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The way ahead: adaptive medical standards to optimize commercial space traveler health, safety and performance

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The promise of space travel opens a new era of opportunity for consideration of space medical standards, health screening, maintenance, and even environmental threat mitigation. There is a significant gap in scientific knowledge between previously well-established aeromedical standards for suborbital, orbital and beyond present a significant gap in scientific knowledge and mission-specific physiologic responses to extended duration activities. This paper will review the current and evolving standards and examine gaps and shortfalls which must be addressed to ensure space traveler safety and security. In addition, we will address the international, cultural and educational challenges of which potential space travelers and their healthcare providers must be aware, and will present an approach to systematically addressing these challenges.

KEYWORDS

aeromedical standards, space medical standards, health screening, environmental threat mitigation, mission profiles to mars

Forward—Introduction

This article will focus on the anticipated ambient and trans-journey environmental and physiologic challenges for commercial space travelers of a long duration spaceflight compared with prior high-atmospheric, suborbital, orbital, and lunar spaceflights to date.

Mission profiles to Mars will be characterized by more numerous and greater degrees of risk than suborbital, orbital, and lunar missions to date. In turn, this will drive risk assessment and risk mitigation to more a anticipatory type of management through early recognition and identification of individual susceptibilities.

In contrast to near-earth missions, five environments will be associated with a Mars mission:

- Active Space Environment (launch and atmospheric entry)—High Risk
- In-space Environment (in-transit travel)—Moderate risk
- Mars Orbital Environment (space station)—Lower risk
- Planetary Surface Environment (surface habitat)—Moderate risk
- Planetary Subsurface Environment (subsurface habitat in lava tube)—Lower risk

Active space environment

Until now, launch and landing have been the only documented space mission environments associated with fatalities for both the U.S. and U.S.S.R. NASA, 2015, (https://nssdc.gsfc.nasa.gov/planetary/mars/marsprof.html). See Figure 1.

Risk management and launch and landing safety have improved significantly in recent years. However, as with airline travel, where the most hazardous parts of a flight are takeoff and landing, this will also be the case with space travel.

In-space environment

There will be significant risks associated with long duration space travel, particularly for missions to Mars where several months of travel will be required, even with more efficient and effective propulsion systems in the future. Radiation, both external from solar and cosmic radiation, and internal if a nuclear propulsion system is used, is associated with genetic mutations and an increase in cancer risk. Higher short-term doses may impact the skin, brain (resulting in cognitive changes), gastrointestinal tract, hematological system, and other tissues. Alerts when radiation levels begin to increase in the event of a solar flare, appropriate spacecraft shielding, and dosimetry for individual astronauts will be essential. Microgravity is associated with osteoporosis, deconditioning, cardiovascular, and ocular effects. These effects may be mitigated by artificial gravity, which could be designed as a feature of the spacecraft, and/or by daily exercise as is practiced by astronauts in low Earth orbit. The impact of long duration spaceflight on both mental and physical health will require ongoing monitoring, with early recognition of and response to health threats such as depression, anxiety, interpersonal conflict, etc. as well as medical events, both minor and major. Overall stress levels are expected to be higher than normal, and adequate rest may be difficult for some astronauts because of stress as well as circadian desynchronization. It will be difficult to carry medical supplies for every contingency, and surgery in-transit will be difficult if not impossible.

Mars orbital environment

It is likely that a Mars orbital space station, based on the experience gathered with the Gateway orbital space station planned for the Moon, will have been assembled robotically prior to human trips to Mars. This will offer a more commodious environment than the spacecraft used in transit, and could include, for example, a surgical suite. Radiation and microgravity will be risks as they are for Earth orbiting space stations, though both can be mitigated to a greater degree in orbit than in transit. Risk to astronauts will likely be relatively low on orbital platforms since they will offer a more controlled environment than that of astronauts on the surface. Landing space vehicles on Mars has been associated with a high rate of failure, and the thinner Martian atmosphere will make landing of humans on the surface more hazardous than terrestrial aviation.

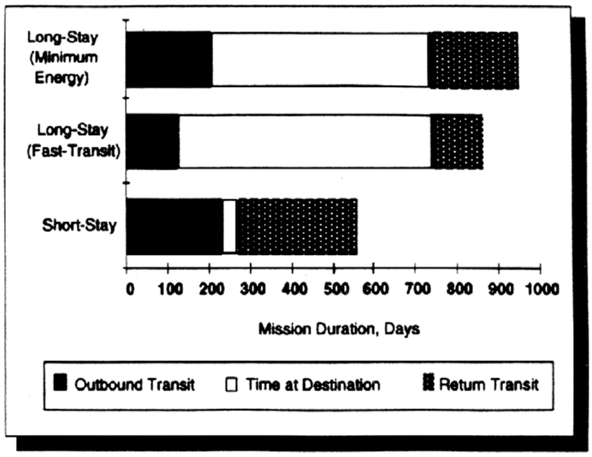

FIGURE 1
MARS mission profile comparison. Reproduced from A crewed mission to mars, by David R. Williams, https://nssdc.gsfc.nasa.gov/planetary/mars/marsprof.html, Nasa, United States public domain.

