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An Analysis of the Effects of Space Conditions on Human Physiology, Psychology, and Genetics, and their Implications for Medicine on Earth

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Abstract

As of November 2023, 676 people have journeyed into space. As this number continues to rise every year, with plans for further, long-term space exploration extending even into the 2030s, it becomes increasingly important to form a comprehensive analysis of the challenges posed by harsh space conditions on human physiology, genetics, and general systems. Understanding these factors can in turn help reinvent medical techniques on Earth, such as the use of pressure adjustable suits to combat extreme acceleration and change in gravitational force for people suffering from postpartum haemorrhages. This paper delves into two main themes: firstly, the impacts of conditions like microgravity, galactic cosmic rays, and isolation on systems such as telomere length, neuro-ocular, and cardiology, and secondly, how these difficulties can be used to advance treatment for illnesses on Earth, by analyzing the NASA Twins Study as well as secondary research for the medical applications. This is essential to lay out a framework and area of reference for future space missions and possible developments in medicine - both in space and on Earth.

Keywords: Space Conditions, NASA Twins Study, Human Physiology, Genetics, Medical Applications.

Introduction

The objectives of this paper are to evaluate the effects of microgravity, galactic cosmic rays (a type of space radiation), and physical isolation on telomere length, DNA damage response, immune response, muscular system, mitochondria, cardiology, neuro-ocular system, psychology (the "break-off" effect), and cognitive performance, and how these lead to novel advancements in medicine on Earth, while synthesizing existing research and offering new perspective. In March 2015, NASA's (National Aeronautics and Space Administration) HRP (Human Research Program) launched a 340-day investigation of a pair of monozygotic twin astronauts called The NASA Twins Study[1]. The purpose of the investigation was to "observe what physical, molecular, and cognitive changes could happen to an astronaut from exposure to the environment of space, as opposed to regular day-to-day life on Earth" (NASA[2]).

Figure 1: Identical twin astronauts, Scott Kelly and Mark Kelly, who participated in the Twins Study (NASA)

This paper aims to synthesize the factors analysed in the Twins Study, telomere length, DNA damage response, mitochondria, cardiology, neuro-ocular system, and cognitive performance, as well as introduce and hypothesize two new affected parameters through further research, the musculoskeletal system and psychological changes. Through this synthesis, an analysis of the applications of space research on medicine on Earth is presented, which is especially significant due to the extensive areas of benefit for the health and well-being of humanity in terms of detection and cure. These implications entail the invention of surgical robots such as neuroArm which was developed from Canadian space robots[3] used in space exploration, as well as the same technology being used to develop robots that are capable of performing biopsies to detect breast cancer.

Problem Statement

This paper is addressing the research question: How do different space conditions affect human physiology, psychology, and genetics, and how do these effects in turn result in direct and indirect developments and advancements in medical instruments and procedures on Earth? This problem is worth investigating due to the rapid growth in space exploration and plans for long-term space exploration within the next few decades, as it provides a detailed analysis of factors to take into consideration when sending humans into the vastly different conditions of space as compared to those on Earth, and also provides a means to use this data to improve Earth medicine, linking two diversely advancing fields of research. This paper also offers a complete, collected analysis of these two areas of exploration, providing ease and multi sourced linkage, as there is a lack of comprehensive analysis and connection of the two ideas elsewhere.

Methods

Firstly, databases such as JSTOR and Google Scholar were searched to find relevant research papers on the topic of the effect of space conditions on humans. These papers were closely studied and analyzed to gain an understanding of the relevant topics discussed. The papers were filtered through the date of publication, ensuring that all the research occurred within the last 5-7 years to maximize time relevance and take into consideration new developments in the field. Next, official space websites such as NASA, ESA, and CSA were searched to find any relevant research conducted on the above topic, as well as medical applications of space research. From here, the NASA Twins Study was deeply reviewed and included as an area of discussion in this paper. The points to be analyzed were narrowed down based on relevance to long-term space exploration and potential for further areas of medical analysis. Data from other research papers were extracted by locating the points to be discussed, as well as outside the Twins Study, such as musculoskeletal and psychological effects. Based on these points, graphs and raw data were also analyzed to identify patterns and relevant information. After the data were extracted, they were combined to create a two-part discussion: i) the effects of space conditions on humans, and ii) the medical applications and relevance on Earth of the functioning of biology and medicine of humans in space. For point i), the NASA Twins Study evidence was merged with the same points of discussion from other research papers, such as one on the effect on telomeres in space, creating a more elaborate and diverse trial description. Secondly, data from other papers from sources such as the NIH and CSA were collected for point ii) to provide a comprehensive and relevant discussion of the applications of space medicine and research on Earth. The quality of the papers were analyzed through the reputability of the journal/website, as well the authors involved in their writing and publication.

