ON FRONTIER'S EDGE

SPACE MEDICINE

– Written by James D Polk, NASA

Spaceflight presents a unique and challenging environment for the human body. The absence of gravity, exposure to space radiation, fluid shifts, adaptive changes in muscle and bone, and the confined living conditions aboard spacecraft all contribute to significant physiological changes and potential psychological challenges. Understanding these changes and developing effective countermeasures is crucial for ensuring the health and performance of astronauts on long-duration missions.

The changes in the human body in spaceflight are also a function of time. An astronaut who is in microgravity for mere minutes on a suborbital flight is not going to experience the same changes as one exposed to microgravity for six months. This means that planning and implementation of medical systems and hardware must take these differing missions into consideration. For example, exercise equipment would not be necessary for a suborbital flight, but it would be crucial for a long-duration mission[2].

DESIGN REFERENCE MISSION

Medical hardware and the ability to treat sickness, injury, or maladaptation typically increases in size and scope based on what is known as the Design Reference Mission. A Design Reference Mission is essentially the base strategic plan that outlines where the astronauts are going (suborbital, orbital, deep space, planetary), how they will get there (capsule, plane-like vehicle, landers, rovers, space stations), and how long they will be exposed to spaceflight conditions (minutes, days, weeks, months, years)[1]. To design a medical and exercise system, as well as plan for contingencies on launch, landing, or during the mission, one must first start with the Design Reference Mission.

NASA typically defines missions shorter than 30 days as Short-Duration Missions, and longer than 30 days as Long-Duration Missions. Although that 30-day mark seems rather arbitrary, there are physiologic changes that take on more importance and more risk the further you go beyond the 30 days[8]. Therefore, it makes a convenient dividing line when trying to plan missions but also assess risks. NASA has medical requirements for short duration missions and more robust medical requirements for longer duration missions. But duration is only half of the story. The International Space Station (ISS) has six-month duration missions, and it likewise will take six months to get to Mars when the two planets are in closest proximity. But the added distance in deep space means that communication to a spacecraft orbiting Mars will take 20 minutes one-way, and the radiation exposures are vastly different[6]. Although a typical ISS increment and the transit to Mars both have six months in microgravity in common, that is where the similarities end. This is why the Design Reference Mission is so important. It outlines not only the function of time, but the distance, destination, vehicles, exposures, objectives, and strategies for a given space mission[1,2].

STANDARDS AND REQUIREMENTS

NASA has both standards and requirements. A standard is typically a hard end-point, and almost biblical. For example: *Plans and vehicle(s) shall be available to transport severely ill or injured crewmember(s) to appropriate Medical Care Facilities, including Definitive Medical Care Facilities (DMCF) in the event of a contingency scenario.* A standard is not optional. It's a must and is usually delineated by the word *"shall"*[3,4].

A requirement is typically designs and hardware required to meet a standard. However, unlike a standard, a requirement can be tailored. It is not biblical, but rather has a lot of room for improvisation and innovation. Let's take another example: There is a standard for what VO2 max is required for the crewmember to maintain in order to ensure optimal health during a mission (32.9 ml/min/kg). The requirement

