Editorial

AI's role in deep space

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Introduction

Astronauts are commonly portrayed returning to earth in a state of physical weakness (1). Space travel in both human and animals has shown that no organ system in the human body is spared from the effects. Scientists have explored how intense terrain changes the human body with experiments in places such as the desert, tundra and deep sea, but there are obvious limitations to recreating the nuances associated with being outside of low earth orbit (LEO) (2).

To exacerbate the problem, data acquisition and analysis of astronauts' wellbeing is imperfect. Parameters such as heart rate, breathing rate, or even sleeping patterns can be monitored on wearable devices (3). More invasive tests such as intraocular pressure, pulmonary function, kidney function, and cancer surveillance require specialty devices and/or trained technicians. Further, it is not known which parameters should be monitored to provide the most benefit for crew members with the least harm. Once sick, diagnostics such as imaging and blood work are limited and communications with earth is delayed (4). Even if a disease is correctly identified, in-flight capacity for medical interventions such as pharmaceuticals and surgery are greatly reduced.

The increasing capacities of space flight comes at a time when artificial intelligence (AI) is beginning to be used on earth to mitigate health risks and predict disease prevalence. AI is defined as the performance of tasks that typically require human intelligence such as visual perception, decision-making, and pattern recognition (5). The objective of this review is two-fold: Part I presents a summary of derangements that occur outside of LEO by physiologic system (*Table 1*), while Part II reviews current and future AI solutions to help bridge the gap between the unknown and long-term space flight (*Table 2*).

Part I: Effects of space flight on physiologic systems (*Table 1*)

Neurologic

Striking changes to the anatomy of the brain are present in MRIs of astronauts on their return to earth. Space flight has caused narrowing of the central sulcus, an upward shift in location of the brain, and narrowing of cerebrospinal fluid (CSF) spaces (6). Overall changes to the neurologic system can be categorized to changes in intracranial pressure, the spinal column, and neurocognition (7). These changes were dependent on the duration of flight and it is not known if they are permanent.

Ophthalmology

Space flight-associated neuro-ocular syndrome, known as SANS, has been found after long missions in space (8,9). Similar to idiopathic intracranial hypertension, astronauts exhibit optic disc edema, globe flattening, choroidal and retinal folds, hyperopic refractive error shifts, and nerve fiber layer infarcts. In some crew members, symptoms persisted even years after return to earth (8).

Cardiovascular

In general, the heart beats faster and blood pressure is

Table 1 Physiologic effects of space travel by system

Field	Impacts in space
Neurology	Increased intracranial pressure, narrowing of spaces for CSF
Ophthalmology	SANS, optic disc edema, globe flattening, etc.
Cardiovascular	Increased heart rate, decreased blood pressure, increased risk of cardiac dysrhythmias
Pulmonary	Lunar dust toxicity
Gastrointestinal	Food stability, alterations in gut microbiome
Urinary	Kidney stones, urinary incontinence
Musculoskeletal	Loss of bone mineral content
Hematology	Anemia, change in hemostasis
Immunology	Immune deficiency, changes in pathogen virulence
Oncologic	Radiation induced cancers affecting the blood, breast, thyroid, colon and lung
Psychologic wellness	Altered circadian rhythms, mood alterations, stress

CSF, cerebrospinal fluid; SANS, space flight-associated neuro-ocular syndrome.

Table 2 AI solutions for space medicine

Intervention	Examples
Wearable technology	Electronic skin, electronic ears, electronic noses, motion sensor, ICP monitor
Biosensors	Genomics, transcriptomics, proteomics, and metabolomics
Surveillance and diagnostic imaging	Tele-ultrasound
Augmented and virtual reality	AR/VR-assisted windows, facial pattern recognition
Telemedicine and telesurgery	Telehealth communications, robotic assisted surgery

AI, artificial intelligence; AR/VR, augmented reality/virtual reality.

lower when in outer space (1). The autonomic nervous system, arterial blood pressure, cardiac contractility, and electrophysiology have all been shown to change in the setting of microgravity (10-14). Researchers have suggested that as little as 6 months of spaceflight is enough to cause alterations in the heart's structure and conduction pathways increasing the risk of cardiac dysrhythmias (15). There is one documented case of a team aborting a mission due to a crew member suffering from a cardiac dysrhythmia after takeoff (16).