Planetary surfaceand subsurface environments

There are two environments on the surface of Mars. One is on the surface (as described in the popular author Andy Weir's book *The Martian*). Exposure to Martian weather, regolith, and dust all carry significant risks. The surface gravitational force on Mars is 38% of that on Earth, so this will be a low gravity environment with some risks like those in microgravity. On the other hand, Martian lava tubes potentially offer protection from surface radiation, weather, and inadvertent spacesuit decompression or an accident involving a rollover or collision of one of the Martian surface vehicles. Live Science, 2020, https://www.livescience.com/radiation-mars-safe-lava-tubes.html. It is likely that the interior surface of a lava tube is safer than the Martian surface since it would be less affected by weather and radiation, though that remains to be seen. In the future it may be possible to house many humans in underground environments on Mars, which will present ongoing health, behavioral, cultural and, in the longer term, evolutionary challenges.

These authors support a methodology that emphasizes education, mission-specific screening, and identification of environmental risks adaptive to the mission profile. Radiation exposure is the highest priority and is well-established in space flight. The radiation risk will be greater for long duration space travel. Research and development of effective countermeasures is rapidly progressing, but still requires mission-specific evaluation. A significant countermeasure is fast transit to Mars and beyond (Annette and Robert, 2020). There will also likely be a need for identification of individual susceptibilities through assessment of metabolomic markers requiring risk mitigation.

History—Current and evolving status

Exploration has been a human trait for millennia. Early seafarers in the Mediterranean, Europe, and Asia kept to their own waters,

