mSv per year, but no more than 3250 mSv per 45 years male astronaut per career, and 2500 for 45 years female astronaut (Space Radiation).

Space radiation affects organic and inorganic materials. In one study conducted on the ISS, silk and collagen samples were exposed through 18 months to space radiation. About 80% of proteins in silk and collagen were crosslinked by radiation (Hu *et al.* 2013).

Highly charged (HZE) particles are more deleterious than a radiation dose received on Earth (Durante and Cucinotta 2011). Ionizing radiation – primary particles – may create secondary particles from objects, which are exposed to radiation. Secondary particles cause extra risk and damage because they produce shower containing mixed neutrons and fragments of shielding materials (Hughson *et al.* 2018).

4.2. Deleterious impact of space radiation on human health

Space radiation contains all elements of the periodic table which can enter the human body with almost speed of light and damage DNA and cells (Maalouf *et al.* 2011). Basic medical hazards caused by space radiation include cancer, mostly lung cancers (Kennedy *et al.* 2018), damage of central nervous system, degeneration of tissues and acute radiation risk causing skin injury or even death (NASA 2018b). Particle radiation may not only increase the risk of cancer after the mission, but it may also cause acute radiation sickness during the mission (Frazier 2015).

Space radiation affects the central nervous system and decreases the cognitive performance of astronauts (Krukowski *et al.* 2018). GCR received during journey negatively affects cognition, motor function and behaviour, which may have a negative impact on efficiency of performed tasks and operating spacecraft (Cucinotta *et al.* 2014, Parihar *et al.* 2015, Blanchett and Abadie 2017b) and is expected to increase risk of death and morbidity, and diseases of central nervous system (Cucinotta *et al.* 2013). Reduced cognitive performance may threaten mission success during interplanetary journey and landing and owing to a delay for round trip communication of up to a maximum of 48 min, astronauts should be able to make autonomous decisions.

Space radiation causes both short-term and long-term physiological changes. In the short-term perspective, space radiation affects haematopoietic cell and immune system. Astronauts during space missions may be more prone to infection than on Earth. Other manifestations may present such as blood coagulation, heart dysfunction, skin and vision abnormalities, which may also be a consequence of the impact of microgravity. Long-term effects include cataract and retinal opacity or cancer (Kennedy 2014, Zhou *et al.* 2018) and this is supported by the observation that airline pilots have been reported to show higher than normal rates of cataracts, possibly as a consequence of higher radiation exposure at aircraft cruise altitudes (10–12 km) (Rafnsson *et al.* 2005, Jones *et al.* 2007).

4.3. Shielding strategies and radiation prediction

Ionizing radiation is harmful for the human body because it easily penetrates the shielding materials of spacecraft. Shielding strategies are highly insufficient to protect against GCR and passive shielding strategies include uniform shielding for the entire spacecraft, safe shelter inside the habitat and generation of a microshelter (Vuolo *et al.* 2017). Special (micro)shelters supported by early warning satellite system are necessary in interplanetary spacecraft due to unpredictable short radiation events like solar flares or SPE (Space Radiation).

NASA is developing shielding hydrogen-rich materials including hydrogenated boron nitride nanotubes (BNNTs). Polyethylene is 50% more effective in protection against solar flares and 15% more effective against GCR than aluminium (Space Radiation). Alternatively, an artificial source of electric or magnetic field attached to spacecraft could be deployed although it would require more energy and materials (Frazier 2015). Some researchers have proposed a plasma shield of ionized gas surrounding the spacecraft where radiation particles will interact with the plasma and lose energy (Bamford *et al.* 2014). A journey of shorter duration and technology to provide faster spacecraft is also a possible solution to decreased time of radiation exposure during an interplanetary journey (Blanchett and Abadie 2017a). Current spacecraft shielding technology enables absorption of total radiation dose for SPE of between 25% for aluminium to 35% for polyethylene to maintain the balance between protection and mass (Durante 2009, p. A55). The ISS offers this rate of protection, but further increasing the mass for interplanetary journeys is not currently possible due to the need for a more powerful propellant with preferably less mass (Chancellor *et al.* 2018).

