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Viewpoint

Bioethical Issues in Human Modification for Protection against the Effects of Space Radiation

Konrad Szocik [a, b, *], Martin Braddock [c, d]

[a] Interdisciplinary Center for Bioethics, Institution for Social and Policy Studies, Yale University, Prospect St. 238, New Haven, 06511, USA
[b] Department of Social Sciences, University of Information Technology and Management in Rzeszow, Sucharskiego 2 St., 35-225, Rzeszow, Poland
[c] Sherwood Observatory, Mansfield and Sutton Astronomical Society, Coxmoor Road, Sutton-in-Ashfield, Nottinghamshire, NG17 5LF, England, United Kingdom
[d] Science4U.co.uk, Radcliffe-on-Trent, Nottinghamshire, NG12 2LA, England, United Kingdom

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ABSTRACT

Protection against the effects of space radiation poses great technical and medical challenges for future human missions and is of interparliamentary concern requiring alignment of multiple scientific, clinical, and ethical parameters. In our article, we highlight the inadequacy of current countermeasures, which may justify the use of human enhancement (HE), or biomedical technologies to increase astronaut protection from the harmful space environment, protect lifespan longevity and increase the chance of survival during spaceflight or as colonists on other worlds. The deleterious effects of space radiation on the human body may justify even the most radical forms of HE, which may incorporate gene editing. As a thought experiment, we propose that an ethical assessment should depend on the anchor and purpose of the mission and we discuss differences and similarities between the bioethics of space missions and military ethics on Earth.

1. Introduction

Space radiation is believed to be the greatest threat to human space missions, particularly those of long duration, for example missions to Mars. The current restriction of human missions to Earth orbit precludes the possibility of real-world testing of the effects of space radiation on astronauts during interplanetary missions. Space radiation, principally galactic cosmic radiation (GCR) may also cause many currently hidden and slow to manifest effects, which to date influence space agency policies favoring avoidance of sending younger astronauts and a perceived bias against females [1].

In this article, we highlight some of the basic problems and risks associated with the effects of GCR and illustrate the bioethical challenges for carrying out future missions, with a focus on future interplanetary missions. We also compare the space environment with the Earth environment and suggest that despite some similarities with military ethics and military missions, space missions offer an environment, which requires distinct ethical considerations to be taken into account depending on the nature of the mission.

2. Cosmic radiation hazards

The risk of space radiation on human longevity is attributed to be extremely high, which is primarily due to the fact that, in a manner distinct from other types of threats to survival in space, both short- and long-term effects are much more difficult to predict and depend on many factors [2]. In general, shielding in a spacecraft provides only partial protection against galactic GCR, at most in the order of 25–35% where the principal limitation of providing bulky or heavy material for protection is the mass to payload lift ratio. A specific problem is measuring the authentic potential impact of GCR on humans [3] and extrapolating from non-human model systems. For example, animal models are not always relevant because of the different genetic responses of different species and the use of analogue sources on Earth that cause biological damage in ways other than GCR may provide an incomplete picture of the scenario for which the risk is to be evaluated and mitigation measures applied.

* Corresponding author. Interdisciplinary Center for Bioethics, Institution for Social and Policy Studies, Yale University, Prospect St. 238, New Haven, 06511, USA.
E-mail addresses: konrad.szocik@yale.edu (K. Szocik), martinbraddock@rocketmail.com (M. Braddock).

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Since the negative effects of GCR are amplified by other stress factors in space, such as isolation or stress [4], no radioprotective agents with proven efficacy are currently used in space [3,5]; there is limited understanding of the long-term effects of GCR on drug stability [6], and rodent studies suggest low-dose, long-term exposure may affect the neurocognitive function [7]. This overview gives some grounds for serious consideration of the concept of human enhancement (HE) through biomedical means. In addition to HE directed at increasing the resistance to GCR, it is reasonable to consider modifications directed at coping with stress or isolation, to minimize the impact of collateral factors amplifying the negative effects of GCR.