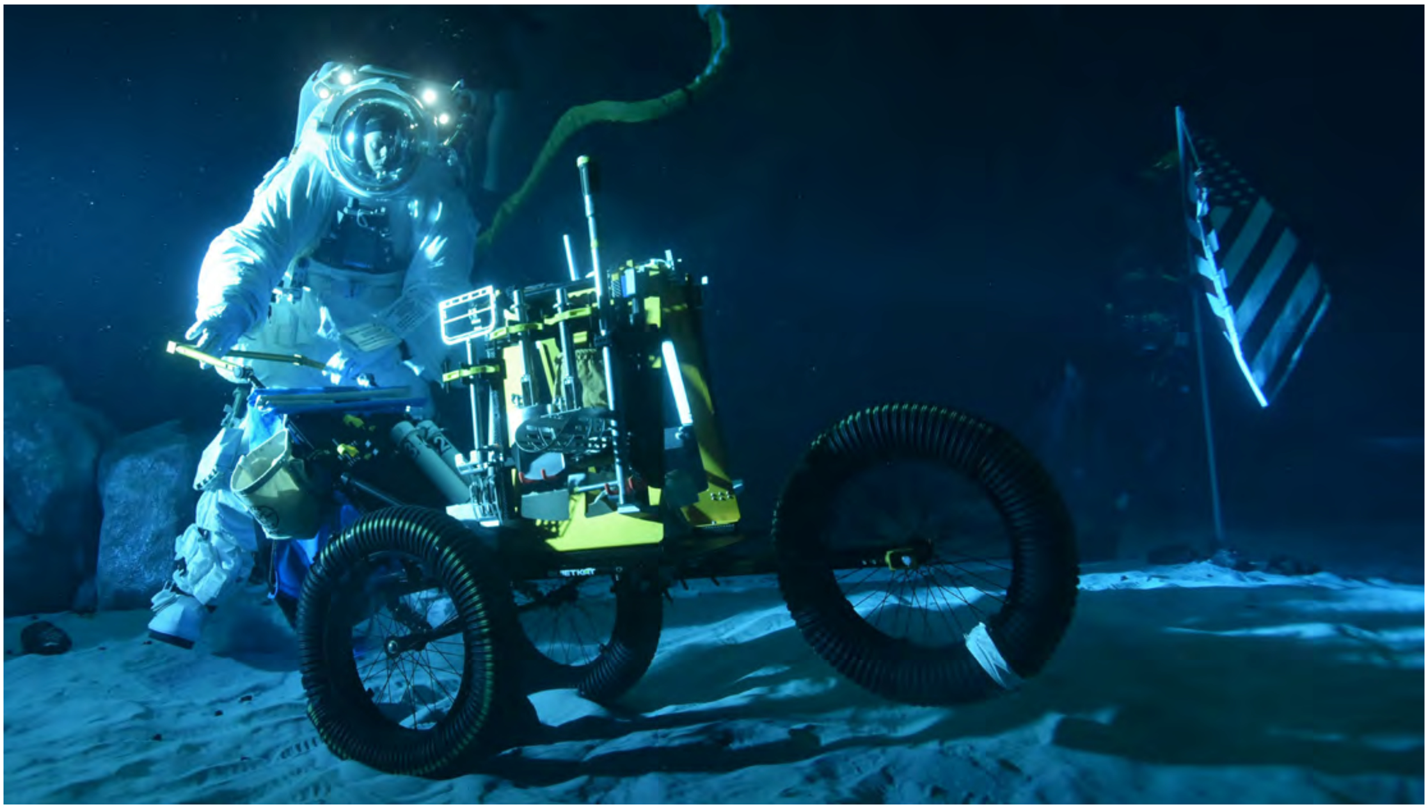

Image 1: Astronaut practices in simulated lunar environment in the Neutral Buoyancy Lab at Johnson Space Center. Photo courtesy NASA.

therefore would be for exercise equipment to help achieve the VO_2 max standard[8]. It's not prescriptive on the design. That requirement might be met with a treadmill, or an ergometer, or a flywheel/rower depending on the volume and design of the vehicle. Therefore, how they meet that standard and what type of exercise and exercise equipment a company/ program/provider deploys can be tailored to the vehicle and can have many options or different designs. The goal is to meet the standard, whereas the requirement is the means to get there[5].

You can actually find our astronaut selection standards, medical and physiologic standards, and vehicle standards here: https://www.nasa.gov/directorates/esdmd/hhp/human-spaceflight-and-aviation-standards/.

FAULT TOLERANCE AND RELIABILITY

Space is a rather harsh and unforgiving environment. In order to ensure that systems perform as designed to keep astronauts safe, the spacecraft have design standards that require either Fault Tolerance or High Reliability. Fault Tolerance simply means that if a system or function goes down, that there is a back-up[3]. This is particularly important for critical systems that have high risk or high consequences if they fail. For example, if a guidance computer onboard the spacecraft stops functioning, there is a back-up computer. If there are no back-ups, we call that Zero Fault Tolerant. If there is one back-up, that is known as One Fault Tolerant. Two back-ups are known as Two Fault Tolerant. For critical operations that have high risk, fault tolerance is a must. Let's take docking as an example. If the guidance computer fails for automated docking, the ground control may be able to command the vehicle for docking. If that fails, the crew may be able to pilot the vehicle manually. Therefore, that system is Two Fault Tolerant[3].

Reliability comes into play when it is impractical to install or place redundant systems due to mass, volume, or other constraints[3]. When relying on a sole system or piece of hardware with no functional back-up, that system has to be tested in such a way that there is almost guaranteed assurance that it will work as designed when needed. A good example here is the Apollo Lunar Ascent Vehicle engine. The Apollo Lunar Module was actually a two-stage vehicle. Once the lunar mission was completed, the astronauts boarded the module and prepared to blast off in the ascent vehicle, leaving the base of the lander behind. Because of mass and volume constraints, there was only one engine on the Apollo Lunar Ascent Vehicle. It would blast off from the lander carriage on the lunar surface and rendezvous with the capsule that was orbiting the moon. If that engine did not light, the astronauts would be permanent fixtures on the moon. Therefore, that engine was tested to excruciating lengths to ensure that it was highly reliable, since fault tolerance by way of redundancy was not an option[2,7].