The shielding wall for the ISS is a maximum of 20 g/cm^2, while for spacecraft it is 5 g/cm^2. 5–7 cm of shielding for walls offers only 30–35% of protection against radiation (Space Radiation). Adding extra shielding materials not only increases the mass of the spacecraft, but it does not necessarily lead to an increase in overall radioprotection (Slaba *et al.* 2017). One of reasons is that a higher shielding mass presents a larger target for GCR interaction and the production of secondary particles (Durante 2014). For this reason, the use of materials currently available during space missions for shielding such as water or organic waste is proposed in a wearable radiation protection space suit designed to protect the astronaut's vital organs (Vuolo *et al.* 2017). However, such a space suit is currently envisaged for emergencies only and even if this shelter protects sufficiently against radiation, there are still unavoidable activities beyond shelter where an astronaut is exposed to higher radiation dose (Baiocco *et al.* 2018), for example astronauts will have to leave the shelter to repair and/or restart computer systems in spacecraft or to prepare habitats on the Moon and/or Mars. As some estimations show, the total mass of the space habitat would have to grow on extra 2548 kg to offer level of protection provided by specially prepared spacesuit (Vuolo *et al.* 2017).

The time of a space flight is an important factor as a substantial reduction of time travel in deep space missions is the best countermeasure for the hazardous effects of radiation, microgravity and isolation. However, faster spacecraft with active shielding such as artificial magnetic fields, are beyond current technological capacities

(Durante 2014). As Marco Durante (2014) suggests, first human deep-space missions might be based on passive shielding and reduced travel time. Reduction of exposition to radiation is important mostly for younger astronauts who have longer expected duration of life and higher risk for development of hazardous health effects (Sion 2011, Barzilay *et al.* 2014).

The greatest challenge for astronauts' health is an interplanetary journey, which will last at least one year to Mars and another year back to Earth. After landing on Mars, anti-radiation protection will be only minimally effective due to an absence of a global magnetosphere and a thin atmosphere (Frazier 2015). It is worth keeping in mind that before the first humans go to Mars, no one can predict the precise radiation dose they will receive or the potential total effects on their health (Blanchett and Abadie 2017a). Current methods of prediction of Mars radiation exposure are based on measurement and models and are not precise. Models, as all calculations, include or should include various factors, and they also bring uncertainty (Matthiä and Berger 2017). One method for space radiation research are simulations conducted in NASA Space Radiation Laboratory, which is able to produce charged particles (La Tessa *et al.* 2016, Schimmerling 2016). HZE particles in space appear to confer greater risk than terrestrial estimations assume (Cucinotta *et al.* 2015, p. 37) and precise prediction of the risk of cancer development in interplanetary missions is still challenging (Cucinotta *et al.* 2017, Kennedy *et al.* 2018). One of reasons is diversity of an astronaut's individual history of radiation exposure (Maalouf *et al.* 2011). Differences between Earth and space radiation exclude earthly radiation to be used to predict impact of space radiation on cancer, and diseases of central nervous and cardiovascular systems (Durante 2014).

5. Philosophy of human enhancement

5.1. Earthly philosophy of human enhancement

The philosophy of human enhancement is usually discussed in regard to earthly issues and applications and generally based upon the idea of physical and psychological 'upgrade'. The philosophy of human enhancement assumes that human life is worthy of living and has inherent value, which should be protected and sustained and improvement of human biology consists of creating new capacities, which are not naturally possessed by humans, and/or of enhancing currently possessed capacities (Miah 2012). Common sense philosophy of human enhancement is quite similar to the rationale for implementation of medicine, for example in the use of analgesics, and managing disease by whatever tools are necessary. Additional reasons for enhancement include equal opportunities and increasing individual quality of life and social well-being.