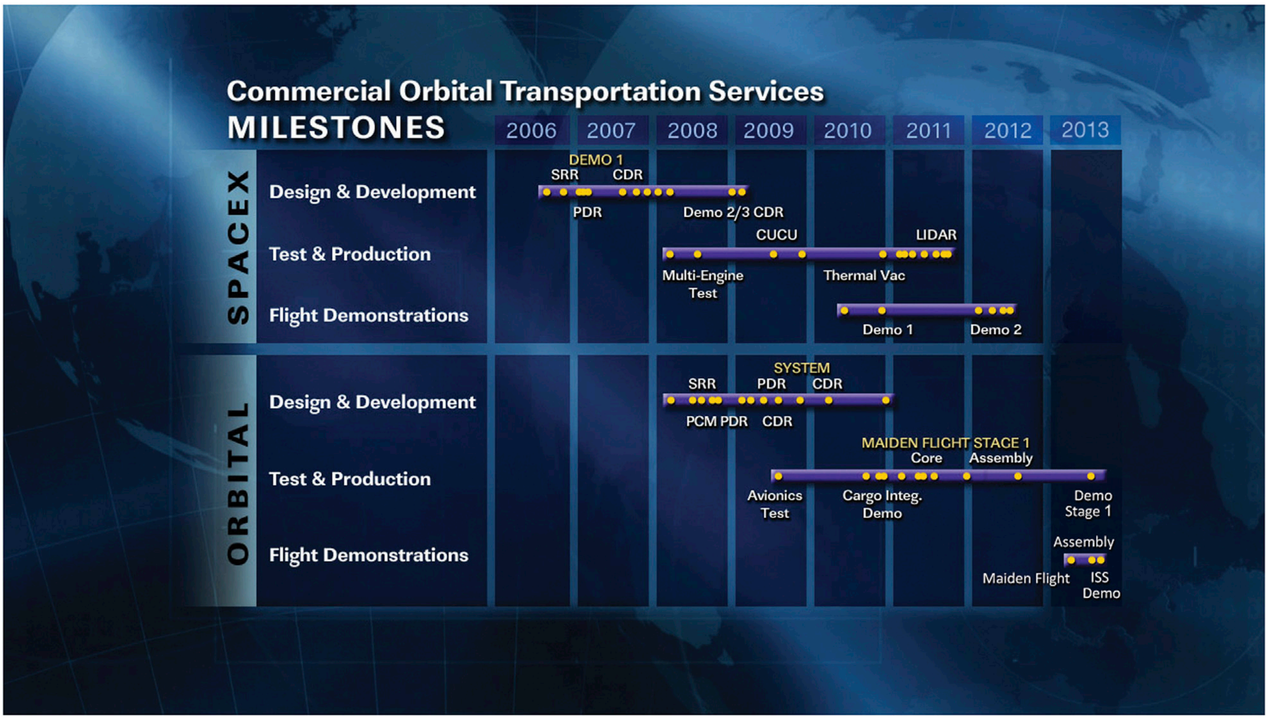

FIGURE 2
Comparison of different types of commercial space missions. Reproduced from Commercial Orbital Transportation Services: A New Era in Spaceflight, https://www.nasa.gov/sites/default/files/thumbnails/image/04_cots_milestones_2013.jpg, Nasa, United States public domain.

preferably within sight of land. Transoceanic exploration started in earnest in the 16th century, initially with most ships returning home after their voyages. Extensive settlement followed in the 17th century in North and South America. Throughout the Age of Exploration from the 15th through the 18th centuries, the main reasons for exploration failure were human physiologic maladaptation, illness, and injury. A similar progression has occurred for space exploration, from sub-orbital, to orbital, to lunar missions over the past 60 years, with plans for manned exploration and possible settlement of the Moon and Mars. The costs are higher, although the trajectory is like that of historic seafaring exploration. Selection and screening, prevention, and appropriate management of inflight medical conditions will be essential to prevent maladaptation, illness, and injury in the Space Age.

Each stage of exploration is associated with hazards and risks, which may be cumulative and incrementally greater over time. High altitude and sub-orbital flights are of relatively short duration, riskier than airline travel, although without exposure to many of the hazards associated with living for weeks or months on a space station orbiting the Earth. The risks are significantly greater for travel to the Moon or Mars, and not fully understood, as are the need for preventive and medical treatment measures. See Figure 2.

Hazards associated with terrestrial flight were recognized early on by aerospace engineers and other professionals, including aerospace medical pioneers during World War I, and medical screening of military pilots was found to be essential, leading to the medical certification of civilian pilots following the war. Governmental agencies were created to establish policy and regulate these examinations for civilians at the national level (e.g., FAA) and internationally (ICAO). Health and safety standards for passengers were developed later by airlines and aviation medical associations, with governments internationally also taking a role, for example, by standardizing the contents of the airline emergency medical kit.

NASA, the National Aeronautics and Space Administration, was created in 1958 as an independent US federal agency responsible for the civilian space exploration and research. NASA's manned space exploration programs included Project Mercury, Project Gemini, the Apollo Moon landing missions, Skylab, the Space Shuttle, and, with 14 other partner nations, execution of the International Space Station. Lunar exploration will include landing astronauts on the Moon's surface and development of a Lunar Gateway Space Station. A manned mission to Mars may follow as early as the 2030s.

NASA developed an astronaut selection process for the Mercury Project, resulting in the selection of America's original seven astronauts, all male and all prior military, and has continued to select astronaut classes periodically since then, with progressively more personal and professional diversity. NASA's astronaut selection procedures between 1981 and 2011 have been reviewed and causes for disqualification identified. The most common disqualifying conditions included visual, cardiovascular, psychiatric, and behavioral disorders. Russia has had an analogous cosmonaut selection process, and the European Space Agency (ESA) has developed a process to select EU astronauts to work on the International

Space Station and to develop and maintain the European space program. More recently, the Chinese Manned Space Agency has selected and trained astronauts for deployment to its Tiangong space station and an eventual manned mission to the Moon. These baseline procedural approaches identify methodologies for more complex and adaptive extended duration mission-specific individual susceptibility and fitness-for-duty assessments.

Current status of the commercial space flight industry, associated hazards and reported events

Commercial space travel companies were created by wealthy entrepreneurs around 2000, leading to spacecraft design and later deployment of manned suborbital and orbital missions in the early 2020s. Two of these companies have been contracted by NASA to transport astronauts to the International Space Station, superseding reliance on Russia's Roscosmos state corporation and Soyuz manufacturer RSC Energia corporation, which had been used to for this purpose after the conclusion of NASA's Space Shuttle program. Although there have been some civilian astronauts willing to pay large sums of money to spend time on the International Space Station, conveyed there by Roscosmos, public opportunities for space travel will be mostly for suborbital flights in the near future. There has been one orbital civilian space mission to date, and others will occur as this industry continues to develop. Orbiting space hotels and possible cis-lunar missions for civilians have also been proposed. The following section addressing medical screening and medical care takes the current trajectory of the commercial space flight industry, associated hazards, and reported events into consideration.

