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HUMAN SPACE FLIGHTS: FACTS AND DREAMS

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ABSTRACT

Manned space flight has been the great human and technological adventure of the past half-century. By putting people into places and situations unprecedented in history, it has stirred the imagination while expanding and redefining the human experience. However, space exploration obliges men to confront a hostile environment of cosmic radiation, microgravity, isolation and changes in the magnetic field. Any space traveler is therefore submitted to relevant health threats. In the twenty-first century, human space flight will continue, but it will change in the ways that science and technology have changed on Earth: it will become more networked, more global, and more oriented toward primary objectives. A new international human space flight policy can help achieve these objectives by clarifying the rationales, the ethics of acceptable risk, the role of remote presence, and the need for balance between funding and ambition to justify the risk of human lives.

Keywords: *human space flight, microgravity, cosmic rays, space biomedicine*

POLETI ČLOVEKA V VESOLJE: DEJSTVA IN SANJE

IZVLEČEK

Človeški poleti v vesolje že zadnjega pol stoletja predstavljajo izjemen človeški in tehnološki dogodek. Potovanja ljudi v kraje in okolja brez primere v zgodovini burijo našo domišljijo, hkrati pa širijo in na novo določajo človeške izkušnje. Kljub temu pa raziskovanje vesolja ljudi postavlja v situacije, kjer se morajo soočati z nevarnim okoljem, kjer vlada kozmično sevanje, mikrogravitacija, osamitev ter spremembe v magnetnem polju. Vsakdo, ki potuje v vesolje, je torej izpostavljen pomembnim pogojem, ki ogrožajo zdravje. V 21. stoletju se bodo človeški poleti v vesolje nadaljevali, vendar pa se bodo spremenili na način, kot sta se na zemlji spremenili znanost in tehnologija: poleti bodo med seboj bolje povezani, postali bodo bolj globalni, prav tako pa bodo bolj osredotočeni na prvotne cilje. Nova mednarodna politika človeških poletov v vesolje lahko pripomore k doseganju teh ciljev, tako da pojasni osnovna načela, etiko sprejemljivih tveganj, vlogo oddaljene prisotnosti in potrebo po uravnoteženju financiranja in ambicij, ki bi upravičila tveganje za človeška življenja.

Ključne besede: *človeški poleti v vesolje, mikrogravitacija, kozmično sevanje, vesoljska biomedicina*

WHY FLY PEOPLE INTO SPACE?

Flying from Earth to the Stars, through outer-space, has represented a Promethean dream, since the beginning of human history. The Greek myth relates the endeavour of the architect Dedalus' young son Icarus trying to travel beyond the clouds to the sun and his unfortunate end. Lucian of Samosata, around the 2nd century BC, described voyages to the sun and moon while spoofing Greek romances. That theme was rediscovered by Cyrano de Bergerac, who described the first space rocket in his Voyage Dans la Lune and L'histoire des Etats et Empires du Soleil (1652). About two centuries later, Edgar Allen Poe sent a man to the moon in a hot air balloon in his hoax, The Unparalled Adventures of One Hans Pfall (1835). Eventually, Jules Verne sent the first "astronauts" by cannon in From the Earth to the Moon (1865), just less than a century before the first cosmonaut, Yuri Gagarin, engaged in true space travel. The Mercury missions demonstrated the "survivability" of space flights and, in addition, proved that humans are an invaluable component of mission success (Nigossian, 1994). Indeed, accomplishing complex, specific tasks, both scientific and technological, that far exceed the current capabilities of robots, all require human intervention.

Since then, what was once the essence of the future – human ventures into space and to other worlds – is now a part of history.