SIX TENETS

When trying to assemble the right medical and exercise hardware for a mission each piece of equipment must be weighed against these six tenets[9,10].

Mass

Although items have no weight once in microgravity, they have mass on launch. It takes a great deal of thrust for a rocket to overcome gravity and achieve orbit. In general, the propellant mass fraction is typically around 0.75, meaning that propellant will account for 75% of the mass of a rocket[2]. The heavier the payload, the more propellant needed and more thrust to escape Earth's gravity and achieve orbital velocity. This means weight and mass of the payload are at a premium and whenever possible, we try to shrink the mass of equipment without giving up function[10].

Power

Power on a spacecraft is provided either by batteries, fuel cells, or solar electric panels. The kilowatts per hour provided by these systems are rather finite and can have variability based on sun exposure or equipment load. Medical hardware therefore needs to be able to run on the allocation of electrical current given and not place a high demand or drain on the rest of the spacecraft. The radio, life support, and navigation and control computers should not be compromised by the load or draw of power from medical or exercise equipment[10].

Volume

If the exercise or medical equipment takes up half the module, then there is less volume on board to do work, move or translate through the spacecraft safely, and less room for other hardware. Therefore, the volume or space that the medical equipment or exercise hardware occupies needs to be taken into consideration[10].

Time

The astronaut's time is well planned while they are in orbit. Medical procedures, hardware, and exercise must be accomplished in a finite amount of time. There are many mission objectives, research, and spacecraft operations to perform. Having any one activity be a time sink and eat up valuable satellite time or time on the schedule is not advantageous[10].

Money

The cost of flying a piece of hardware is not just the cost associated with the purchase. Medical hardware flown in space has to be subjected to vacuum, to radiation, hardened against electrical surges, have its batteries replaced with batteries that are safer for an enclosed environment and prevent thermal runaway, noise and vibration testing, off-gas testing, and structures/durability testing. That means a defibrillator that costs $10,000 off the shelf will actually cost several hundred thousand dollars by the time it is flown[10].

Risk

Whatever we fly must have an evidence-based reason for being there. It has to mitigate or lower or address a risk that is known or could occur as part of the Design Reference Mission. We simply can't take everything with us that we would like, so it is paramount that what we do take adequately addresses or mitigates high risk items or multiple moderate or low risks. For example, a portable ultrasound can be used for a host of different evaluations and diagnostics[6]. A broad-spectrum antibiotic can be used to treat a myriad of infections. Both of those examples do not address a

Image 2: Japanese crewmember onboard the ISS using the ARED exercise device. Photo courtesy NASA.

Image 3: NASA flight surgeon, Dr. Joe Schmid, being holoported with the Microsoft Hololens to perform telemedicine onboard the ISS- Photo courtesy NASA.

single risk, they buy down risk for many different ailments or injuries.

HUMAN SYSTEMS INTEGRATION

Human Systems Integration (HSI) is a critical aspect of space missions, focusing on the interaction between astronauts and their spacecraft to ensure safety, efficiency, and overall mission success. There are many key elements involved under the umbrella of HSI including human factors, occupant protection, environmental control system optimization, design elements for safety, optimizing functions and workflow, and decreasing human error[14].

Human-Centered Design

This involves designing spacecraft and equipment around the astronaut, with the astronaut's needs and limitations in mind. This includes everything from the layout of the spacecraft to the design of spacesuits and tools used during missions. But it must also consider physiologic changes that occur in microgravity. For example, vision changes in long-duration spaceflight may necessitate the ability to change the size of fonts, ensure dials are not too close together, and ensure caution and warning signals are clearly marked[11,14].

Health and Safety

HSI ensures that all systems support the health and safety of astronauts. This includes managing exposure to space radiation, designing out sharp edges or head strike areas in the cockpit, maintaining physical and mental health, occupant protection (to include landing loads, the number of G's and the direction of the force of gravity), and ensuring that life support systems are reliable and bringing gases (such as CO_2) into manageable levels[14].

Performance Optimization

By integrating human factors into the design process, HSI aims to maximize the performance of both astronauts and the systems they use. This includes ergonomic design, intuitive interfaces, checklists to ensure Crew Resource Management, and minimizing the cognitive load or the potential for task oversaturation on astronauts[11,14,15].

Training and Procedures

HSI also involves developing training programs and operational procedures that are aligned with human capabilities and limitations and design out the possibility to error. This ensures that astronauts are well-prepared for the tasks they need to perform, the instructions for execution of those tasks are clear and concise, and that they can operate systems effectively under various conditions[14,17].