Current GCR protection measures are unlikely to provide sufficient protection for interplanetary missions of a number of years duration where the lifetime exposure limit is likely to be exceeded. The National Council on Radiation Protection and Measurements (NCRP) has issued guidelines on the recommended lifetime exposure to radiation, which has been revised over the years [1] and differs by sex and age. Career radiation exposure limits vary by age and are lower for younger astronauts as they have a longer life span and may have a greater probability of developing subsequent health problems in later life. Career radiation exposure limits also vary by sex and are lower for female astronauts who are perceived to be at generally higher risk of radiation-induced cancer. NASA's current space radiation health standard, based on a risk model intended to set a limit of no more than a 3% additional lifetime risk of radiation exposure-induced death, recommends a lifetime exposure limit ranging from 180 mSv for a 30-year-old woman to 700 mSv for a 60-year-old man. The new proposed standard [8], based on a 35-year-old woman as being the most vulnerable population, sets a single lifetime occupational limit of 600 mSv and applies to all ages and sexes.

Magnetic protection cannot completely eliminate the risk of radiation-induced cancer, and more effective radiation protection strategies are needed especially for future interplanetary missions that require the participation of younger astronauts and that will also extend beyond the time frame currently accepted in the context of cancer prevention [9] and irrespective of present or future guidelines for lifetime exposure limits.

Today, by contrast, the alternative to the discovery and development of major advances in radiation protection technology is to significantly increase the range of tolerance to GCR exposure [9]. The potential for HE is bioethically controversial for any application, and in the context of protection against the effects of GCR would require a special ethical justification in the mission objectives, regulatory review and approval before deployment. This is a serious challenge not only politically but also ethically and culturally. It may require a change in the current space policy and the replacement of the monopoly of leaders in spacefaring countries and space entrepreneurs with a democratic and pluralistic model that represents the global interests of planet Earth.

3. Human modification against space radiation

In this article, we will assume a hypothetical scenario in which advocates of space exploration intend to pursue human interplanetary flights in the future.[1] We also assume that current means of protection from space radiation, primarily GCR, will be unavailable to guarantee complete protection. As a consequence, astronauts sent on a mission to Mars or any other object will be exposed to serious medical risks that will not be fully predictable because of the difficulties outlined above. Therefore, this leads us to assume that a scenario in which HE is the only reasonable protective tool is likely. The type of HE we are considering in this article is hypothetical genetic modification, which could involve utilization of p53 genes from elephants and/or Dsup genes from tardigrades, which are well known to have high radiation resistance [10]. This simple, although radical concept implies a number of bioethical challenges, which will be discussed in the following sections.

The main purpose of such biomedical enhancements is to protect human health and life in the hazardous space environment, as well as to enhance the performance at the same time. The issue of performance enhancement becomes problematic, but even here the consideration of enhancements for space missions is to prevent or compensate for the loss of performance, not to raise it to supra-performance far beyond the standard human capabilities. This rationalistic approach constrains us to not consider highly speculative forms of enhancement as today, they appear scientifically unjustified such as the philosophers' favorite idea of intelligence enhancement but also because, regardless of their technical feasibility, they seem unrelated, or distantly related to maintenance of quality of life and survival.

4. Bioethical issue 1: Justification for a dangerous mission

This issue could be considered more of an ethical issue than a bioethical issue, since it does not directly involve interference with the biology of the human body. Nevertheless, sending humans to other planets with our current state of knowledge and technical and medical capabilities is also a bioethical issue and full analysis is required to both legitimize the use of HE and to justify the mission purpose, which may require the application of procedures otherwise regarded as controversial. Below, we will turn our attention to how strong the rationale for the three basic types of space missions is in the context of potentially related bioethical controversies. We will further include a brief consideration of space tourism as source of risk as this industry is currently in its infancy and is expected to grow significantly in coming decades.