However, the question "why fly people into space?" is not a trivial one. And it is highly probable that the answers to it have changed with each generation. Early on, Cold War competition provided a "sufficient" rationale; later, the goal became to develop routine access to space with the promise of commercial benefits. Recently, as plainly stated by the Augustine Report, only the loftier aims of exploration seem to justify the risks and costs of sending humans into the hostile space environment: "too often in the past we've said what destination do we want to go to, rather than why we want to go there. It's a question that in our view we have probably not answered correctly in the past". (Augustine Report, 2010)

It is now recognized that the primary objectives of human spaceflight, those that can only be accomplished through the physical presence of human beings, have benefits that exceed the opportunity costs and are worthy of significant risk to human life. By contrast, secondary objectives (including science, economic development, jobs, technology development, and education) have benefits that accrue from a human presence in space but do not by themselves justify the cost or the risk. Scientific data collected from the Fifties indicate that if humans are to travel in space for long distances and durations, then it is ethically imperative to understand the biomedical implications of prolonged exposure to Space and planetary environments. Indeed, the medical challenges associated with maintaining the safety, health, and optimum performance of astronauts and cosmonauts participating in long-duration missions are considerable and must be overcome to enable missions beyond low Earth orbit—missions to extend the time-distance constant of human space exploration.

A HOSTILE ENVIRONMENT

It has been insightfully stated, "patients on earth with illness can be described as people who live in a normal earth environment but who have abnormal physiology. In contrast, astronauts are people with normal physiology who live in an abnormal environment" (Williams, 2009). Indeed, Space is perhaps the most hostile environment to human life yet encountered. Characterized by extreme variations in temperature, the absence of atmospheric pressure, solar and galactic cosmic radiation, and zero-gravity, astronauts who meet the challenge of long duration spaceflight must confront a host of unique physiological issues, many of which will require either partial or complete solutions to allow for sustainable human exploration beyond the protective environment of Earth (van Loon, 2007).

According to a schematic framework, space exploration will subject astronauts to three main challenges and related threats: 1) changes in physical forces (reduced gravity, modified electromagnetic field) acting on every level of organization of the human body (from cells to organs); 2) exposition to cosmic rays; 3) psychosocial threats induced by long-term confinement. The overall risk induced by such factors is hardly to be profoundly understood and, till now, it does not seem that most of these risks may be reduced to an acceptable level for missions lasting more than 6 months.

Medical data from astronauts in low earth orbits for long periods dating back to the 1970s show several adverse effects of a microgravity environment: loss of bone density, decreased muscle strength and endurance, postural instability, and reductions in aerobic capacity. Over time these deconditioning effects can impair astronauts' performance or increase their risk of injury. In a weightless environment, astronauts put almost no weight on the back muscles or leg muscles used for standing up. Those muscles then start to weaken and eventually get smaller. If there is an emergency at landing, the loss of muscles, and consequently the loss of strength can be a serious problem (Baldwin, 1996; Sandonà, 2012). Sometimes, astronauts can lose up to 25% of their muscle mass on long-term flights. When they get back to ground, they will be considerably weakened and will be out of action for some time. In most cases, muscle mass and strength is fully recovered after 1–2 months back on earth (Shackelford, 2008).

Astronauts suffer from significant bone demineralisation (Whedon, 2006), mimicking osteoporosis lesions, as documented by bed-rest models (Rittweger, 2009). Radiographic studies documented a significant loss of calcium from weight-bearing portions of the skeleton; some regional losses were greater than two standard deviations from normal. This mobilization and loss of calcium suggests a significant risk of renal stone formation on missions of long duration (Whitson, 1999). Osteoporosis and bone remodelling induced by microgravity are of major concern given that "bone loss is likely to be progressive, at least to the point that fracture poses an immediate risk during space flight, such as a proposed 3.5 years exploration mission to Mars" (White, 2001). Undoubtedly, studies on microgravity-related osteoporosis have led to fruitful insights into bone and osteoblast physiology understanding; however, no reliable countermeasure has yet been proposed. Indeed, exercise regimens in space have not been proven effective nor have pharmacological treatments and vitamin supplementation counteracted bone loss (Smith, 1999). Most astronauts on long duration missions will fully recover their bone density within 3 years after the flight. However, some astronauts will never regain pre-flight levels, and the recovered bone may have different structure and mineralization (Clement, 2003; Lang, 2006).

