Quantifying Medical Risk on a Long Duration Lunar Mission: A Demonstration of NASA's IMPACT Tradespace Analysis Tool

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Background
NASA's human exploration spaceflight missions to the Moon and Mars present unprecedented challenges for in-mission medical care. The distance from Earth will mean increased mission durations, communication delays, limited to no resupply opportunities, and constraints on the medical evacuation of astronauts. Mass, volume, power, and data will be limited while higher demands will be placed on the crew to manage medical care. NASA's Moon to Mars exploration strategy lays out increasingly complex Artemis missions both in terms of duration and operations. In these more challenging deep space missions, it is important to quantitatively estimate the human medical risk to inform a traditional heuristic approach to medical risk. Prior tools have been developed for missions in low Earth orbit, but a new tool is required to plan for future exploration missions.

Methods
IMPACT (Informing Mission Planning via Analysis of Complex Tradespaces) is a risk assessment tool developed by NASA to advance exploration mission medical system design by quantitatively estimating mission medical risk. IMPACT v1.0 includes a novel evidence library baselined to exploration environments; an expanded list of 119 medical conditions; the addition of medical resources; and the ability for rapid and iterative analysis. Medical system risk estimates include loss of crew life, consideration of the need for return to definitive care (medical evacuation), and an estimate of crew time affected due to medical conditions. A notional long duration lunar orbit and lunar surface design reference mission (DRM) was chosen with a 4-astronaut crew to represent a sustained exploration Artemis mission.

Results/Discussion
Overall, IMPACT successfully quantified medical risk and derived an optimized medical system to support crew on a long duration lunar mission. In this DRM, the calculated loss of crew life from a medical event was 0.008 events per mission, risk of potential need for evacuation was 0.30 events per mission, and cumulative crew time affected by medical conditions was 103 days. The medical conditions that most contributed to overall medical risk were decompression sickness, trauma conditions, and respiratory failure. The conditions that had the largest effects on crew performance included musculoskeletal injuries and lunar dust exposure. The IMPACT-generated medical system included resources that target the most common and highest risk conditions. This systematic analysis demonstrates the value of the IMPACT tool in medical system design for human exploration spaceflight missions.

Keywords: Missions to mars, mission medical risk, risk modeling, medical system design, probabilistic risk assessment

Introduction

NASA's human exploration spaceflight missions to the Moon and Mars present unprecedented challenges for in-mission medical care. Human spaceflight operations for the last 30 years have occurred only in low Earth orbit (LEO) and focused on missions to the International Space Station (ISS) where the approach to medical care takes advantage of the proximity to Earth. In-mission medical care in LEO follows a telehealth model where astronauts can consult the crew flight surgeon at Mission Control for real time audio-visual support. The Crew Medical Officer (CMO) onboard the ISS may perform some minor care independently, but in higher acuity settings will frequently rely on the Mission Control flight surgeon to make diagnostic and treatment decisions in conjunction with the flight director. In this way, medical care is considered ground-dependent, relying on experts outside of the crew to dictate care. However, NASA is in a period of transition with plans to retire the ISS in the coming decade[1] and shift its focus beyond LEO to exploration missions to the Moon and Mars with plans to maintain a long-term human presence in deep space. To maintain the health and performance of the astronauts on these novel mission profiles, NASA's approach to medical care also must change to meet these needs. The NASA Artemis missions have the stated goal of returning American astronauts to the Moon in the coming years to test and develop the skills and technologies necessary for a crewed mission to Mars[2]. Missions beyond LEO will result in extended communication latency, decreased medical system size, limited opportunities for resupply, and prolonged or absent opportunities for medical evacuation in an emergency to reach definitive medical care on Earth. Each of these factors creates challenges to the current model of ground-dependent medical care. Missions to the Moon for example, may have up to a 5-14 second communication latency, long enough to impair real-time communication with the ground and require a staggered communication system between crew and ground support[3]. The propulsion requirements of transporting a vehicle to the Moon will likely limit spacecraft mass, power, and volume when compared to the ISS, which may require a reduction in medical system size despite the increased overall mission medical risk[4]. In the event of unanticipated need for specific supplies like an oral anticoagulant to treat a novel jugular venous thrombosis[5], crews may have to wait weeks to months to get resupplied from Earth. On the ISS, medical evacuation is estimated to require less than 24h to reach definitive care[6], but due to the multiple vehicles and orbits involved in deep space Artemis missions, medical evacuation from the lunar surface may require the CMO to stabilize and maintain an critically ill crewmember for up to an estimated 14 days[7] during a return to Earth. In short, these missions will have higher risk and demands placed on the medical system and crew with less support and resources than any mission in the recent past.