Some authors argue that enhancement may be distinguished from therapy (Bostrom and Roache 2008), and that medical and technological intervention are justified only for patients who have the right to recovery and a better quality of life, in contrast to healthy individuals where the ethics of the right for individuals to improve or upgrade their capabilities and well-being may be questioned. It is worth noting (Lin and Allhoff 2008), that humans have aspired to become *Homo superior* since ancient times. Whilst many basic human limitations such as physical power, endurance or velocity have been enabled by technology, some other limitations remain and these include aging, susceptibility to disease and death, although progress in extending lifespan and in management of disease has been substantial even over the last 100 years. The argument for enhancement for space missions should be acceptable, because it may be considered as prophylactic medical protection and provision of a route to enable adaptation to a new environment through artificial means.

Humans accept and achieve their success as a species by radical modification of the entire world. One of the arguments discussed by bioconservatives who criticize enhancement is the 'playing God' objection. Scepticism to enhancement is correlated with the fact that human morality evolves much slower than human progress in technology and science. Reference to religious ideas and beliefs is a secondary factor which may produce a 'closed-mind' effect. For example, many new techniques in medical treatment including transplantation, abortion, in vitro fertilization or euthanasia, were strongly criticized when first practiced. They are still the subject of ethical debate and public controversies in some societies and there are good reasons to assume that the same initial beliefs will be prevalent in the case of human enhancement.

5.2. Space philosophy of human enhancement

The space philosophy of human enhancement fundamentally assimilates the main ideas of earthly philosophy and adds further justification. The ethical position presented in this paper is a permissive position which accepts enhancement because of the lack of human adaptations to live in the space environment and as such is not necessarily the result of human ambition, competition or extravagancy, but it is a mandatory protocol.

Space philosophy is deeply rooted in evolutionary thinking and as we stated in the introduction, humans evolved in the Earth environment. Given that the space environment possesses different physical parameters, it might be taken for granted that under these conditions, the evolution of life would occur in different way from evolution on Earth. For instance, an upright position of humans has evolved in Earth gravity and enhancement applied to space assumes a directed evolution, which is necessary to adapt human beings to live in new physical conditions. This philosophy is different from earthly philosophy, where on Earth, human enhancement of healthy, fully physically able individuals is not necessary, at least not in regard to fundamental physiological processes, which function effectively in their natural environment of evolutionary adaptedness. Thus, the space philosophy for human enhancement is not only inspired by the idea of enforcing human performance, like on Earth, but mostly by the need for survival in the new environment. In such cases it may become the norm, and perhaps no longer regarded as enhancement. In summary, the key difference between philosophies of enhancement on Earth and in space lies in the fact that in space, enhancement is always considered as a necessary procedure applied to healthy individuals.

Biological human enhancement in space is considered, because currently applied non-biological tools seem to be insufficient for long-term deep space missions. Space radiation is exceptionally challenging, more challenging than, for instance, the lack of an Earth-like atmosphere composition. The latter challenge is solved by a life support system in space, whereas exposure to space radiation may be only partially reduced. Life support systems are able to solve the problem of non-breathable Martian atmosphere and because this basic human need may be satisfied, there is no incentive to adapt humans to breathe in a Martian atmosphere as relatively simple current technology solves this problem. This is not the case for space radiation which – despite all currently applied countermeasures – has not yet been effectively managed for future long term missions exceeding 2 years duration.

The philosophy of enhancement in space is also supported by the fact that the rationale for human space missions is not strong enough to justify a disproportionately high risk of fatality and health problems of the crew. As the MIT Space, Policy, and Society Research Group directs, the rationale for human space missions may be divided for primary and secondary objectives. Primary objectives may be achieved only by human presence in space and they justify risk for human life. They include 'exploration, national pride, and international prestige and leadership.' Secondary objectives do not justify either the costs nor the risks for astronauts' life. They include 'science, economic development, new technologies, and education and inspiration' (Mindell *et al.* 2008, Levine and Schild 2010). For a mission to Mars, none of the objectives are so substantial and important to justify the costs of the mission and risk for to human health. While all of these reasons may add value, the overall inherent value which justifies the risk and danger associated with the mission is to ensure survival of the human species in a safe harbour as a consequence of existential risk to Earth. Such an idea of Mars as a backup planet for humanity is worthy of consideration and effort and the challenges associated with establishing a colony and building a society can in part be predicted and modelled (Braddock *et al.* 2019). However, public policy planners and experts in global catastrophe studies should provide the cost–benefit analysis which would be able to simulate a comparison between efficacy of a human refuge on Mars and refuges located on Earth.