Discussion and Analysis

1. Variations in space conditions as compared to Earth

Analyzing the vast and varied effects of the space environment on human biology prompts the question "What makes space conditions different from those on Earth?" For starters, space consists of a multitude of environmental stressors that are out of the range of their presence on our planet. The main factor that causes the most objective change on human physiology is the gravitational force. On Earth, the acceleration due to gravity is constant at 9.8m/s2, however, this value is reduced by 20% for shuttle astronauts, leading to them experiencing it at $7.84 m/s^2$ (National Space Society). Alongside this, astronauts also experience microgravity, which is the state of continuous free fall towards the Earth caused due to the low gravity conditions in orbit, resulting in the feeling of weightlessness. Since humans are adapted to the normal gravity conditions on Earth, experiencing significantly lower gravity for a relatively long period of time can lead to changes in their neuromuscular, cardiological, and neuro-ocular systems. Secondly, there is a strong presence of galactic cosmic rays, which are the "slowly varying, highly energetic background source of energetic particles that constantly bombard Earth" (NOAA[14]). Earth is surrounded by a powerful magnetic field which shields it from most of this remnant radiation by diverting it away, strongest at the equator and weakest at the poles. In space, however, there is no source of protection against this ionizing radiation, which causes any human that travels to space to be exposed to a significant amount of the rays. The ISS, on the other hand, is partially protected through hydrogen-rich shielding in the most frequently occupied locations, however this is solely a reduction rather than total prevention, which means that all astronauts are subject to greater amounts of galactic cosmic rays than they would be on Earth. This radiation leaves lasting effects on the human body, such as chromosomal abnormalities, oxidative stress, and increased likelihood of cancer and degenerative diseases[7]. Lastly, the confinement and isolation experienced by astronauts in space due to i) lack of a large number of crewmates, and ii) increased distance from Earth making communications with friends and family more challenging leads to significant psychological impacts like disturbances in the circadian rhythm, decreased performance, and increased boredom and loneliness.

Fig 1: Identical twin astronauts, Scott Kelly and Mark Kelly, who participated in the Twins Study (NASA)

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2. The effects of these adverse conditions on humans

In the NASA Twins Study, researchers analyzed the effects of the above space conditions on two monozygotic twin astronauts, to establish a lack of genetic variance that could lead to an unfair test, for approximately 1 year - Mark Kelly was studied on Earth as a control and Scott Kelly in low Earth orbit aboard the ISS (International Space Station). This section of the paper will expand on a select number of the parameters investigated, integrating them with further research that has been carried out since.

a) ***Telomere Length:*** Telomeres are structures at the ends of chromosomes that protect DNA from damage - their length therefore shortens with age. Scott's telomeres elongated during his time in space while Mark's were stable the entire time - both had the same lengths before Scott left. Another study conducted on three unrelated astronauts showed in accordance with these results, reporting a significantly longer average telomere length along with an increase in the number of long telomeres during spaceflight (ScienceDirect, 2020[4]). Scott's telomere length increased by 14.5% during the flight compared to his pre and post flight measures and it was observed during all points of flight only in CD4, CD8, and LD cells, but not CD19 cells. After he returned to Earth, the telomere length rapidly shortened within 48 hours and stabilized to preflight measures within months, which was also supported by the same study. However, there was an increase in the number of critically short telomeres, indicating some permanent telomere loss. Analysis using Telo-FISH in both studies confirmed these trends. There were also changes observed in DNA methylation (when methyl groups are added to the DNA molecule, affecting gene expression) of the TERT gene promoter, which is a mutation involved in telomerase regulation, specifically in CD4 and CD8 T cells. Scott generally had lower telomerase activity compared to Mark throughout the study. Telomerase activity could not be measured accurately during the flight in both studies likely due to inevitable factors like heat and time during the investigation. However, it can be hypothesized that Scott would have shown lower telomerase activity compared to Mark. From the results of these studies, we can hence confidently state that telomere length increases in space, with a consequent rise in the number of long telomeres. From this conclusion, we can thus draw a hypothesis that the process of aging is slower in space, which offers promising implications for long-term space exploration and the search for life outside Earth.