Traditional approaches to medical risk and medical system design have depended on heuristics, employing the experience of current and prior NASA flight surgeons to decide on the types and number of medical resources to include on a given mission. While a heuristic approach to clinical decision making can be effective, it also is prone to biases which may put astronauts at risk[8]. In the last decade, NASA mission planners have employed from risk assessment tools like the Integrated Medical Model (IMM)[9] which can model medical events on spaceflight missions to estimate medical risk, but these tools were simple and designed to help support missions in LEO on the ISS. Exploration missions are significantly more complex, and with limited historical experience to depend on, mission planners may benefit from a standardized quantitative methodology.

NASA has approached this problem by developing a new mission modeling tool that utilizes the best available clinical evidence to quantify medical risk. The Informing Mission Planning via Analysis of Complex Tradespaces (IMPACT) tool uses a clinical evidence library database and a computational engine to model medical events, risk, and medical system components[10]. Mission planners can then combine this quantitative approach with medical operations experience to develop medical systems within mission constraints to support astronaut crews most effectively on complex missions to the Moon and beyond.

As a proof-of-concept demonstration, we aim to use the IMPACT tool to model a notional long duration, lunar mission to represent a sustained Artemis mission to identify risk metrics, high likelihood and consequence medical conditions, and potential resources to inform medical system design.

Methods

A complete description of the IMPACT tool, the development of the IMPACT medical condition evidence library, and the computational modeling engine is beyond the scope of this manuscript, but an overview is necessary to describe our findings. The IMPACT evidence library consists of 119 medical conditions that were selected as significant for spaceflight by an internal NASA review process[11] with a best-case and worst-case definition for each. For example, the condition "appendicitis” could be uncomplicated and resolve with antibiotics alone or complicated and require procedural intervention. A rapid systematic review was performed by a group of subject matter experts (SMEs) for each condition to quantify condition incidence and outcomes including need to return to definitive care (RTDC) based on defined thresholds for medical evacuation well as loss of crew life (LOCL). Literature reviewed was ranked based on applicability to medical care in exploration spaceflight and the highest quality evidence was selected with a normalized distribution. Additionally, task time lost (TTL), a novel measure of how medical conditions impact the crew’s ability to perform mission tasks, was calculated for each condition [12]. For each condition, a capability resource table (CRT) was developed using a consensus process that linked the necessary medical resources and skills to manage that condition, for both the best-case and worst-case definitions, in the spaceflight environment based on the best available evidence and SME opinion[13].

The Medical Extensible Dynamic Probabilistic Risk Assessment Tool (MEDPRAT) is the computational engine of IMPACT. Using the data from the evidence library, MEDPRAT performs a Monte Carlo simulation of a given mission hundreds of thousands of times to reach convergence. Average risk metrics (LOCL, RTDC, TTL) and medical system resources are reported based on the mission profile and inputs defining the relative importance of each risk metric and the cost balance of mass and volume used to evaluate the benefit of each medical resource while calculating an effective medical set meeting the provided size constraints. The optimization begins with the resources required to fully treat all conditions and systematically removes the least valuable (in terms of the benefit of reducing risks per unit mass or volume) resources over a series of steps until the desired mass and volume are reached.