The cardiovascular response to microgravity are both immediate, involving reflex responses to blood and fluid redistribution in the body, and chronic, including changes in cardiac pumping capacity and establishment of new reflex set points. The changes in cardiovascular reflexes are likely functional and necessary to establish cardiovascular stability in the microgravity environment. At the same time, the changes create unknown risks for return to earth.

Pulmonary

The inhalation of lunar dust from Mars, the moon, and other planets has been shown to be toxic to humans (17). Also known as regolith, lunar dust has been analyzed from the space suits of astronauts. Cleaning the suits between wears resulted in direct contact and respiratory exposure to the dangerous particles. Spacesuits were found to be permeable to regolith, increasing the risk of suit induced injury (18). In addition to the pulmonary system, the toxicity of the dust has also been demonstrated in the cardiovascular and nervous systems (19-23).

Gastrointestinal

It is unclear how to best provide a sustainable food source for long-term space missions. Variables range from food availability, reproducibility, freshness, stability from radiation, and nutritional content. Investigations of the gut microbiome are in their infancy but may be important to identify which essential supplements would best benefit crew members (24). Researchers demonstrated minimal effects of radiation on food in short-term missions, but long-term effects remain unknown (25).

Genitourinary

Kidney stones, which can be medically or surgically managed, are potential causes of aborted missions (26). This is especially true with conditions that increase the urinary excretion of calcium (i.e., increased bone resorption while in microgravity conditions), dehydration, and high sodium diets. There has been one episode of a renal stone that was luckily passed in space before the crew turned the ship back towards earth (27). Urinary retention, which can also cause acute pain and chronic renal damage, has been demonstrated in space. In-flight treatments of urinary retention have ranged from self-catheterization to percutaneous drainage of the bladder using ultrasound guidance (18,26).

Musculoskeletal

In addition to overall weight loss, astronauts exhibit loss of bone mineral content due to the diminished load bearing environment. Cartilage is also suspected at being negatively affected by microgravity causing increased issues with spinal pathologies (28). Efforts to counteract musculoskeletal wasting include resistive exercise and changes in dietary habits while in flight (29).

Hematology

Plasma protein synthesis has been shown to be depressed in astronauts on missions, with expected decreases in red blood cell counts, causing symptoms of anemia worse with longer duration in extreme environments (30,31). Data also indicates that spaceflight may alter mechanisms of hemostasis associated with clotting factors and endothelial cell changes (30,32).

Immunology

Similar to hematologic concerns, the decreases seen in plasma protein synthesis increases the risk of immune system compromise while in space (30,31). Not only are changes happening to the human genome, but studies suggest that pathogen virulence can be changed by extreme environments (30,33).

Oncologic

Radiation from space is greater than that on earth due to loss of the earth's magnetic shielding, but the extent of space travel's cancer risk is not yet known (4,34). On earth, radiation can induce leukemias, breast, thyroid, colon and lung cancers (35-37). Some permanent effects of cosmic radiation exposure were found in the epigenome of human bronchial epithelial cells (38).

Psychologic wellness

It is well demonstrated in the literature that astronauts have trouble sleeping (1). Research shows that even before departure, sleep deprivation is common in the months of preflight training (39). More pharmacotherapy was used for insomnia than any other medical condition while astronauts were in space for 79 early US missions (40). Reasons for altered sleep-patterns could range from microgravity effects on the atmosphere, to radiation and light-dark patterns. Other theories are non-functioning lymphatic drainage systems, diminished brain perfusion, or sleep apnea exacerbations causing even further tissue hypoperfusion (18).

In addition to and likely related to insomnia, other psychological changes include alterations in mood, alterations in neurocognitive performance, increased stress levels and conflicts both between crew members as well as with mission control (3,7,41).

Part II: Solutions to monitor and mitigate risks associated with the effects of space flight on human physiology (*Table 2*)

Wearable technology

Wearable health technology augmented by AI is already in use. These tools are likely to be some of the most prevalent noninvasive additions to spaceflight. For example, rest-activity data has been obtained by wrist-worn actigraphs by astronauts (3). Experts already recommend periodic monitoring of bone density, muscle strength, cardiac output and energy expenditure to identify crew members at risk of losing bone strength below the fracture risk level (42). Wearable devices that can measure these parameters in real-time and analyze data on a personal level have the potential to identify issues with bone health earlier.