Microgravity induces several other effects, among which are reduced cardiac function (Grigoriev, 2011), orthostatic hypotension (Reyes, 1999), enhanced susceptibility to ventricular arrhythmias (Fritsch-Yelle, 1998), circadian rhythm disruption (Gündel, 1997), endocrine changes (Stein, 1999), immune-related problems involving higher rates of infections and immunodeficiency (Taylor, 1993). Adaptive physiological changes to microgravity in space can alter the pathophysiology of diseases, the clinical manifestation of illness and injury, as well as the pharmacokinetics and the pharmacodynamics of drugs (Czarnik, 1999; Putcha, 1991).

Astronauts experiencing weightlessness will often lose their orientation, get motion sickness, and lose their sense of direction as their bodies try to get used to a weightless environment (Senot, 2012; Zago, 2005). When they get back to Earth, or any other mass with gravity, they have to readjust to the gravity and may have problems standing up, focusing their gaze, walking and turning. The predominant symptoms of "space motion sickness" include facial pallor, cold sweating, stomach awareness, nausea and, in some cases, vomiting (Heer, 2006).

Importantly, those body motor disturbances, after changing from different gravities, only get worse the longer the exposure to little gravity. These changes will affect operational activities including approach and landing, docking, remote manipulation, and emergencies that may happen while landing. This can be a major roadblock to mission success.

During long missions, astronauts are isolated and confined into small spaces. Depression, cabin fever, and other psychological problems may impact the crew's safety and mission success (Ephimia, 2001). Moreover, astronauts may not be able to quickly return to Earth or receive medical supplies, equipment or personnel if a medical emergency occurs. The astronauts may have to rely for long periods on their limited existing resources and medical advice from the ground. Neuropsychological correlates of space flight are generally studied in the laboratory, in special natural (like Antarctica) or artificial (like that provide by the Mars500 experiment) (ESA-MARS500) environments. The ultimate goal is to avoid unexpected and potential harmful consequences (like in those represented by the movie Solaris) through appropriate countermeasures.

HEALTH THREATS

Any space traveler far removed from the protective shield provided by both the Earth's atmosphere and the magnetic field that enshrouds our planet is subject to a continuing (low) dose of Galactic Cosmic Rays (GCR), to trapped ionizing radiation and to transient radiation from solar particle events (solar flares). Radiation hazard will exert radiobiological consequences at all levels of the organism, even four major challenges can be recognized: 1) carcinogenesis, 2) central nervous system damage, 3) tissue degeneration, 4) acute radiation disease (Shiver, 2008). Despite the increased knowledge accumulated during the last decades, assessing radiation risk is a difficult task, given that radiations interact according to non-linear dynamics (Durante, 2010; Averbeck, 2010) and the natural space radiation environment has a stochastic character (Petrov, 2011). Moreover, radiation-related biological damage in Space is currently considered to be induced by previously unknown mechanisms, based in the communication between damaged and undamaged cells (Azzam, 2001). Indeed, space radiation has been shown to produce distinct biological damage compared with radiation on Earth, leading to large uncertainties in the projection of cancer and other health risks, and obscuring the evaluation of the effectiveness of possible countermeasures (Durante, 2008). Spacecraft walls have helped to protect astronauts orbiting aboard the ISS and making short journeys from the Earth to the Moon or the ISS, but for longer flights such a "conventional" shielding cannot block radiation below the required level without making the vehicle far too heavy. In fact, shielding is very difficult in space: the very high energy of the cosmic rays and the severe mass constraints in spaceflight represent a serious hindrance to effective shielding. Shielding remains the only feasible countermeasure, but it cannot be a full solution for the GCR problem, even though it can significantly contribute to risk reduction (Parker, 2006). Very heavy shields are impractical on spaceships, although small ''storm shelters'' can be designed against intense SPE. Other strategies include the choice of an appropriate time of flight, i.e., mission planning and ability to predict solar particle events, administration of drugs or dietary supplements to reduce the radiation effects, enhancement of cell repair, and crew selection based on genetic screening. New promising solutions are underway, specifically those based on active magnetic shielding (Towsend, 2001). The experience gained during the development of the alpha magnetic spectrometer (AMS) super-conducting magnet has been useful to develop ideas and techniques to be applied to radiation shield for exploration missions (Battiston, 2008). However, significant money and time must be invested in the next decades to develop an effective shielding strategy.