b) ***DNA Damage responses:*** Chromosomal abnormalities were studied from galactic cosmic rays, one of the environmental stressors explained above. High-resolution directional genomic hybridization was used to examine chromosomes 1, 2, and 3 for changes like translocations (where parts of one chromosome move to another) and inversions (where parts of a chromosome flip). Initially, both twins had similar levels of chromosomal changes, with inversions more common than translocations. In flight, Scott's inversion rate increased more rapidly than translocation rates, possibly due to the radiation. Genes whose expression was altered inflight were significantly enriched in pathways related to DNA damage[4] responses in flight. Scott's inversions continued to rise post flight, possibly indicative of IR-induced DNA damage to stem cell compartments. Although Scott's translocations varied, there were also increased inflight and postflight compared with preflight, additional evidence of inflight radiation exposure and the consequential galactic cosmic ray-induced genetic damage. The reason ionizing radiation damages DNA is due to the induction of DNA breaks, which then generate reactive oxygen species that oxidize proteins and lipids, resulting in basic sites and single strand breaks (NCBI, 2015). These changes to the DNA mimic aging, which is why galactic cosmic rays sometimes lead to degenerative diseases or other diseases normally linked to aging. It is also why ionizing radiation is often used to treat cancer - it damages the DNA of the rapidly dividing cancer cells.

c) ***Mitochondrial changes:*** Analysis of RNA sequencing data showed increased levels of mitochondrial RNA (mtRNA) during spaceflight, with a strong correlation between time spent on the ISS and elevated mtRNA levels. This was further validated by consistent mitochondrial genome coverage across samples and qPCR results. An extracellular flux assay on muscle cells treated with astronaut plasma indicated altered mitochondrial function. Additionally, increased lactic acid levels were detected in urine during spaceflight, showing a shift from aerobic to anaerobic metabolism, which was supported by higher lactic acid/pyruvic acid ratios and trends in plasma TCA cycle intermediates. Gene expression analysis revealed changes in pathways related to mitochondrial processes, oxygen metabolism, and hypoxia, despite the ISS maintaining near sea-level oxygen levels. These changes in the functioning of mitochondria occur mainly due to a condition known as oxidative stress, resulting from both microgravity and ionizing radiation, which occurs when there are too many free radicals and a lack of antioxidants to neutralize them. Because mitochondria overproduce the reactive oxygen species during oxidative stress, an increased number of mtDNA mutations and damage to the mitochondrial respiratory chain is induced.

d) ***Cardiological changes:*** There was a 10% increase in cardiac output and a decrease in systolic and mean arterial pressure as compared to Earth. Carotid artery distension developed early in flight and persisted, while carotid intima-media thickness increased in Scott during spaceflight and remained elevated for several days postflight. This occurs due to the translocation of fluid to the head, which also results in a reduced circulatory blood volume. Astronauts also commonly experience a decrease in central venous pressure, which is hypothesized to be a result of the lack of compression of external structures on the veins[5]. These cardiovascular changes occur largely due to the effects of microgravity, when the body also experiences uniform arterial pressure due to lack of gravity increasing the pressure below the heart.

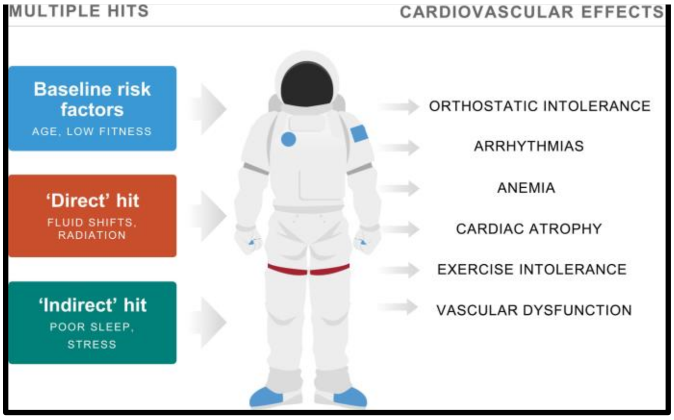

Figure 2: The effects of varying spaceflight conditions on the cardiovascular system (American Heart Association Journals)