Extensive research is being performed in the field of "electronic skin" for monitoring vital parameters and future integration into AI platforms (43). Things like the "electronic nose" with the ability to sense harmful compounds and the "electronic ear" to detect pathology in lung sounds, are also under development (5). These electronic sensors could alert crew members of high-risk situations such as elevated levels of lunar dust. AI could further be used for predictive modeling to determine what may be the safety limitations for human exposure to regolith in potential colonization sites.

The combination of motion sensors and machine learning has been studied to identify fatigue and fitness levels in cancer patients (44). Wearable devices have also demonstrated feasibility detecting cognitive decline and episodes of agitation in patients at risk for and suffering from Alzheimer's dementia (45,46). Another noninvasive AI device called BrainCare™ (San Paulo, Brazil) evaluates intracranial pressure in real-time (47,48).

Wearables could be incorporated into T-shirts or space suits, acting as "exoskeletons" (49). Helmets and hats could have electroencephalographic (EEG) like capacity to monitor disturbances in brain activity and sleep cycles (50). In the future, technology may go further than personal wearable devices and the architecture of the spaceship itself may be able to monitor significant changes in parameters such as heart rate, blood pressure, and temperature (34).

Biosensors

Biosensors are analytical devices that measure chemical substances and tend to be a more invasive form of monitoring than the previously described wearables. Their function can range significantly to evaluate metabolites, blood, urine, hair, feces, muscle and saliva (30). Panomic studies, which include genomics, transcriptomics, proteomics, and metabolomics are mostly limited to pre- and post-spaceflight analysis. Limitations include the bulk and great expense of storage, preprocessing, and analytic machinery (30). As technology advances to become smaller, more efficient, and less expensive, real time analysis using AI solutions may become a reality in-flight.

In a groundbreaking NASA study, one pair of genetically identical twins was analyzed over 25 months (24). One twin spent a year on the International Space Station, while the other stayed on earth. Both agreed to be "panomically" monitored. Results demonstrated no significant difference between the twins in a vaccine study, indicating that this part of the immune response was minimally affected. Major differences were found in telomere length, epigenetics, gastrointestinal microbiome, body weight, inflammatory cytokines, carotid artery dimension, ocular parameters, and metabolites within the blood. Many of these changes returned to baseline after time back on earth. The authors conclude that while many parameters did normalize, it highlights vulnerable organ systems at higher risk of irreversible damage on long-term spaceflight outside LEO. This study also serves as a model for future datasets which integrate information across multiple physiologic systems.

Solutions to identifying at-risk organ systems with machine learning includes investigation of bone loss genomics, circulating tumor cells in blood samples, and circulating neutrophil transcriptomes to detect unruptured intracranial aneurysms (51-53). Biosensors can also be used to evaluate the food and pathogens brought aboard. Manual in-flight analysis of drug safety is an onerous task, but with advanced AI algorithms, can be autonomously analyzed for safety (54,55).

Personalized implantable medical devices both for monitoring and administration of treatment is under investigation (56). Space shuttles' inventory needs to be reserved for essential items only. Theories on the utility of 3D printing, especially those augmented with AI, include the creation of personalized implantable devices on an as-needed basis while in-flight when emergencies arise (57).

Augmented and virtual reality

Augmented reality/virtual reality (AR/VR) has been suggested as a relief to neurologic and psychologic challenges by creating audiovisual stimuli after sensory deprivation in space. Advances in skin-integrated haptic interfaces would amplify the auditory and visual sensory interventions to include touch (58). An example includes AR/VR assisted window or room to retrain eyesight so that visual damage may be mitigated upon return to earth.

Behavioral and psychological assessments are currently performed with survey data such as Beck Depression Inventory-II (BDI-II), Profile of Moods State short form

(POMS), Psychomotor Vigilance Test (PVT-B), visual analogue scales and conflict questionnaires (3). Promising technology in AI may be able to identify disturbances autonomously and mitigate the shortcomings of subjective surveys. Neural networks can use facial expression recognition to visibly detect alterations in mood, stress, and overall health level in the astronaut, which may indicate the need for increased sleep time, a quicker return to earth, or a health evaluation (59).