4.1. Scientific missions

The only mission to Mars currently being officially considered is for scientific purposes. The main expected beneficiary of such an expedition are institutes supporting astrobiology and aeronautics. Regardless of potential astrobiological discoveries, scientific exploration of space has the potential to benefit other disciplines such as, medicine, communications, and material and engineering sciences. With respect to astrobiology, the confirmation of life beyond Earth could be a momentous event for humanity. It could have an impact beyond science such as cultural, social, ethical, and religious [11] and could lead us to propose life to be likely widespread within the Universe and possibly our solar system. Despite the importance of this discovery for science, the question arises about the rationale and moral legitimacy of sending astronauts on any exploratory scientific mission knowing the health risk posed by exposure to GCR. If we accept that astronauts could be genetically modified only to enable them to achieve their astrobiological goals, then humankind is admitting we place more value on scientific discovery than on the bioethical issues generated by genetic modification or the decision not to modify. Consequently, astronauts sent on science missions are treated instrumentally as research tools. The alternative to applying HE to science missions is either to suspend such a mission until countermeasures are invented that do not require biomedical HE, to send a fully

[1] For the purposes of this article, we assume, following many philosophers and ethicists considering the question of future human space missions in the long term, that humans will pursue such missions for a variety of reasons, and that expansion into space will be an important part of the human future [13,14,23–29].

automated robotic mission or, to suspend a human mission until adequate advances in space robotics are made. In this light, the dispute between proponents of human missions and proponents of robotic missions is not only a dispute over a risk of contamination of space objects, dexterity, intelligence, and cost, but also a dispute which may have important biomedical implications [12].

A position supporting the use of even risky HE can invoke the argument from informed consent as a sufficient measure. This is standard procedure in many biomedical procedures currently used on Earth. For at least the first astronauts pursuing deep-space missions, giving them full knowledge of all possible effects of HE will be impossible, so their informed consent will not come from having comprehensive knowledge of the procedure. It is also difficult to expect the possibility of having comprehensive knowledge of the mission and the possibility of success. The negative consequences of not being able to obtain complete knowledge are compounded by the risk of astronauts being experimented on and sought to be exploited by either state space agencies or private mission contractors.

4.2. Commercial exploitation of space

In considering the bioethical implications of commercial space exploitation in this section, we have no particular location in mind and turn our attention to how space missions are justified, their purpose and context. Mars is not an attractive location for *in situ* resource utilization—except to obtain the resources needed to build and maintain the building to support a space base. Assume that space mining will require astronauts, in addition to robots, and that due to high doses of GCR each astronaut will have to undergo genetic modification, we believe that the justification for space mining will affect the bioethical evaluation of the right to apply such modification.[2] Consider here two separate scenarios. In the first scenario, commercial space mining will be treated as strategic for the survival of humanity. Space mining will be pursued because of the strategic interests of either a particular state or humanity as a whole. In the second scenario, space mining will represent a new area of commercial activity aimed at increasing profit, without correlation with the needs of humanity or the threatened interests of either a given country or the entire planet. It appears that the justification for applying HE for commercial space mining is greater in the first scenario. However, the situation in scenario two may change when an individual voluntarily submits to modification, for example, as one of the terms of a contract with a space mining company. In that case, it is challenging to envisage how an autonomous decision can be made by an individual who is interested in a particular type of work. There is also the context of socio-economic pressure to be considered, where only a job in space mining may be available to an individual, or only such a job may satisfy their current financial needs. The full autonomy and freedom of action of the individual could then be questioned, although this situation is not only unique to space mining [13].

Commercial space exploration brings additional risks compared with scientific exploration. This is the risk of exploiting people who may be exploited as space business employees at the risk of their health and lives.[3] The moral assessment of this risk is ambiguous. On the one hand, we might suggest prohibiting commercial exploitation because of the ongoing risk of exploitation as well as the ongoing risk to health and life. This includes the risk of experimenting with new biomedical technologies on humans just for the expected future benefits. But on the other hand, we might suggest approval of this type of mission using HE assuming that HE will protect commercial mission participants from health and life risks.

4.3. Space settlement

While the above two types of space missions are expected in the near future, the last type of space exploration discussed, for habitat or refuge for humanity, is a distant prospect, although the intent of public and private enterprise retains the ambition of Mars colonization in the 2030s. The concept is worthy of discussion, as it illustrates the importance of justification for biomedical procedures and the dependence of bioethical assessment on the purpose of the mission. The concept of space refuge or space settlement is proposed as a policy to increase the chances of survival of the human species and to protect it from possible extinction in the event of existential catastrophes. We do not discuss here many important nuances taken up in the literature on space refuge such as the possibilities of survival on earth, the issue of sustainability development, quality of life on Earth and in space, and others which are beyond of the scope of this article [13,14]. Let us also assume that for the purposes of interplanetary flight, as well as in the context of space refuge, life requires biomedical HE to be mandatory for every member of such a mission. It would seem that survival is such an important value as to justify the implementation of procedures that, if not applied, would jeopardize the realization of the value of life.