Environmental Control

Maintaining a habitable environment within the spacecraft is crucial. This includes controlling temperature, humidity, and air quality (oxygen, CO_2, and scrubbing of particulates), as well as providing adequate lighting (which can change to mimic diurnal variations to mimic biorhythms and allow for good sleep hygiene) and noise control[15].

Adaptability and Flexibility

Space missions often encounter unexpected challenges. HSI ensures that systems are designed to be adaptable and offer enough flexibility to meet those challenges while meeting mission objectives. It also ensures that astronauts (and ground control teams) are trained to handle unforeseen situations effectively[14,16].

By focusing on these aspects, HSI helps to create a safer and more efficient environment for astronauts, ultimately contributing to the success of space missions. You can find our Human Integration Design Handbook here: https://www.nasa.gov/human-integration-design-handbook/[17].

MEDICAL FORECASTING AND EQUIPMENT

NASA uses Monte Carlo analysis, Integrated Medical Models, Modified Delphi of Expert Opinion, previous spaceflight missions, undersea missions, and analog missions to help inform the possible medical diagnoses that can occur in austere environments[18,20]. This has allowed NASA to forecast what ailments to be prepared for and fly the most appropriate equipment, medication, and procedures to deal with those common diagnoses. The result has been one of the most stunning statistics in space medicine to date: in over 65 years of human spaceflight, NASA has never had to return an astronaut from space for a medical reason. They have been able to safely treat many medical ailments successfully, despite nearly every statistical model stating they would have to return at least once every three to five years for a medical reason[20].

In addition to thoroughly screening potential candidates for selection, NASA has a rigorous preventive medicine program. The agency utilizes Clinical Practice Guidelines aimed specifically at aerospace medicine diagnoses, as well as routine follow up and care of the astronauts[11,19].

NASA also performs exams on the astronauts throughout their entire lifetime, well after they have left active service to the agency, as part of occupational surveillance. This program, called the Lifetime Surveillance of Astronaut Health, has multiple exams that are performed

Image 4: Astronaut practicing in simulated lunar gravity in the Neutral Buoyancy Lab at Johnson Space Center- Photo courtesy NASA.

annually, looking for potential latent effects of exposures to radiation, microgravity, or chemicals. The TREAT Act also allows NASA the legislative authority to treat or render care or services to a NASA astronaut (current or former) for any malady, illness, or injury thought to be associated with human spaceflight[11].

HUMAN RESEARCH PROGRAM

NASA's Human Research Program (HRP) is the research arm of the medical team, aimed at understanding the changes to the human body associated with spaceflight and mitigating the untoward effects of spaceflight on human health and performance[12]. HRP also works to enable missions by researching new pre-breath protocols, new exercise hardware or regimens, and new therapies or hardware to prevent or treat disease. The ultimate goal is to ensure astronauts can safely and effectively perform their missions, especially as NASA aims for longer-duration missions to the Moon and Mars. Their research portfolio is broad and may include open research that takes advantage of the microgravity environment (e.g.- such as pharmaceutical research aimed at medicines for patients on Earth) or directed research that is more tactical (e.g.- refining specific NASA standards or testing of treatments for astronauts). You can find the Human Research Program risks here: https://www.nasa.gov/hrp/ [12].

PHYSIOLOGIC CHANGES DURING LONG-DURATION SPACEFLIGHT

NASA places the physiologic changes from Spaceflight into five main categories in order to identify the main risks and group them for research and countermeasure purposes: Space Radiation, Isolation and Confinement, Distance from Earth, Altered Gravity Fields, and Hostile/Closed Environments[13]. This is by no means an all-encompassing list, but below are several of the physiologic changes and adaptations that must be considered in long-duration missions:

1. **Altered Gravity Fields:**
    - **Bone Density Loss:** In microgravity, bones are not subjected to the same mechanical loads as on Earth, leading to a decrease in bone density. Wolff's Law states that bones will adapt to the amount and degree of mechanical loading. Because microgravity unloads the forces on the bone that astronauts can lose up to 1% of their bone mass per month[9,11,23,24].
    - **Muscle Atrophy:** Muscles, particularly those in the lower body and spine, weaken and shrink, but also change morphology (gravitational unloading leads to the transformation of some slow-twitch muscle fibers in the lower extremity to become fast-twitch fibers) due to reduced use in a weightless environment and blood volume moving cephalad[9,11].
    - **Fluid Redistribution:** Fluids in the body shift towards the head, causing facial puffiness and nasal congestion. This can also lead to increased fluid in the upper thorax and cranial vault, which may increase intracranial pressure and edema of choroid, causing either papilledema or choroidal folds, both

Image 5: Artemis 1 SLS rocket on the pad at Kennedy Space Center. Photo courtesy NASA.