Diagnostic and interventional imaging

Large CT and MRI imaging modalities are not expected to exit the earth's orbit for some time, but ultrasound imaging is already in use. Similar to what would be done in an emergency department during a trauma activation, the Focused Assessment in Sonographic Technique (FAST) exam has been performed by crew members while in outer space to rapidly investigate life-threatening intra-abdominal and thoracic pathology (60). This modality has been expanded to include traumatic ocular changes (61).

Remote ultrasound, also termed "tele-ultrasound" has been investigated under the NASA Extreme Environment Missions Operations (NEEMO) expeditions (60,62). While working in the extreme underwater conditions of a submarine, "aquanaut" crew members were able to diagnose and perform interventions using ultrasound and remote physician guidance. Future work is being done to apply automated robotic assistance to the ultrasound users motions to better identify key structures, diagnose, and treat with ultrasound-guided interventions (60,63).

AI is also being employed to detect risk of cerebrovascular disease using estimates of carotid-femoral pulse wave velocity using doppler ultrasound (64). To this day, the ultrasound remains the only imaging modality on the International Space Station and its utility ranges from successful diagnoses of trauma, musculoskeletal, cardiovascular, genitourinary, and decompression sickness pathologies (60).

Telemedicine and telesurgery

Telehealth visits are already routinely performed in space, but are limited by the lack of continuous real-time communication with increasing distance from the earth (4,34,65). Due to the difficulty with delayed terrestrial communication, space missions traveling outside of LEO require the crew to have increased medical training so that they can operate independently in a medical emergency (66,67). AI has the potential to mitigate some of the communication barriers to create more autonomous in-flight medical care systems via integration of wearables, biosensors, imaging, and the subsequent decision support systems (4).

Examples of telesurgery, in particular, include intercontinental robotic surgery and robotic surgery in zero gravity (66). In addition to the tele-ultrasound studies, NEEMO expeditions examined the feasibility of using robotic surgery on astronauts in extreme conditions by operating in a submarine with similar guidance from a remote physician (66,68).

AI is already being employed to advance the fields of radiology, cardiology, ophthalmology and pathology, but its role in autonomous surgery is less explored (69). The robotic surgery we are familiar with today relies on the surgeon being in complete control of the movements. While AI may play a role in a hands-off approach in the future, it has already been introduced to assist in the shortcomings associated with remote surgery and communication latency issues. One example is a predictive algorithm which displays the projected motion of the surgical tool to adjust for increasing communication lag-time (66,70).

An example of completely autonomous intervention supplied by a robot is the Heartlander. The Heartlander is a miniature mobile robot which adheres to the surface of the heart, travels to the desired location, and administers therapy. While still in development, applications include ablation for atrial fibrillation, lead placement for cardiac pacing, and delivery of myocardial pharmacotherapies (71,72).

Conclusions

Long-term human space travel faces many challenges but creates great opportunity for innovation. The translation of large AI datasets developed for and from patterns seen on earth should not be blindly applied to the everchanging gravity and microenvironment found at different aspects of spaceflight. New datasets built from multiple flights over many years will be required for medical AI to be functional outside of LEO (34).

Current terrestrial datasets while of high significance and great necessity, are fragmented, small-scale, and manually analyzed, limiting our knowledge on how best to prepare for long-term space flight. Currently, medical practice and its respective datasets (and therefore the organization of this review) are under a systems-oriented approach. The clinical community is divided into experts such as cardiologists, pulmonologists, and neurologists, but physiologically these systems are interconnected. In order to properly use AI technology, it will be crucial to create a panomic dataset that integrates existing "omics". It will be important to strategically plan how to acquire data so that AI can best power end-product analytics that can keep human-life safe beyond LEO.

The future of AI in space medicine is not quite as grim as its seemingly insurmountable obstacles. The technology transfer from space medicine exemplifies the importance of investment in AI for the benefit of society. Neural networks initially created for detecting meteors and missiles in space have been translated to detect changes in imaging features indicative of a higher risk of breast cancer (62). Information on bone demineralization from space missions sheds light on bone disease found with advancing age (62). Lessons learned from telemedicine and telesurgery performed in extreme environments can be applied to instances where wartime or remote areas limit access to immediate standard care (62). Exploration allows society to discover new capabilities, but also introduces new illnesses. Within and beyond our own orbit, AI can greatly support this new discovery in all aspects of healthcare including prediction, diagnosis, treatment, and prevention.

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