4.4. Space tourism

Space tourism is currently a luxury accessible to very few, which may become more common place in future due to the successes of missions flown by Virgin Galactic and Blue Origin in 2021. These short duration missions of 10 and 11 min, respectively, will result in a negligible increase in radiation exposure, but longer duration missions planned for 2022 and the proposed dearMoon project to take 8 fare paying passengers on a week long journey orbiting the Moon in 2023 will increase the risk. All airline passengers, particularly those on long haul flights receive elevated doses of radiation, well within current guidelines of acceptability. Radiation exposure levels are not regulated for high-altitude balloon flights or space tourism, and it would seem prudent to consider standards to be defined, implemented and regulated across the space tourism industry. Current research aims to create a prediction tool to enable providers and passengers and to calculate their potential radiological dose during such flights assisted by on board radiation detectors, which have already been successfully used on commercial aircraft [15].

It seems that for space tourism involving short flights around the orbit, applying HE is not necessary. The challenge would be to implement longer stays in space of a tourist nature. Equal access to space is a bioethical issue [16]. The openness of space for tourism is threatened both by its costliness and the possible need to apply biomedical enhancements—assuming that this will be necessary in the future. In the latter case, there could be a risk of two types of bioethics, one applied on Earth, where, for example, certain types of HE are prohibited, and another applied in space, where analogous types of HE are allowed or even recommended [13].

[2] Perhaps more likely is the fully automated exploitation of raw materials in space, at least in the first instance [30]. As a point of conjecture, however, we allow for the possibility of some human involvement in the exploitation of raw materials in space to show the specificity of the bioethical argument.

[3] An additional risk is the issue of social justice and the risk of widening global inequality. This depends, among other things, on the intensity of commercial space exploration. In any case, the risk of repeating processes analogous to the colonizing exploitation of the past, as well as to today's unequal distribution of resources and wealth, must be taken into account.

5. Bioethical issue 2: Specificity of the space environment. Comparison with military ethics on Earth

Accepting that genetic modification is a controversial procedure, we assume that the space environment is unique and requires a specific bioethics understanding and approach. This specificity increases the tolerance for the application of biomedical procedures considered controversial on Earth [10,13]. To better show not only the differences but also possible similarities between space and terrestrial environments in a bioethical sense, we will make some comparisons with military ethics on Earth as we may regard the military mission environment as similar to the space mission environment. The space environment is unique in terms of physical factors and hazards. Therefore, it is reasonable to compare the space environment with other extreme environments on Earth such as those experienced in warfare and in Arctic expeditions [17,18]. In this respect, the ethical and bioethical concepts inherent in these environments can be referred to as the ethics and bioethics of extreme environments. What most closely aligns the concept of HE for space missions with military enhancement (ME) applications is its preventive nature. If we wish to apply this term to the classical division between therapy and enhancement, we may see some difficulties related to the lack of precise and unambiguous divisions. A solution may be to recognize the existence of a separate category of enhancement, preventive enhancements [19].

However, even this distinction is not clear-cut. Preventive enhancement may be either essential or optional. In the former case, it is necessary to prevent the negative effects that may be predicted in the absence of the modification. Preventive enhancement becomes optional when it is not known whether an individual will come into contact with a harmful agent, or in the event of such contact, the agent will not illicit deleterious effects sufficient to justify the preventive application of a modification that may be considered controversial. An example of preventive enhancement currently applied for military purposes is anthrax vaccination [19]. A technically feasible application today could be CRISPR/Cas 9 and subsequent next generation gene editing technologies applied to enhance resistance to various biological weapons. Analogous status may be given to all types of biomedical enhancement that can be considered for future space missions. This is due to our assumption that biomedical enhancements for space missions will be treated as necessary or at least highly recommended procedures and will be justified by increasing an individual's ability to reside in a harmful environment. While the introduction of the category of "preventive enhancement" into the conceptual scheme is arguably helpful in classifying many cases at the intersection of enhancement and therapy, a new and specific conceptual problem arises. In relation to prevention, it is necessary to determine to what extent the applied modification is necessary for the preservation of health, maintenance of acceptable quality of life or life itself, and to what extent it is optional. This will also require a determination of the degree of risk between 1 and 99% chance of occurrence and whether the modifications are direct or indirect in character.