A further reason for considering enhancement as a pre-launch requirement is the distance from Earth to Mars and the length of time a signal will take for the round trip. Medical treatment will be limited, evacuation will probably not be possible (Explore Mars 2018). Progress in tele-medicine might solve the problem of availability of expertise but cannot change the laws of physics which determine the length of communication time between Mars and Earth. If medicine and human biology confirm that enhancements are able to protect humans against illness occurring in space, it further justifies application of enhancements.

6. Practice of human enhancement

Human enhancement includes various strategies, which differ in their magnitude of interference with the human body and the genome. Probably the most invasive strategy is genome editing that is currently applied for example using the CRISPR-Cas9 methodology. CRISPR is regarded as a solution for many currently unsolvable human conditions and although the technology is in its infancy, it promises much for the field of restoration of human function and perhaps for human enhancement (Cyranoski 2016, Dai *et al.* 2016, LaManna and Barrangou 2018, Zeng *et al.* 2018)*et alet al.* Gene editing by this approach is being tested in numerous clinical trials in patients with cancer (Cyranoski 2016), although clinical applications are limited due to the experimental nature of the technology. Interestingly, there appears to be some polarization on the public view of human enhancement. A number of surveys have found significant opposition to forms of human enhancement such as gene editing in babies to reduce risk of disease,[5] brain implants to improve cognition and synthetic blood to enhance physical ability (Funk *et al.* 2016, Centre for Genetics and Society 2018). As with all new technology, it will take time to objectively understand the opportunities, mitigate the risks and communicate clearly to everybody where the line is between restoration of impaired function for humans on Earth, what if any form of enhancement beyond normal function is acceptable on Earth and what level of enhancement is an absolute requirement for future space missions. Further discussion on recent gene editing of germline cells in China and possible legal regulations in forthcoming decades will be a test for human moral intuitions contrasted with progress in technology, and they will set directions for medical and academic communities' attitudes to the challenge of gene editing.

Pharmacological enhancement of human cognition, and stress and fatigue resistance is widely used by civilians, and service personnel together with athletes who defy rules on substance abuse or the armed forces (Braswell 2005, Ajir n.d.). Further types of enhancement which may be considered are the development of a protective exoskeleton (Ferris 2009, de Looze *et al.* 2016) and programmes of cognitive and neuronal enhancement (Reschke *et al.* 2009). These kinds of enhancements are less controversial than gene editing because they are usually not invasive and are fully reversible. They are also non-heritable and non-heritable enhancement procedures meet the criterion of autonomy understood as a lack of pre-determination and programming of an individual without his/her knowledge and consent (Schaefer *et al.* 2014). Gene editing of germline cells is probably the most controversial mode of enhancement because it is irreversible, invasive and heritable. The possible scenario of space exploration in which gene editing of embryos could be considered, includes establishment of a stable human colony beyond Earth and human reproduction in space. This is possibly the unique situation in which germline cells could be or likely should be modified to adapt better the future space colonists born in space to new environment. However, this is not a scenario considered for the near future of human missions to Mars, and only gene editing of somatic cells of adult astronauts is considered as a viable option today. Currently applied biological enhancement technologies do not include genetic engineering

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[5] Recently born Chinese twins have been genetically modified as embryos with an attempt to immunize them against disease. This experiment has been widely criticized (Cyranoski and Ledford 2018), and the Chinese researcher He Jiankui who conducted it, has been fired by his university (Cyranoski 2019).

focused on improving human performance and health conditions and this will be a subject for philosophical, ethical and scientific debate in future.