To model a notional long duration Artemis mission most accurately, we gathered inputs from NASA mission planners and the NASA space medicine operations team. Long duration Artemis missions could include multiple mission segments including outbound and inbound segments on Orion, stays at the Gateway space station and lunar habitats, and lunar surface extravehicular activity (EVA). Some medical conditions are specific to a given segment(s)(e.g., space adaptation syndrome occurs only upon introduction to microgravity) to improve model fidelity while other conditions are equally likely across all mission segments (e.g., appendicitis). The long duration lunar mission profile chosen for this study included a 10-day outbound phase on Orion, 10 days on the Lunar Gateway, 168 days on the Lunar Surface with 2-crew EVAs occurring twice weekly (total 96 person-EVAs), 10 days on Lunar Gateway, and 5 days return to Earth on Orion (fig. 1).

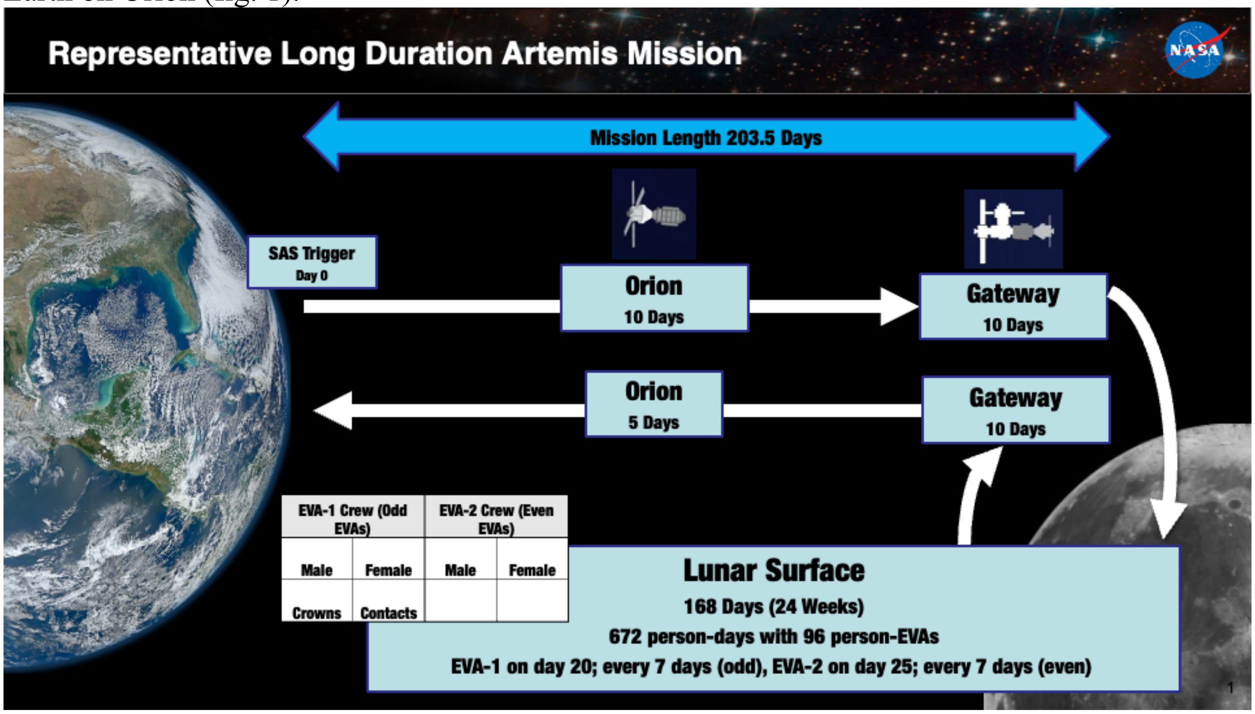

Figure 1. Mission profile for a long duration Artemis mission with duration and location of each segment

For this mission we chose 2 male and 2 female astronauts that have met the NASA Astronaut Medical A standard[14], with one a contacts lens wearer and one with a history of dental crowns to demonstrate specific medical history and how that affects risk outcomes. Medical system size was constrained to 50kg and 150L based on ISS medical system size[15] and subject matter expert opinion on a reasonable medical system size for a mission of this duration and complexity. This mission profile was modeled 200,000 times to reach convergence and was set to weigh all 3-risk metrics (LOCL, RTDC, TTL) equally.