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of which may adversely impact the astronaut's vision[9,11,28].

- **Cardiac Deconditioning:** The heart muscle can weaken, and cardiac function can decrease or be less proficient. There is also a reduction in blood volume and preload, which can lead to less tolerance of G forces in the Gz direction on re-entry and orthostatic intolerance (difficulty standing upright) upon return to Earth[9,11,23].
- **Thrombosis:** Venous stasis changes from the lower extremities to the upper torso, especially in the left internal jugular in some astronauts. Harnesses to hold an astronaut onto the treadmill compress areas about the upper torso and shoulders, and there may be other risk factors (estrogens or genetic predisposition) that have caused left internal jugular thrombosis in several long-duration astronauts[9,27].
- **Proprioception Loss:** The sense of body position and movement is altered, fluids in the middle ear and otoliths may be floating, and the eyes are not even with a fixed horizon (the astronauts may literally be running on a treadmill that is on the side of the wall or doing squats/deadlifts on hardware that is on the ceiling) affecting balance and coordination[9].
- **Visual Impairments:** Changes in intracranial pressure can lead to vision problems, due to either papilledema or edema of the choroid, a condition known as Spaceflight-Associated Neuro-ocular Syndrome (SANS)[23,28].

2. **Space Radiation Exposure:**
   - **Increased Cancer Risk:** Space radiation, particularly beyond the Earth's magnetosphere, increases the risk of cancer and other radiation-induced diseases[7,21,22,23].
   - **DNA Damage:** Radiation, especially from Galactic Cosmic Radiation, can cause genetic mutations and damage to cellular structures. These are High Energy Transfer (HET) particles that can mutations after striking and deforming DNA strands[7,11].
3. **Isolation and Confinement:**
   - Psychological Effects: The psychological stress of isolation and confinement can lead to mood swings, depression, and anxiety. Separation from family and friends can make an astronaut feel isolated from their typical support system[7,9,11].
4. **Distance from Earth:**
   - The further astronauts get from Earth, the more independent and self-sufficient they will need to be. Increased autonomy, decreased ability to resupply, and independent systems and control will require new training methods, new skillsets, and ability to solve problems in-situ[7,9,11].
5. **Hostile/Closed Environments:**
   - Toxic substances like ammonia coolant, rocket fuels like hydrazine, and other hazards are ever-present threats that can occur on space missions. But even the management of CO_2 poses a significant challenge on-board a spacecraft and are typically many times that of Earth. Fire and smoke are threats to any enclosed environment or habitat as well. Enclosed environments with limited resupply require that recycling and regeneration be used. Recycling of water, gases, and composting of materials will be needed for habitats[9].

COUNTERMEASURES FOR SPACEFLIGHT-INDUCED PHYSIOLOGICAL CHANGES

1. **Exercise Regimens:**
   - **Resistance and Aerobic Exercise:** Astronauts engage in daily exercise routines that impart loads to the bone using specialized equipment like the Advanced Resistive Exercise Device (ARED). This exercise is typically performed for an hour per day on long-duration missions to maintain muscle and bone health[12,25].
   - **Treadmills and Stationary Bikes:** Aerobic and cardiac conditioning are through either the treadmill or stationary bike, and are also performed for an hour per day to provide both lower extremity strength and cardiovascular workouts[7,12,25,26].
2. **Nutritional Support:**
   - **Balanced Diet:** A balanced diet with plenty of protein, good fat, and carbohydrate is flown not only for nutritional health, but also psychological health. Items rich in calcium and vitamin D help to mitigate bone loss. Adequate protein intake helps to support muscle maintenance[12].
   - **Supplements:** Vitamin and mineral supplements are provided to address specific needs for space physiologic changes and potential deficiencies[12].