7. Terraforming Mars as an unrealistic alternative

Let us consider two alternatives to 'traditional' countermeasures of nutrition, exercise, pharmaceutical intervention and anti-radiation shielding. The first stems from Clynes and Kline (1960) who argue that it is better and more reasonable to adapt humans to space, than space to humans, and is provides much of the rationale to create terrestrial conditions in space by the generation of artificial or simulated gravity (Braddock 2017b). The second alternative is planetary terraforming with Mars being the preferred candidate. With a thin atmosphere and a temperature range much colder than on Earth, the immediate challenge is to warm the planet and generate a dense atmosphere. Exposure to space radiation on the surface of Mars could be limited by a new Martian atmosphere although as the planet has no magnetic field, full protection from radiation will not be possible and astronauts will still face exposure to radiation during transit to and from the planet and throughout the duration of their time on Mars.

In addition, terraforming Mars, at least with technology available today has been shown to unfeasible. Warming the planet by providing a dense atmosphere of the greenhouse gas CO_2 is constrained by the available inventory of the gas in measured deposits on Mars which is insufficient to warm the planet and liquid water, which could appear on the surface as the result of terraforming, will likely be immediately vaporized (Jakosky and Edwards 2018). Other methods of terraforming based on nuclear attack or directed asteroid impact (Impey 2015) are well beyond current human technology. Even if the concept of terraforming includes becomes a feasible reality, an extremely long time scale from between an estimated 100 years for increasing the temperature on Mars to about 100,000 years to produce an oxygen-rich atmosphere (McKay *et al.* 1991, McKay 2009), makes terraforming Mars an unfeasible alternative today.

Even if Society must wait decades for enhancement to become acceptable, it will likely be closer to reality than terraforming Mars with an oxygen-rich atmosphere and this argument gives a good reason to intensify our effort in a human enhancement and put to one side, at least today, the terraforming alternative. When considering possible catastrophic scenarios on Earth including both anthropogenic and exogenous scenarios,[6] the timescales suggest that humanity cannot wait hundreds or thousands of years for terraformation of Mars or any other space body.

8. Hibernation of crew does not protect against space radiation

Another alternative to human enhancement and the countermeasures described so far is hibernation or stasis (Braddock 2018b). Hibernation during a journey to a space body in a journey of many years may offer some potential benefits. One is

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[6] One of the recent and quasi-comprehensive overviews of possible catastrophic scenarios on Earth has been published in the special issue of *Futures* journal entitled 'Futures of research in catastrophic and existential risk', *Futures*, edited by Adrian Currie, Volume 102, Pages 1–164 (September 2018).

reduction of the mass of spacecraft as a full range of exercise equipment may not be necessary and the consumption of consumables during the journey will be reduced. There are also some potential medical benefits, which include removal of negative circadian rhythm effects and psychological hazards due to confinement. However, hibernation is not able to prevent the effects of space radiation and even if astronauts were to hibernate in microshelters, the consequences of microgravity without the ability to exercise regularly would be expected to have severe consequence of hard and soft tissue atrophy neither altered gravity (Ayre *et al.* 2004).

Putting human astronauts into torpor is a challenge for human biology. This can be no less challenging than introducing genetic changes. Another problematic issue may be the fact that not the entire personnel of the spacecraft should enter hibernation at the same time and crew members who are not in a state of hibernation might experience harmful effects of spaceflight and be more exposed to space radiation or hazardous impact of microgravity.

9. Enhancement in space as a unique choice

We suggest that enhancement for purposes of human deep space missions is a reasonable solution. If humans for the first time in their history change their global ecological environment by becoming an interplanetary species, they should upgrade their biology to live in this new environment. This is the evolutionary need to control and direct evolution in the situation where humans plan to leave the Earth environment of evolutionary adaptedness. Because enhancement in space would be as a consequence of the lack of biological adaptation, the above mentioned basic distinction on therapy and enhancement applications (Miah 2012) is not applicable to the space environment. Enhancement in space is neither a therapeutic application nor a trivial procedure but an obligate requirement for adaptation to a new environment.