Results

The simulated long duration lunar mission had a duration of 203 days (812 person-days) with 96 person-EVAs on the lunar surface. The calculated rate of LOCL was 0.008 events per mission, the rate of RTDC was 0.30 events per mission, and the TTL was 103 person-days (Figure 2). There was an average of 298 medical events per mission with the most commonly occurring medical events being lunar dust exposure, spacesuit contact injury, spacesuit paresthesia, sleep disturbance, barotrauma, spacesuit hand injury, headache, spaceflight rash, corneal abrasion, and skin abrasion (Figure 3). The conditions with the greatest effect on LOCL were decompression sickness, traumatic hypovolemic shock, respiratory failure, urinary tract infection, and abnormal uterine bleeding. The conditions with the greatest effect on RTDC were wrist fracture, corneal abrasions, and decompression sickness. The conditions with the greatest effect on TTL were spacesuit shoulder injury, barotrauma, spacesuit contact injury, and upper and lower extremity sprains (Figure 4).

Medical Risk on Long Duration Lunar Mission	
Loss of Crew Life (LOCL)	0.008 events/mission
Return to Definitive Care (RTDC)	0.30 events/mission
Task Time Lost (TTL)	103 days/mission

Figure 2. Quantified risk for the long duration lunar mission profile

Spaceflight Medical Condition	Number of Occurrences
Lunar Dust Exposure	168
Spacesuit Contact injury	17
Spacesuit Paresthesia	12
Sleep Disturbance	11
Barotrauma	10
Spacesuit Hand Injury	8
Headache	6
Spaceflight Rash	5
Corneal Abrasion	5
Skin Abrasion	4

Figure 3. Top 10 Medical Conditions and Occurrences per Mission

Loss of Crew Life (LOCL)	Events/Mission	Return to Definitive Care (RTDC)	Events/Mission	Task Time Lost (TTL)	Days/Mission
Decompression Sickness	0.0025	Wrist Fracture	0.140	Spacesuit Shoulder Injury	19.1
Traumatic Hypovolemic Shock	0.0013	Eye Foreign Body	0.046	Barotrauma	9.8
Respiratory Failure	0.0007	Decompression Sickness	0.021	Spacesuit Contact Injury	8.2
Urinary Tract Infection	0.0006	Corneal Abrasion	0.011	Upper Extremity Sprain	5.5
Abnormal Uterine Bleeding	0.0005	Risk for Pregnancy	0.010	Lower Extremity Sprain	5.2

Figure 4. The five most influential medical conditions for each of IMPACT's three risk metrics: loss of crew life, return to definitive care, and task time lost

The medical system optimized by IMPACT was 49.4 kg and 146 L. There was a total of 535 unique capabilities or resources included in the medical system with 1,398 total resources. The top ten resources by mass and quantity are listed (Figure 5).

Resources by Mass	Resources by Quantity
Multimodal Vitals-Assessment Device	Lozenges
Skin Cleanser	Anti-inflammatory pills
Normal Saline Intravenous Fluid Bags	Inhaled Nasal Steroids

Medical Device Cleaner	Topical Hydrocortisone
Mupirocin	Antihistamine pills
Mental Health - Cranial Stim Device	Eye Drops
Ultrasound Gel	Modafinil pills
Oxygen Mask and Tubing	Gauze pads

Figure 5. Resources selected by the IMPACT model ranked by the total mass and quantity.

Discussion

The IMPACT tool was able to simulate a complex design reference mission that represented a notional Artemis long duration lunar profile. The tool created a medical system based on a given set of constraints such as duration, size, crew number etc. and designed a medical system that was optimized to have the lowest risk metrics (LOCL, RTDC, TTL).