In the context of space missions, therapeutic modifications may not always have the highest risk-benefit ratio. For example, a modification of lower risk-benefit ratio may be more acceptable for restoring the vision poorly sighted person to see compared with the risk-benefit ratio of improving the degree of vision of an already well (normal) sighted person [19]. To undermine this claim, however, requires a fair amount of variation in the population of those traits that are being modified. This is the element that can significantly differentiate HE in space from ME. Suppose we wanted to improve the accuracy of shooting at a target in healthy well-trained soldiers. Imagine that despite the same training, there is nevertheless a degree of biological variation even among the best soldiers. This would appear to have some validity as a potential explanation for snipers with unique abilities who appear from time to time in history. Thus, in the human population there is a diversity of predispositions to be a sniper, which is not eliminated even by undergoing the same cycle of training.

An analogous situation is not found in the case of HE for space missions. We, therefore, assume that each candidate must undergo the same level of radical, invasive enhancement of a preventive nature. The exception to this is the moral bioenhancement hypothesis, where we know that there is diversity in the human population regarding differing degrees of resistance to stress or isolation. This diversity makes it possible for moral bioenhancement to be applied to different degrees to different candidates, as well as the controversial nature of moral bioenhancement may justify a special selection procedure only for those candidates who exhibit the highest possible degree of such resilience in the population. Thus we can say that the risk-benefit ratio for the difference between different degrees of predisposition does not play a role for enhancement for space missions, as opposed to military applications, while it can only play a role for moral bioenhancement.

A parallel to military ethics may be the ethos of the astronaut, associated with particular risks to health and life, especially with the assumption that the longer the mission carried out to further regions of the solar system, the greater these risks. If there is a consensus on the ethos of a soldier, who is willing to give their life not only for their colleagues but also for the nation and homeland, an analogous situation may exist for deep-space astronauts. In the latter case, however, justification for the space mission again plays a role. It is worth noting that for each type of mission, there are beneficiaries who gain from the mission. For missions of a scientific nature, the beneficiaries are scientific institutions, scientists, and possibly the societies that will become the recipients of the technology should it have value for terrestrial applications. For commercial exploitation, the primary beneficiaries are the owners of the space companies, either private or public who will seek to extract value. It would appear that paying attention to the beneficiaries of particular types of missions may somewhat devalue the ethos of an astronaut participating in them, especially compared with the traditional ethos of a soldier fighting for his country. It is worth remembering, however, that wars and armed conflicts have many conditions and can also be interpreted, at least to some extent, as serving the interests of particular political leaders.

Despite similarities between the moral ecology of space missions and the moral ecology of the battlefield or functioning within army structures, there are also some differences. It seems that a greater degree of restrictions on autonomy and the importance of the principle of informed consent, as well as the correlated greater right to apply radical forms of HE, applies to military ethics than to space bioethics. This is related to the fact that soldiers carry out tasks in which not only can they kill others, but they themselves can also die relatively easily [20]. This specific situation makes modifications that can both serve to protect their own lives and make their decisions about who, where, and when to kill more precise and justifiable desirable, and perhaps even morally obligatory [21]. The context that reinforces this argument is the situation of fighting in defense of others, where the good at stake is theoretically the life or independence of an entire nation. It can be seen here that this argument can only be applicable to certain soldiers and only in specific situations. However, this does not change the fact that it is relatively easy to imagine situations in which decisions as well as skills regarding the killing of others require constant improvement. Space missions are devoid of such a situation. Naturally, some analogies can be found, but they appear too distant and lack credibility. It can be said that controlling the landing of a spacecraft on the approach to landing on Mars after several months of flight in microgravity requires excellent cognitive and physical fitness. Otherwise, the spacecraft is in danger of crashing (assuming that at least some of the strategic maneuvers must be done manually). If a small mistake caused by a grueling flight can cause a catastrophe, and only HE can guarantee a minimum good fitness, then it becomes a requirement. Analogous questions may be asked about many other situations in which the mission commander or any of the members must not only be minimally physically fit, but also have some cognitive and moral fitness. If one could find such situations in interplanetary flight and a space base as in the military ethics example discussed above, then the modification in question—whether physiological, cognitive, or moral—become mandatory. The issue, however, is that it is probably impossible to predict their necessity prior to such a mission on the basis of near 100% certainty that characterizes the aforementioned military ethics situations. The fundamental question is that the space mission environment will contain life and death decisions analogous to the military action environment.