3. Pharmacological Interventions:
   - **Bisphosphonates:** These drugs help reduce bone density loss by inhibiting bone resorption[12].
   - **Medications for Radiation Protection:** Antioxidants and other compounds are being researched to protect against potential immune deficiencies and/or radiation damage[29,30].
4. Psychological Support:
   - **Counseling and Communication:** Regular communication with family and mental health professionals helps to maintain connectivity to home and manage stress and is a part of maintaining psychological well-being[12].
   - **Recreational Activities:** Engaging in hobbies and leisure activities, music, and exercise can alleviate the monotony of space missions. Most astronauts state that exercise has been particularly important for psychological well-being as well as physical[12].
5. Time, Distance, and Shielding:
   - **Time:** Minimizing the total transit time by using propulsion that shortens the time between planets acts to reduce the astronaut's exposure to Galactic Cosmic Radiation. Ironically, departing during Solar Maximum (when the Sun is at its most energetic) is actually preferable. Solar radiation particles are Low Energy Transfer (LET) particles and much more plentiful such that they interfere with Galactic Cosmic Radiation. Low Energy Transfer particles are also more easily shielded. This means that although the Sun is more active, the threat from Galactic Cosmic Radiation is less during the solar maximum cycle[29,30,31].
   - **Distance:** The further the distance from the Sun, the more time astronauts have to prepare for potential radiation activity from energetic solar activity. Early warning satellites allow for notification of potential hazards and allow the astronauts the ability to seek shelter[29,30,31].
   - **Shielding:** Shielding can take the form of gray water, fuels, and any substance that has a prolific amount of hydrogen, including plastics. But in order to conserve mass and volume, each of these should serve a dual purpose and not be exclusively for radiation protection. On the planetary surface, regolith and soils can be used in habitats to provide some amount of protection[29,30,31].
6. Technological Solutions:
   NASA often partners with expeditionary medics or those looking to have light and lean medical architectures and follows the progress of technologies that may enable or reduce risks to spaceflight missions. We will watch the literature or tech demonstrations to identify what level of evidence, what phase of human research or clinical trial, or what Technology Readiness Level therapies or technologies are currently[22,32].
   - **Technology Readiness Levels:** NASA's Technology Readiness Levels (TRLs) are a systematic way to measure the maturity of a particular technology that may be used for future space missions. When NASA evaluates technologies, we are evaluating how mature they are currently, and what gaps exist between where the technology is now, and how mature that technology is, and whether it will be ready for flight. This allows for directed research to help mature the systems[32]. There are nine levels, ranging from basic research to fully operational systems (See Table 1).

Just a few examples of some of the representative technologies that have rapidly moved along the Technology Readiness Levels which may enable future exploration missions are the following:

- **3D printing:** The use of 3D printing has allowed the printing of everything from engine parts, habitats, medical instruments, medications, and even human tissue. The RedWire BioFabrication Facility on the International Space Station recently 3D printed a human knee meniscus and beating cardiac cells earlier this year, using human stem cells as the feedstock for the print material. The Mars Crew

Table 1

TRL 1: Basic principles observed and reported. This is the starting point where scientific research begins to be translated into applied research and development
TRL 2: Technology concept and/or application formulated. At this stage, practical applications are identified, but there is no experimental proof of concept yet.
TRL 3: Analytical and experimental critical function and/or characteristic proof-of-concept. Active research and development are initiated, including analytical studies and laboratory-scale studies to validate predictions.
TRL 4: Component and/or breadboard validation in a laboratory environment. Basic technological components are integrated to establish that they will work together.
TRL 5: Component and/or breadboard validation in a relevant environment. The technology is tested in a simulated environment that is as close to the real operational environment as possible.
TRL 6: System/subsystem model or prototype demonstration in a relevant environment. A model or prototype that represents the final system is tested in a relevant environment.
TRL 7: System prototype demonstration in a space environment. The prototype is tested in the actual operational environment, such as space.
TRL 8: Actual system completed and "flight qualified" through test and demonstration. The technology has been tested and qualified for flight.
TRL 9: Actual system "flight proven" through successful mission operations. The technology has been proven to work in its final form and under mission conditions.

Table 1: Example of the screening and monitoring roles of an interdisciplinary team.

Image 6: Photo of U.S. Air Force Pararescue Jumpers from Detachment 3 practicing crew rescue and retrieval from the NASA Orion Capsule. Photo courtesy NASA.

Image 7: NASA flight surgeon Dr. James Pattarini performs a routine "tentside" assessment with a portable ultrasound on astronaut Serena Aunon-Chancellor immediately after landing in the Russian Soyuz. Phot courtesy NASA.

Health and Performance Exploration Analog (CHAPEA) habitat was 3D printed out of simulated Mars soil. These technologies, which have rapidly risen on the TRL level, will be important the further away from Earth[33,34,35].