The condition that occurs most frequently within the model was lunar dust exposure, which occurs once a crewmember has doffed their spacesuit after a lunar surface EVA. The lunar regolith is composed of extremely fine particulates that coated surfaces and contributed to skin, eye, and lung irritation among Apollo astronauts[16]. IMPACT models this condition to occur to a crewmember after they return from EVA and to most crewmembers within the vehicle, resulting in a high incidence rate where almost every crewmember is affected on every EVA performed. This condition was informed by experts at NASA on lunar dust exposure and evidence from the Apollo missions, which depressurized the entire cabin during EVA, and may be updated based on final vehicle designs and Artemis crew health and performance data. The other conditions of highest predicted prevalence by IMPACT reflect real world spaceflight data[17].

Loss Of Crew Life (LOCL)

IMPACT predicted that there will be approximately 1 death in 150 missions with this profile due to a medical condition (IMPACT does not account for potential crew injuries due to catastrophic vehicle failures), a mortality rate that is extremely low. Identifying an acceptable mortality rate among astronauts is beyond the scope of this paper and was not the objective of this demonstration, but accurate modeling of potential mortality risk is critical for medical system design and balancing medical risk with risk from other systems. As a point of comparison, there have been no deaths due to a primary medical event in the history of human spaceflight. The risk of loss of crewmembers over the course of the Space Shuttle program was 1/90[18], but this rate was due to vehicle failure during the Challenger and Columbia disasters.

Decompression sickness (DCS) was the condition IMPACT calculated most contributed to LOCL. Decompression sickness occurs when traveling from a high to low pressure environment which in spaceflight occurs when crewmembers transition from a vehicle to a spacesuit to perform an EVA. Historically, there have been no confirmed cases of decompression sickness in spaceflight, however DCS has been observed in vacuum chamber training[19]. Prebreathe protocols to prevent DCS on the ISS are conservative and symptoms of mild DCS can often mimic the aches and pains associated with spacesuit use, so astronauts may not have realized their symptoms could be due to DCS.

The predicted LOCL rate from DCS is likely representative of the projected number and cadence of EVAs for these long duration Artemis missions. While there have been approximately 450 EVAs in the history of human spaceflight[20], this modeled mission has 48, greater than 10% of all previous EVAs. The Artemis vehicle and spacesuit atmospheric compositions and prebreathe protocols have not been fully elucidated and may change the calculated LOCL rate, nonetheless DCS has the potential to contribute significantly to crew medical risk and substantial NASA research is being performed to reduce this possibility[21], [22], [23].

The other conditions contributing to the predicted LOCL rate include traumatic hypovolemia, respiratory failure, urinary tract infection, and abnormal uterine bleeding (AUB). The inclusion of conditions like AUB within the top 5 conditions contributing to LOCL is unexpected, however the absolute rate of LOCL due to AUB is extremely low and comparable to the next dozen or so conditions and representative of random variability that occurs in the model when calculating conditions with very low incidence or risk of LOCL, even after 200,000 simulations.

Return To Definitive Care (RTDC)

The IMPACT calculated rate of RTDC was approximately 1 in every 3 missions of this profile, much higher than has been observed historically. In LEO, there have been no missions involving American astronauts that have required medical evacuation, but, there have been 3 missions during the Russian space program that suggested an early return to Earth for definitive medical care[24], [25]. However, the long duration Artemis mission modeled here is much more complex than any prior human spaceflight mission. The high calculated rate of RTDC via IMPACT may be due to the challenges of managing injury patterns that require definitive treatment that has historically only been available on Earth.