Medical screening and medical care for commercial spaceflight passengers

In 2001, the Aerospace Medical Association established a Task Force for the purpose of facilitating safety of passengers, fellow passengers, crew, and flight operations. A system of medical clearance was recommended, based largely on guidance developed several years earlier for passenger travel on commercial aircraft, and specific criteria were enumerated that might be considered disqualifying for civilian space travel, such as symptomatic coronary artery disease, active seizure disorder, pneumothorax, etc., though several conditions were also included which would not be likely to pose a risk over the short duration of the flight. The Task Force therefore subsequently issued a second report in 2002 which focused on less stringent medical screening appropriate for short duration suborbital flights. Several medical conditions still of concern were identified, including space motion sickness (with vomiting occurring within minutes after launch, which might occur in up to 85% of the passengers based on astronaut data), pregnancy, and medical conditions involving the risk of sudden incapacitation such as unstable angina or congestive heart failure, frequent unexplained syncope, uncontrolled seizures, and significant mental health illness including psychosis and a suicidal proclivity.

Soon afterwards, the FAA Civil Aviation Medical Institute completed a 2003 report which recommended that passengers on suborbital flights (less than +3 Gz load) should not be required to complete a simple medical history questionnaire, but not to undergo a physical examination or complete medical laboratory testing unless deemed necessary by the physician authorized by a commercial aerospace vehicle operator to conduct medical assessments. However, passengers participating in orbital aerospace flights (greater than +3 Gz load) should complete a more comprehensive medical history questionnaire and undergo a physical examination with laboratory testing as specified in the report. The Commercial Space Launch Amendments Act of 2004 required launch operators to inform spaceflight participants in writing about the risks of launch and reentry and about the safety record of the launch vehicle. The Act also required informed consent by spaceflight participants to participate in launch and reentry.

Additional FAA guidance was provided in 2006 which identified specific medical conditions for which orbital flight would be contraindicated, and several chronic diseases to be evaluated on a case-by-case basis. The Final Rule regarding Human Space Flight Requirements for Crew and Space Flight Participants was published in the Federal Register on 15 December 2006. These regulations required the provision of safety-related information, identified what launch operators must do to conduct a licensed launch with a human on board, and required operators to inform passengers of the risks of space travel generally and of the operator's vehicle, and required training and general security requirements for space flight participants. Also established were requirements for crew notification, medical qualifications (FAA Class 2 airman medical examination) and training, as well as requirements governing environmental control, life support systems, and operational verification of vehicle hardware and software performance before allowing any space flight participant on board. Much of this history is reviewed in greater detail in a 2008 report from the International Academy of Astronautics Study Group entitled "Medical Safety Considerations for Passengers on Short-Duration Commercial Orbital Space Flights." The report includes detailed information concerning the operational and environmental risk factors in orbital space flight including acceleration, barometric pressure, microgravity, ionizing and non-ionizing radiation noise and vibration, temperature and humidity, cabin air, and behavioral factors. Finally, it includes recommendations for preflight medical interview, physical examination, and health stabilization of prospective space passengers in addition to in-flight and post-flight considerations. Since 2008, we have become aware of additional effects of orbital flight in microgravity on human health including "decreased body mass, telomere elongation, genome instability, carotid artery distension and increased intima-media thickness, altered ocular structure, transcriptional and metabolic changes, DNA methylation changes in immune and oxidative stress-related pathways, gastrointestinal microbiota alterations, and some cognitive decline postflight."

In 2008, an Ad Hoc Committee of the Space Medicine Association and the Society of NASA Flight Surgeons published Human Health and Performance for Long Duration Spacecraft, noting that "there is a need to develop more stringent medical screening for crewmembers to minimize risk factors for disorders which cannot be successfully treated in flight. These foregoing reports therefore recognized that hazards and risks differed between suborbital, orbital, and long duration spaceflight, and that the needs for medical screening and treatment differed also.

For short high altitude or suborbital trips, an aircraft first aid kit (AFAK) should suffice, with supplies and equipment updated and replenished as needed. The kit should be checked before every flight. The kit should include over the counter (OTC) medications to manage emesis, headache, GI distress, etc. and allergies. Orbital flights will require a more extensive AFAK and a medical kit that is like that used by NASA for the ISS, with contents varying depending on length of mission. An oxygen concentrator should be provided. This will generate oxygen from the ambient cabin air, reducing oxygen buildup in the cabin over time, a fire hazard. For all spaceflights antiemetics and motion sickness bags must be provided, given the prevalence of space motion sickness. Long duration spaceflight will require a more extensive supply of medications, instruments, equipment and supplies as well as onboard personnel with medical training, and training specific to the space environment.