- **Artificial Intelligence:** NASA's Project A.I.D.E.N. (Artificial Intelligence Diagnostic Enhancement Network) is envisioned as a cutting-edge Artificial Intelligence that will integrate various medical databases and software tools to support medical operations in space missions. This project aims to develop an AI system capable of mining data, forecasting medical issues, aiding diagnosis, supporting clinical decision-making, and responding to research queries. AIDEN will be a voice-responsive system that leverages over 65 years of spaceflight medical data, Earth-based medical knowledge, and the nuances of spaceflight physiology to provide comprehensive medical support to astronauts on the Moon and Mars[36,37,38,39].
- **Advanced Medical Diagnostics and Therapeutics:** For NASA's exploration missions, advanced diagnostics and therapeutics will be crucial to ensure astronaut health and performance during long-duration spaceflights and planetary surface missions. These missions will require compact, multifunctional medical devices capable of performing a wide range of diagnostic tests, such as blood analysis, imaging, and monitoring vital signs, all in either microgravity or partial gravity conditions. Additionally, non-invasive therapeutic tools and automated clinical laboratory devices will be essential to manage medical conditions autonomously, given the significant communication delays and the impossibility of immediate medical evacuation from distant locations like Mars[38,39].
- **Telemedicine:** Telemedicine enables real-time medical consultations, diagnostics, and treatment guidance from Earth, ensuring that astronauts receive the necessary care without the need for immediate physical presence of the flight surgeon. However, for missions like Mars, that may have upwards of a 20 minute on way delay in communications, Artificial Intelligence

may be used to augment the medical knowledge of the crew. Although a physician has not been mandatory on the International Space Station in part due to immediate telemedicine with the ground, this may change for planetary missions. Additionally, NASA has used new telemedicine tools, such as the Microsoft HoloLens, for holoportation. This technology allows 3D models of people to be transmitted live, enabling more immersive and interactive communication between astronauts and Earth-based teams[37,38,39].

- **Radiation Shielding:** Advanced materials and spacecraft designs, as well as active forms of shielding, may reduce future radiation exposure. NASA has evaluated active radiation shielding, in which powered systems giving different polarities could act to deflect radiation particles away from the spacecraft. However, this latter technology still requires a great deal of research, and it also currently requires a great deal of mass and power[9,30].
- **Artificial Gravity:** Research is ongoing into the use of rotating habitats to create artificial gravity and mitigate the effects of microgravity. However, to give a 1G load at the level of an upright astronaut's right atrium, with an angular velocity of 2 revolutions per minute (any faster would cause a Coriolis effect and dizziness) it would require a radius arm of the centrifuge to be 223 meters (you can calculate this on the SpinCalc at https://www.artificial-gravity.com/sw/SpinCalc/). That means you are essentially rotating the large spacecraft (the movies Interstellar and The Martian did a nice job of showing this) to obtain that G-load, which itself requires a fair amount of mass and power and will require control moment gyroscopes to maintain course. We can get to Mars without artificial gravity currently and provide sufficient countermeasures. But exploration beyond Mars with progressively longer deep space microgravity exposures will most likely require artificial gravity as a countermeasure[11].

Image 8: Mike Barratt in the ISS. Photo courtesy NASA.

CONTINGENCIES

Contingencies can occur during crucial phases of spaceflight operations. Pad aborts occur when a launch vehicle has an anomaly on the pad, but the rocket may already be fueled, necessitating that the crew escape the launch pad in a timely manner. This may involve a slide wire or basket to rapidly separate the crew from the launch tower. After the crew access arm is rotated away from the rocket, the abort now involves the Launch Escape System. This is where rockets and or thrusters on the capsule rapidly separate and lift the capsule away from the rocket and down range[41,42].

Aborts on ascent are another example of an active system where rockets or thrusters are used to rapidly take the capsule away from the launch booster. Landing contingencies may involve an anomaly with the parachute system, rolling of the capsule on landing, or unexpected forces on landing. In flight contingencies include fire, depress, micro-meteoroid impacts, and unforeseen circumstances that require the crew to abandon the vehicle in orbit in favor of the return spacecraft[40,41,42].

Figure 9: Dr. J.D. Polk, NASA CMO, visits the 3D printing lab at the University College London to view the 3D printing of medications. Photo Courtesy of UCL.

Rescue forces responding to a NASA spaceflight contingency must undergo extensive and specialized training to ensure they can effectively handle various emergency scenarios.