e) ***Neuro-ocular changes:*** During spaceflight, Scott experienced a cephalad fluid shift and ocular changes not observed in Mark. Retinal oedema was indicated by increased sub foveal choroidal thickness and peripapillary retinal thickness, and Scott's choroidal folds worsened in severity during spaceflight, whereas Mark's ocular structures remained unchanged. Additionally, Scott and Mark both had low serum folate levels, which has been associated with ophthalmic issues in astronauts. The presence of specific genetic risk alleles related to ophthalmic changes was also noted in the twins. Another condition known as Spaceflight Associated Neuro-Ocular Syndrome (SANS) is observed in many astronauts where exposure to altered gravity can cause ocular and brain structural changes to develop during spaceflight; these changes could lead to vision alterations, cognitive effects, or other harmful health effects. It is hypothesized to occur due to cephalad fluid shifting to the head, neck, and orbits occurring in microgravity environments due to impaired lymphatic, cerebral spinal fluid, and vascular drainage that normally are assisted by Earth's gravity.

f) ***Cognitive performance:*** During the study, Scott underwent computerized cognitive testing throughout the mission phases, including preflight, early inflight, late inflight, and postflight. Compared to Mark, Scott consistently took more risks on the Balloon Analog Risk Test (BART) during all phases, particularly inflight. Although Scott's cognitive speed improved early inflight and his spatial orientation increased, he experienced a decline in emotion recognition task (ERT) speed, and a significant decrease in abstract matching accuracy during late flight. Postflight, Scott's cognitive speed and accuracy declined across most tests, with cognitive efficiency significantly lower compared to preflight and inflight levels. This decline in cognitive performance persisted up to 6 months after returning from space. This probably resulted from prolonged exposure to microgravity, sleep pattern changes, fluid shifts in the brain, and galactic cosmic rays (ScienceDirect, 2022[6])

With the changes in microgravity and increasing isolation that comes from spaceflight, there are also alterations in the musculoskeletal and psychological systems in humans. Firstly, the musculoskeletal system experiences one of the most pronounced impacts of microgravity. Since this system is very reliant on the force of gravity as a source of structure and support, the weight bearing bones particularly feel the effects of microgravity. Since there is fixed pull on the bones, they can reshape and remodel themselves, which consequently results in bone loss and osteoporosis. Due to this, astronauts are at higher risk for fractures. Alongside bone loss arises muscle atrophy, the thinning of muscle mass[8]. This is a direct result of the lack of demanding physical activities and the loss of postural muscle. Since the heart is also a muscle, this muscle atrophy also affects the heart, leading to a higher risk of heart failure and reduction in blood volume and pressure. For this reason, people also experience back pain due to the shrinking back to the normal height after the full effect of Earth's gravity takes effect. Sunita Williams, an American astronaut, made these statements about her experience in space in terms of the effects on her musculoskeletal system: "On Earth, our bones and muscles are in a state of being pulled down towards the ground by gravity, so doing frequent weight-bearing exercises will keep them strong and dense. This organic stress encourages muscle upkeep and bone remodelling. Since this does not happen to astronauts in space because of the lesser force of gravity, it results in the loss of their muscular mass and bone density. Since there is no weight to be carried by the bones nor any regular physical activities such as walking and lifting, their bones and muscles are less activated. Due to lesser tension, muscle and bone structures break down a lot faster." Secondly, there are pronounced psychological effects that arise from being in constant confinement and isolation. Due to the requirement to adapt to microgravity, simple tasks such as preparing food become incredibly challenging. There is a lack of fruitful social interactions, and this coupled with the high-stress situation of monitoring and controlling the space-flight to prevent anything from going wrong can lead to adverse mental health effects. Due to the lack of natural light, there is also a shift in normal circadian rhythms, which further exacerbates mood swings and irritability[9]. There is also a difference in noise type and noise level, which could result in performance issues and a change in the neurobehavioral system. A phenomenon called the "break-off" effect has also been identified in some astronauts, when they feel a profound sense of isolation from Earth. In the long-term, this could lead to serious mental health conditions such as depression, making it essential to find ways to combat the sense of confinement by improving communication technologies and adding interesting exercises and games to the routine of an astronaut in flight.