These decisions will not, of course, involve direct decisions to kill, as in the case of military ethics, but they may indirectly involve decisions affecting crew survival. Such an example could be a situation where an equipment operator on a spacecraft or space base may have limited attention and perceptiveness, and the lives of other members performing a task may depend on his or her mistakes or slow decisions. In such a situation, there could be some parallels between space missions and military missions, but provided that we first establish that HE is necessary to maintain an adequate level of cognitive or manual ability. This is a stronger version of the argument. The weaker version may justify such modification even if it is known that HE will certainly increase an astronaut's potential and performance, but it is not known whether such an intervention will actually be necessary and we will assume that it is known not to be harmful.

The purpose and context of the possible application of HE is not always analogous for military and space missions. Even within military missions, which we have found to be more likely to justify limitations on the autonomy and scope of applicability of informed consent than space missions, there are differences that affect the ethically acceptable limitations on soldiers' autonomy. The greater limitations attached to the principle of autonomy and the informed consent rule in military ethics are due, among other things, to its hierarchical nature. The specifics of space missions are also hierarchical to some extent, and the degree of similarity between the space mission environment and the military environment will depend, among other things, on the degree of hierarchy in the conduct of space missions. If we assume that the degree of hierarchization is one of the main factors constituting the limitation of autonomy, then depending on the type of mission, the specifics of its organization, its purpose, as well as the number of people involved, the degree of hierarchization may be fluid, and with it the degree of autonomy.

It is also worth keeping in mind another possible difference between HE applications in space and for military use. While we assume that HE for military purposes should, as in the case of space missions, be preventive in nature, protect health and life, and guarantee adequate performance, we cannot exclude applications aimed at creating a so-called super-soldier, whose goal will be to gain an advantage over the enemy by increasing its performance and potential also where this has so far been achieved by conventional modifications [22]. It seems that the specifics of the military and the battlefield favor the possibility of HE applications for such needs more than the specifics of space missions.

In summary, the ethics and bioethics of extreme environments such as battlefield and military ethics, Arctic expeditions and space missions are linked by the idea of self-sacrifice. The circumstances, the rationale for the idea of self-sacrifice, and the duty to self-sacrifice may vary from situation to situation and may be different in nature. Nevertheless, the idea takes on a stronger meaning primarily due to the harsh environmental conditions that characterize the aforementioned types of ethics.

6. Conclusions

The thought experiment posed in this article purports that the danger caused by GCR is not only one of the greatest types of threats posed to humans during space missions, it is a hazard that is difficult to predict and against which, at least today, there are no adequate countermeasures to support future interplanetary missions. Thus, we propose that the negative effects of exposure to GCR justifies the considered application of countermeasures in the form of genetic modification. We describe that the context and justification for the mission are factors that significantly affect the ethical evaluation of HE decisions and although the highest priority is given to colonization missions directed at protecting the survival of the *Homo sapiens* species, we may envisage that the same status be given to scientific and commercial missions, as it scientific missions with commercial goals may represent an intermediate stage to colonization of other worlds, where at least today, ameliorating the effects of surface exposure to GCR on, for example, Mars is on the critical path for a successful mission. Lastly, the short duration and exposure to GCR received during current goals for space tourism do not appear to pose a significant health threat to fare-paying passengers.

Author statement

Konrad Szocik, Martin Braddock: Conceptualization, Methodology, Writing - Original draft preparation, Writing - Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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