The status of human enhancement for purpose of space mission will face challenges and have issues which require careful thought, planning and acceptance of risk. Genetic editing, for example to design radiation resistance is not purely a medical or therapeutic application as it would be applied to healthy astronauts and not to patients who require treatment. Great care would need to be taken that this technology was not abused in, for example, Earth-based warfare where an army of designer soldiers could prove more capable of combat that armies not enhanced (Mortazavi *et al.* 2013). The unique criteria which should be followed by mission planners who will decide to enhance future astronauts, should be based on care for health and well-being of enhanced individuals to enable them to execute their mission. No ideological arguments traditionally referred to the risk of breaking human nature or ‘playing God’ should be considered by policy makers and mission designers.

In any case, the rationale for human enhancement in space is different from the rationale for enhancement on Earth. As enhanced astronauts are considered a necessity, standard ethical objections discussing dangers for equity, equality, human dignity or autonomy are secondary. Despite this, we identify two ethical issues, which should be addressed for human space enhancement. The first is the reversibility and stability of applied enhancements. If enhanced astronauts are adapted to live in altered space gravity and/or are biologically resistant to space radiation return to Earth, all risks of living a normal life on Earth should be estimated and advice provided on whether adaptation will be possible. The second issue refers to the risk and potential safety effects of applied enhancements such as genetic technologies, which are poorly understood at present (Zhang *et al.* 2017, Brokowski 2018).[7] The latter objections were discussed recently by philosophers such as Julian Savulescu who is the prominent advocate of human enhancement including gene editing. Savulescu has criticized that Chinese experiment on embryos of twin girls due to its risky nature and unpredictability of the potential future hazards for health (Cyranoski and Ledford 2018, 608), although these objections were from a purely medical and not ideological standpoint. Savulescu and Peter Singer (2019) add that gene editing of germline cells should be focused primarily on coping with severely damaged embryos, then with population diseases and next, should be oriented on secondary benefits such as 'enhancing immunity' or 'delaying ageing.' The main reason for biological human enhancement in space is the fact that currently applied countermeasures are not sufficient. The only protection against GCR is spacecraft shielding, which is not effective (Li *et al.* 2018). Pharmaceuticals used to manage the hazards of radiation are probably ineffective and potentially cause side-effects unacceptable in space, such as amifostine, to be applied for provided for use by astronauts (Hughson *et al.* 2018).

Indeed, we could consider that astronauts not adapted to the space environment may slow down progress in science and space exploration. For instance, Europa, a moon of Jupiter, is attractive for astrobiological research due to subsurface ocean of liquid water. However, radiation emitted from magnetosphere of Jupiter strongly affects Europa (Nordheim *et al.* 2018) and radiation is one of the basic factors, which inhibits possibilities of human exploration deeper into the solar system (Cucinotta and Durante 2006).

Lastly, genetic engineering may be treated as a tool that increases human adaptive potential as a species. Humans display a very limited diversity of phenotypes (Gyngell 2012), which may biologically inhibit full and effective human exploration of space. Gyngell discusses the idea of genetic engineering of the entire human species or some selected population, which does not distinguish between an enhancement programme of an individual, group or population. Macromutations implemented by genetic engineering, not as the possible result of incremental changes but as bespoke radical alteration are envisaged. Such a genetic strategy could be applied to a selected group of astronauts destined for Mars and/or entire communities of future deep space astronauts.

10. Production of the new capabilities

What types of artificial capabilities could or should be applied to astronauts in future? One of the most desirable capacities in space may be living without a life support system. This opportunity would require breathing unaided in the Martian

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[7] See: discussion on the risk of antibodies response to CAS9 (Elliott 2018).

atmosphere but as terraforming appears even more challenging than previously thought, the only currently achievable solution is the life support system, at either an individual level or a population level such as in a biosphere.