3. The contribution of space research to enhancing medicine on Earth

Space research can be used to accomplish many feats humanity once thought were impossible. However, the under-discussed implications of space research are those of developing medicine on Earth. The effects of microgravity, ionizing radiation, and confinement and isolation experienced by astronauts in space are similar to those of people who are aging and engaging in an unhealthy lifestyle, as shown by the reduction in bone and muscle mass, psychological changes, and DNA damages. Using this research, it becomes possible to advance healthcare for people on Earth. Firstly, the musculoskeletal problems experienced by astronauts are similar to those experienced by people with neuromuscular diseases. To counter this, measures such as genetically engineering mice to be more resistant to muscle and bone density loss have been proposed, which would be ideal since the effects of microgravity on mice have been studied in lunar orbit (Nature, 2023[11]).

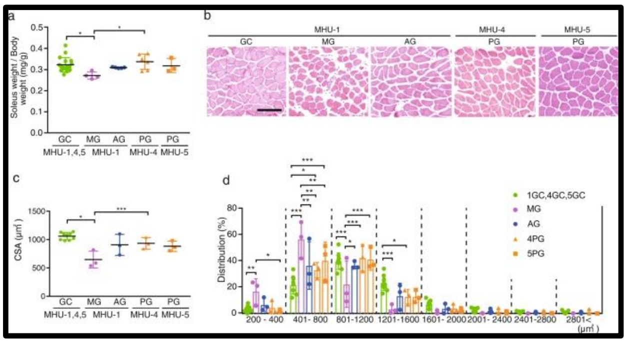

Figure 3: Graph showing the effect of lunar gravity on the soleus muscle in mice (Nature)

Additionally, the In Vitro Bone experiment, which was sent to ISS in 2018, monitored the degradation of bone cells with and without the protein irisin. Its presence was found to counteract microgravity, which could result in the development of an irisin based substance to help aging people or people with musculoskeletal disease[12]. Secondly, the lack of proper access to all necessary medical sending equipment in space due to lack of space or resources has led to the development of various remote monitoring systems. One of these technologies is known as telemetric health monitoring, and allows the physiological changes in astronauts to be monitored through real-time sensors remotely. This technology has been utilized in smartphones and fitness trackers, and is even helpful for doctors who want to monitor their patients outside of the hospital. Thirdly, the use of space robots utilized in space exploration has resulted in two major developments in human medicine. i) Canada's space robots have led to the invention of a surgical robot called neuroArm, which is a highly precise robotic arm that can perform complex brain surgeries, and ModusV, a microscope that assists in various brain and spine conditions. These advancements allow neurosurgeons to undertake surgeries more efficiently and safely. ii) The technology behind the space robots has also been used to develop IGAR, a tele-operated robot that can perform precise biopsies to detect breast cancer with high accuracy. As more resources are poured into space research, there will also probably be consequential developments in the use of the technology behind the equipment to advance the use of accurate robots in human medicine. Lastly, the use of pressure-adjustable suits that astronauts wear to help prevent blood from collecting in their legs in the extreme acceleration during space flight can be used in a hospital setting for people suffering from postpartum haemorrhages[10], a condition that occurs after birth that consists of extreme bleeding, possibly helping prevent the 70,000 maternal fatalities (WHO[13]) that occur worldwide due to this issue.

Conclusion

The record for the largest number of people in space at one time is currently 20. As this number will keep increasing over the next decade, especially with plans for human exploration of Mars in the 2030s, the effects of space conditions on human health become increasingly significant. These space developments also consequently lead to advancements in healthcare on Earth, since conditions in space are similar to aging people and those who suffer from degenerative and neuromuscular diseases. This paper has analyzed the effects of the space conditions microgravity, galactic cosmic rays (ionizing radiation), and confinement and isolation on human physiology, psychology, and genetics, with the factors being telomere length, DNA damage response, mitochondrial changes, cardiological changes, neuro-ocular changes, cognitive performance, musculoskeletal system, and psychology using the NASA Twins Study, Sunita Williams' experience, hypotheses, and personal insights. Overall, it is shown that telomere length increased, there was more damage to the DNA due to ionizing radiation, oxidative stress which contributed to a reduction in mitochondrial activity, reduced blood pressure and volume, shift of fluid to the head region, decrease in emotional tests and increase in risk taking tests, muscle atrophy and bone loss due to change in gravity, and an increase in adverse psychological effects. These effects were then discussed in relation to improving medicine on Earth by conducting research in space due to the similarity of effects of aging and degenerative disease in conditions of microgravity. Through advancements in long-term human missions and space exploration, a stronger link is formed between human biology and the universe as we delve back into the place we originated from.

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