Respecting medical care during space missions, NASA has developed a Medical Extensible Dynamic Probabilistic Risk Assessment Tool (MEDPRAT) to help quantify medical components of spaceflight health risk. That data may be used, in conjunction with astronaut's symptoms and physical findings, by an Exploration Clinical Decision Support System based on adaptive learning, to address both chronic and acute conditions and symptoms, and identify the crew member with the optimal knowledge, skills, and abilities (KPAs), to manage a particular medical event. NASA's Human Research Program (HRP) Exploration Medical Capabilities (ExMC) element has developed the Space Medicine Exploration Medical Condition List (SMEMCL), based on the ISS and other NASA medical check lists. It includes medical conditions most likely to occur during space missions, and is dynamic in nature, with future additions and deletions expected. Since the early days of spaceflight, medical telemetry for monitoring cardiac function has been used. Laboratory testing, pulmonary function testing, tonometry, and even electroencephalography can be done during spaceflight. Ultrasound has become handheld and is now the primary imaging modality on the ISS. NASA has developed a Medical Optimizatrion Network for Space Telemedicine Resources (MONSTR) to categorize medical resource needs based on the medical condition list, which will continue to evolve over time. Augmented reality eyewear will likely be used for surgery and other medical procedures in space, and medical decision making will improve with the use of artificial intelligence.

International and cultural challenges

The astronaut/cosmonaut corps selection process has served as the best means to ensure effective communication and cooperation among international and culturally diverse spacecraft crew members. This rigor will not be as easy, or even possible, in the selection of commercial spaceflight participants, since those passengers will be mostly self-selected. This means that there will be a higher prevalence of chronic medical conditions, chronic injuries or musculoskeletal weaknesses, and implants or transplants in addition to greater diversity in language comprehension and fluency and in cultural expectations and tolerances of others on the same flight. This will be less of a problem for high altitude or short duration spaceflights. Negative interpersonal interactions are increasingly likely as the length of the flight increases. Particularly for orbital or longer missions, passengers should be evaluated for possible medical contraindications to flight as well as neuropsychological assessment for cognition, memory, coordination, non-aggression, and emotional stability. They should also be required to train together with respect to launch and flight procedures, and emergency procedures including escape and egress from the spacecraft if available. The possession of weapons, equipment that could be used as a weapon, and controlled substances such as alcohol or cannabis should be restricted.

Both medical screening and educational processes for new astronauts are essential parts of the pre-flight process. Ideally, self-awareness plays a central role in fitness for duty. Aeromedical screening standards cannot anticipate all potential hazards. The astronaut him- or herself must therefore be able to determine whether or not they are fit to perform a given task or mission safely and successfully. Cultural differences in admitting concern or challenging an assignment must be addressed in advance so that appropriate decisions are made by astronauts when and where they are needed. Both active and passive countermeasures play equally important roles as lines of defense. These countermeasures should be adaptive, dependent upon mission profile and astronaut duties. Over time, these authors believe artificial intelligence will assist in development of more sophisticated, human-centered, and culturally appropriate education and training tools intended to optimize individual health, safety, and performance.

Augmented and virtual reality formats are expected to greatly enhance and accelerate the learning experience and provide for realistic distributed team training. Simulated microgravity conditions and hazards may be simultaneously imposed on participants with suggested responses and assessment of effective behaviors and actions to be taken.

Conclusion and recommendations

This article has begun to address the unique opportunities available to the medical community to engage with mission designers to optimize health, safety, and performance during commercial space flight. Through adoption of a more anticipatory and individualized approach relative to mission profile, a heightened benefit through scientific knowledge available to improve experiences for the individual, and future space travelers will be achieved. The medical community will gain a more comprehensive understanding of physiology and psychology of space travelers and opportunities to improve personalized healthcare on Earth. The private sector and platform developers will also benefit through enhanced understanding of the extended duration space flight environmental challenges and opportunities for improvement.

Although this paper is rudimentary and only begins to address the complexities of the human-spacecraft-mission triad, we anticipate by beginning this open-source dialogue, the medical community, scientists, engineers and planners of the future will gain a more adaptive perspective on human health maintenance and anticipatory management of both external and endogenous health threats and susceptibilities. Marlene Grenon et al., 2012, Tomorrow's World, 2012, Wikipedia, 2006.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

AS developed the manuscript and content components, organizational lead, final synthesis of ideas, and references. RO contributed several sections, and references. KK contributed medical standards perspective and a summary perspective based on clinical practice. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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