Another essential capability is the ability to detect space radiation. This could be satisfied by conventional dosimetry using today's technology, and humans could be enhanced to enable detection of a change in radiation dose by a connectivity devices being developed to monitor drug delivery to patients. This augmented technology for radiation detection could function analogously to brain–machine interfaces, which enable vision of infrared and ultraviolet lights (Zrenner 2002). Ultimately, but perhaps not necessary today, the ability to detect radiation by an extra sense would fulfil one of the essential ideas of transhumanists who argue humans should be equipped with new capabilities possessed by other non-human animal species, or a sensor which relays an alert and danger signal to the brain.

Current planning for human missions to Mars envisages self-sustainability which is necessary in the long-term scenario for the settlement and to ultimately build a civilization and implies no supply chain from Earth. Resupply of food from Earth to Mars will be cost-ineffective and very challenging to maintain even a minimal healthy diet for astronauts living and working in such a harsh and exhausting environment. Synthetic biology might enable *in situ* resource utilization including growing plants in a Martian biosphere (Menezes *et al.* 2015, Verseux *et al.* 2016).

The requirement for humans to live in microgravity and a reduced gravity environment in the same manner as on Earth, is beyond technological capacities although the capability for developing in situ artificial gravity is under development in an International Roadmap for Artificial Gravity Research (Clement 2017, Braddock 2017b). Such an adaptation would be of high value for improvement of quality of life and daily function by negating the effects of reduced gravity where currently applied countermeasures which include physical exercise (Braddock 2018a) offer a partial solution.

Our recommended modifications include genetic enhancements focused on coping with hazardous effects of radiation and genetic engineering could be also be applied to improve bone and muscles structure and the immune system (Hendrickson 2016, Cortese *et al.* 2018). Regenerative medicine technologies developed for Earth application could also be added to the armamentarium for future enhancement of crew post launch during the mission (Braddock 2019a). A plausible planning assumption is that the space industry either uses solutions which are previously invented and applied for civilian use on Earth or exploits the space environment to develop organoids where cell architecture is unconstrained by gravity. Pre-launch screening of the astronaut genome may identify genes which will predispose to future disease and which are candidates for gene editing. Though this technology is still in its infancy and has yet to be proven in clinical trials for patients with genetically predisposed disease on Earth, once accepted as main stream prophylactic and corrective treatment, the potential for human enhancement will likely be explored.

Genetic engineering such as CRISPR could be used to optimize or eliminate genes responsible for coding particular tasks and functions, which limit human activity in space. Other genes could be added to enhance radiation resistance or immune system function (Klompe and Sternberg 2018, Thai and Floor 2018). Currently, protocols for human enhancement should permit gene editing of somatic cells, whereas editing of germline cells should remain prohibited until ethical controversies and the unpredictable nature of possible harm for enhanced individuals is more completely understood.

11. Conclusions

Space agencies and other companies interested in human deep space missions may wish to consider the application of human enhancement as a potential way to increase mission success. The physiological and psychological barriers of the space environment preventing human astronauts undertaking long term missions of greater than 2-year duration are well known and current countermeasures appear not to be sufficient.

The ideas discussed in this paper go beyond space applications and refer to issues related to the future of humanity, which is a rich area of debate by scientists, philosophers ethicists and politicians interested in the concept of human enhancement in general. Questions for further considerations include:

- What is an expected and acceptable role played by advancement in technology and science in regard to human biology and psyche?
- Where is the current science limited in progress and in fields of application?
- Should humans go to Mars when the rationale for an interplanetary mission is weak, especially given the challenges for human health and the need to solve issue on Earth?
- Should and could humanity accept a prophylactic programme of human enhancement justified by the predicted requirements for medical science in deep-space missions?
- What is the alignment between human moral intuition, ethical rules and progress in science and technology and how should it be regulated?
- Is humanity ready or will it ever accept scientific justification as the last and unique criterion for making decision in bioethical issues?

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