Here are some key areas of training:

1. **Spacecraft Familiarization:** Rescue teams must be familiar with the specific spacecraft they might encounter, such as SpaceX Crew Dragon, Boeing Starliner, or Lockheed Martin Orion capsules. This includes understanding the layout, entry points, and potential hazards to include pressurized systems, radiation sources, toxic vapors, and pyrotechnic devices[42,43].
2. **Medical Training:** Teams need advanced medical training to provide immediate care to astronauts and an understanding of spaceflight specific physiologic or medical changes and/or impacts including triage, stabilization, and evacuation of injured crew members, hypobaric injury (the bends), injuries from failed parachutes, dynamic roll of the spacecraft (flail) and a host of other potential illnesses or injuries[41,42].
3. **Survival and Egress Procedures:** Training includes procedures for safely extracting astronauts from the spacecraft, especially in challenging environments like open water or remote land areas, rough sea conditions, night-time operations, and difficult terrain[41,42,43].
4. **Environmental Adaptation:** Rescue forces must be prepared to operate in various environments, including ocean, desert, and mountainous regions and must be prepared to be self-sustaining until additional forces arrive. This involves training in different rescue techniques, survival techniques, and the use of specialized equipment[42,43].
5. **Location, Coordination and Communication:** Locating the spacecraft is paramount to getting rescue forces there as soon as possible. GPS and satellite tracking systems are used to monitor the location of a spacecraft. Radio equipment and emergency beacons help located the spacecraft in a contingency[42,43,44]. Effective communication and coordination with NASA, military units, hospitals, and other agencies is crucial. This includes understanding protocols for different types of emergencies and ensuring seamless collaboration and is one of the main reasons NASA and its partners perform multiple simulations for launch and landing contingencies[42,43].
6. **Simulated Exercises:** Regular drills and simulated exercises are conducted to practice and refine rescue operations and give the teams insight into the nuances of spacecraft/astronaut rescue. These exercises help identify potential issues and improve response times as well as teach responding teams about the nuances of space physiology and safe operation around potentially hazardous spacecraft[42].
7. **Alert Posturing:** Rescue forces must be on alert and ready to respond at a moment's notice during space launches and landings. This involves maintaining a state of readiness, communications, and training and having all necessary resources and personnel in place[42].

These comprehensive training programs ensure that rescue forces are well-prepared to handle any contingencies that may arise during NASA spaceflight missions.

ETHICAL CONSTRUCTS

1. **The Life, Limb, Mission Paradigm Shift:** Currently, if an astronaut on the International Space Station has a medical issue, a corneal abrasion for example, the astronaut has medications and therapies to treat that diagnosis successfully. But if the cornea did not heal, became horrible infected, and was at risk of scarring – we would bring that astronaut home and have them in a definitive medical care facility getting the appropriate therapy. In essence, the astronaut's life and limb comes before the mission. However, when we go to Mars, the two planets (Earth and Mars) do not line up again for close to 18 months. This means if an astronaut has an injury that requires more definitive care, they will not be able to obtain it – as medical evacuation will not be plausible. In this instance, the mission now supersedes the astronaut's life and limb. This is a reversal of the Life, Limb, Mission Paradigm. Essentially, the further the mission is from Earth, the more the mission takes on importance and individual needs are subservient to that mission[10].
2. **Genetics and Precision Medicine:** NASA is currently bound by the Genetics Information Non-Discrimination Act (GINA) and cannot make hiring or assignment decisions based on genetic information. Instead of looking at genetic pre-disposition, NASA instead has moved toward precision medicine as

Spaceflight poses numerous challenges to human physiology, but through rigorous research and the development of effective countermeasures, we can ensure the health and safety of astronauts as they venture into the cosmos.

a means to tailor therapies to individual astronaut needs as opposed to using only population health. For example, population health uses normative means as targets to assess health; such as a target for a Total Cholesterol less than 200mg/dl, or an LDL less than 130mg/dl. But NASA goes further, looking at LPa subtypes of cholesterol and even has its own cardiovascular disease risk calculator, AstroCharm to assess the specific risks of astronauts. One astronaut may lay down soft plaque at an LDL of 130mg/dl whereas another astronaut with LPa subvariant cholesterol may lay down soft plaque at an LDL of 100mg/dl. This allows NASA to tailor mitigations or treatments to the specific astronaut and their specific physiology as opposed to the mean of a population[7].

NASA also has a bioethics advisory panel that convenes often to wrestle with ethical issues, policies, and constructs. The panel is made up of ethics experts from across the United States with specific expertise in a myriad of subjects. This has allowed NASA to forecast what policies or legislation need to be put into place, what strategies need to be used, what gaps exist, and allows teams to understand and plan for aspects of a mission that may have critical questions, including ethical ones.

SUMMARY

Spaceflight poses numerous challenges to human physiology, but through rigorous research and the development of effective countermeasures, we can ensure the health and safety of astronauts as they venture further into the cosmos. Many crucial aspects and nuances of spaceflight must be taken into consideration when designing medical systems. It requires knowledge of the spacecraft, the mission, the physiology, and the constraints on therapies and mitigations. The lessons learned from these endeavors not only advance space exploration but also contribute to medical and technological innovations that benefit life on Earth.

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