While considerable knowledge exists regarding the physiological changes associated with the adaptation of humans to short-duration missions in space, there is less information regarding the physiological changes associated with long-duration missions extending from 30 days to months in orbit (Williams, 2003). In attempting to gain insight into the biological impact of prolonged manned space flights, scientists are at best forced to extrapolate data obtained from the International Space Station or produced during short-duration flight missions, neither of which can completely represent the characteristics of a real interplanetary flight. In such a condition, one has to rely mostly on simulated microgravity-based experiments as well as on computer modelling, these methods are largely unsatisfactory and, overall, remain immature to date. In addition, space physiology is considerably more constrained than most other fields of medical study. High costs, fewer subjects, inadequate experimental models, limited opportunity for reproducing the experimental conditions and a high incidence of unexpected intervening threats make predictions unaffordable. So far, experience accumulated to date highlights the need for highly robust biomedical research and development in human spaceflight – particularly as today's space programs begin to consider longer-term human expeditions beyond near-Earth space, to destinations such as Mars.

MISSION TO MARS

Data collected about the hazards of spaceflight requests new assessments and the development of new capabilities. The Apollo-era clear only in recent years. More rigorous techniques for quantitative risk assessment, developed in response to Apollo's preliminary analytical procedures, showed in hindsight that Apollo had indeed been "safe enough" to fly: calculations indicated that crew survival chances were better than 98% and mission success chances were in the 75% range for the early missions. But when applied to the then-popular Mars astronaut mission profiles, the same techniques generated horrifying results: mission success chances were less than 10%, and crew survival chances were less than 50% (Rapp, 2007). Early estimates of the uncertainty on space radiation cancer mortality risk ranged from 400% to 1500% (NASA, 1998), with more precise estimates showing uncertainties at the 95% confidence level of 4-fold times the point projection (Cucinotta, 2006). In addition, space flight will expose crews to the significant risk of medical problems: from 1981 through to 1998, 1777 separate medical events occurred in space; of these, 141 events were due to injury, including seven fatalities (Billica, 2000). It is quite anomalous that such a central problem is only rarely (or marginally) addressed by future options for human space flights, generally aimed to analyse the technical and socio-economic implications related to space explorations (Sherwood, 2011). However, the first limiting factor that makes a generalized human space exploration strategy still unsuitable is strictly depending on safety and biomedical considerations.

Space exploration is a risky adventure and cannot be reduced to a challenging technological endeavour, even if the crew could be (unlikely) "limited" to only two-astronauts (Salotti, 2011). It is widely accepted that a long-term human expedition to Mars will require approximately 2.4 years for completion, characterized by a 6-month flight to the red planet, an approximately 500 day surface stay, and a 6-month journey back to Earth (Bonin, 2005). Almost all of the physiological issues previously reported will manifest themselves over the course of such a mission, from radiation exposure beyond the protection of Earth's magnetic field, to cardiovascular and musculus-skeletal deconditioning, to neurovestibular and orthostatic intolerance upon Mars descent and landing. Over 2.4 years, the cumulative and interactive effects of these physiological problems could potentially be devastating to astronauts (and thus, the mission itself), even if no overt or serious singular incident occurs throughout the duration. Martian gravity is approximately 40% that of Earth's, and the physiological degradation experienced by astronauts in zero-g can be expected to slow somewhat during surface exploration. Since no data are yet available regarding the existence of the threshold value of microgravity in inducing measurable biological effects, and no studies have been carried out in order to ascertain the reversibility of microgravity-related effects after prolonged exposure, it is a matter of speculation if, even a 'limited' reduction in g levels might trigger significant health threats. Eventually, the same issues experienced by astronauts on the outbound leg of the trip can be expected to re-present during the inbound voyage. Therefore, the Mars missions will pose significant physiological and psychological challenges to crewmembers.

That worrying scenario could hardly be reconciled with the popular, funny misconception too easily diffused in the media by authoritative scholars ("A man can stay in space for more than 6 months – even 1000 days! – without experiencing irreversible health risks", "We can send humans to Mars in ten years" with "the primary objective of having them to remain there") (Rapp, 2007). Such unwise statements cannot have a place in the context of a scientific and rational debate. Moreover, it is quite alarming that some reports wilfully omit dealing with the safety challenges posed by human space flights, outlining that they are "not discussed in extensive detail because any concepts falling short in human safety have simply been eliminated from consideration". (Salotti, 2011)

THE NEXT STEP

Advances in Space Biomedicine allow us to ensure better astronaut performances and recovery after return on Earth. In addition, the biomedical support to space missions had significant impact on the delivery of terrestrial health care for years after the program concluded (Bizzarri, 2008). Namely, improvements in the ability to monitor astronauts in space during Projects Mercury and Gemini, as well as research programs performed on the Skylab Space Station (Johnston, 1977), fostered the early development of monitored patient environments and hospital intensive care units with similar technologies (Turner, 1997).

In almost 5 decades of manned spaceflight, our understanding of physiological change during long duration missions remains limited, and the implications of coupling both long duration and long distance space exploration remain largely unknown at present. Nevertheless, our experience in both low-Earth orbit and on brief lunar expeditions allows us to make reasonable assumptions about the primary stressors which human explorers will encounter as space missions grow longer. The physiological impact of human spaceflight is both significant and varied. Some issues – such as radiation exposure and immunologic depression – represent serious concerns during the course of a mission, while others – such as cardiovascular deconditioning and orthostatic intolerance – only manifest themselves upon return to Earth. A successful space mission means not just ensuring crew health for the duration of their journey, but minimizing the impact of spaceflight-induced deconditioning after returning to Earth as well. Counteracting both in-flight and post-flight physiological issues is vital to developing an aggressive, sustainable program of human space exploration beyond Earth.

Several key-questions have been left aside from the scientific mainstream: is the microgravity-related effect on living organisms an irreversible one? Or, can some kind of adaptation be envisaged for long-duration space flights? Is there a threshold value for microgravity effects? Can its biological effects be efficiently counteracted by some kind of drugs, exercises or artificial gravity devices? (Kotovskaya, 2011) Can we obtain satisfactory protection from radiation exposure through appropriate shielding? The unfathomed nature of gravity-biology interactions is still waiting for a reliable understanding. It is hardly understandable how a weak force (like gravity) could produce such "catastrophic" events at both molecular and physiological levels (Kondepudi, 1981). We know that several biological structures (cell shape, bone architecture) and cell functions (cell cycle control, apoptosis, differentiation) are noticeably affected by microgravity, and several molecular pathways have been extensively studied and recognized in the last decade (Hammond, 2000). However, we are far from having an overall exhaustive comprehension of the processes involved. This means that, first of all, a general theory about the relationships between gravity and life is urgently needed. From a clinical point of view we have to know if gravity-induced alterations are irreversible beyond a temporal threshold value. Several attempts have been made to extrapolate both predicted and experienced risks to longer-duration flights – but the actual biological impact of endeavours such as interplanetary flight currently remain both unknown and unknowable. The answers we will provide to such questions will decide our future in space.

Manned space flight has been the great human and technological adventure of the past half-century. By putting people into places and situations unprecedented in history it has stirred the imagination while expanding and redefining the human experience. In the twenty-first century, human space flight will continue, but it will change in the ways that science and technology have changed on Earth: it will become more networked, more global, and more oriented toward primary objectives. A new international human space flight policy can help achieve these objectives by clarifying the rationales, the ethics of acceptable risk, the role of remote presence, and the need for balance between funding and ambition to justify the risk of human lives.

No doubt sooner or later, we will hit the mark! However, for now, we must outline that a long and unrecognised way is waiting for us: "it's a long way to Tipperary". As Ariosto's masterpiece (Ariosto, 1516) tells us, walking on the Moon has been always considered pure madness; will this sentence still be true in the future?

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