The condition that most contributed to RTDC events in this analysis was a distal radius wrist fracture. On review of the IMPACT Evidence Library for this condition, incidence was derived from an internal NASA model that predicts fracture rate based on time in space and proportion of time in partial gravity[26]. Terrestrial standard of care for treatment of a distal radius fracture is surgery and, because there are no orthopedic surgical capabilities available within the anticipated medical system, a distal radius fracture triggers an RTDC event. However, using a model to inform a model may introduce uncertainty in these risk outputs. There is also reasonable debate as to whether an in-mission distal radius fracture would trigger a medical evacuation during a real mission, or whether the crewmember could have the injury reduced and splinted prior to receiving definitive surgical treatment after return to Earth, weeks or months in the future. Conflict is likely to occur between mission objectives and medical treatment in the most significant medical conditions, and the decision to medically evacuate will likely be situational with substantial input from stakeholders including crew, medical operations, and mission planners.

Alternatively, the IMPACT calculated RTDC rate may reflect the increased risk associated with long duration lunar missions when compared to missions in LEO. Multiple EVAs per week in partial gravity using heavy equipment introduces risks like traumatic injury, dust exposure, and other conditions with which NASA has limited operational experience. The risk of injury may be much higher on these missions as humanity attempts to establish a permanent presence in deep space, and the risk profile calculated by IMPACT suggests that medical systems may need to be more robust or include a broader set of capabilities to adequately support astronauts on these novel missions.

Task Time Lost (TTL)

Based on the results of this IMPACT analysis, approximately 1 in 8 days was affected by a medical condition. The risk metric TTL was designed to represent the effect of a medical condition on a crewmember’s work performance and quality of life. Without this metric, IMPACT will always preferentially include lifesaving capabilities over resources that support the overall health and performance of the crew. An exhaustive discussion of how TTL is calculated is beyond of the scope of this text and available elsewhere[27] but it is important to note that tasks cannot be partially impaired by a given condition. With this method for example, an ocular foreign body can either fully impair your ability to pilot a vehicle or not. The TTL calculated by IMPACT should be considered the upper limit of what is likely to occur. This risk metric does not imply that a crewmember is incapacitated during TTL but rather that their work performance may be impaired. Nonetheless, mission planners can use the rate and conditions of significance to design a medical system that minimizes the effects of medical events on crew performance. When comparing conditions that contribute most to TTL, minor musculoskeletal injuries associated with EVA are the most common. The current spacesuit has a hard upper torso which limits normal shoulder movements, particularly depending on crew anthropomorphic dimensions[28], resulting in a large number of shoulder injuries during both training and EVA. Other challenges with suit sizing can result in contact injuries that can accumulate over time. Strains and sprains were also calculated as significant contributors to TTL as EVAs in partial gravity resulted in frequent falls during the Apollo program. In short, the biggest contributors to TTL are conditions associated with the number and cadence of EVAs on the lunar surface during this mission, however a new spacesuit in development for the Artemis missions aims to address some of these injury patterns.

Resources

One unanticipated finding within this IMPACT medical system analysis was the limited number of lifesaving interventions. While the proposed medical system included an automated external defibrillator (AED), it did not include advanced airway supplies including a bag-valve mask, intubation equipment, or positive pressure ventilation capability. These devices are been included in medical systems for decades and are currently present on the ISS [29]. However, overall risk of LOCL is low particularly when considering the limited number of conditions treated definitively with these devices. The IMPACT calculated rate of the condition “respiratory failure” was 0.0002 events per mission and the rate of LOCL from a respiratory cause was even lower. The IMPACT tool likely calculated other medical capabilities like pain medication or antibiotics more effectively reduced the total mission risk rather than the relatively large pieces of lifesaving equipment. Whether this exclusion is the “right” decision is beyond the scope of this paper, but it illustrates the ability of a quantitative, evidence-based risk modeling tool to challenge conventionally held wisdom on medical system design decisions.

The most common medical resources included in this IMPACT medical system analysis (e.g., ibuprofen, nasal steroids, artificial tears) were for the management of low acuity but high incidence conditions like lunar dust exposure or musculoskeletal injuries. These conditions do not increase mortality risk but have a substantial effect on performance and quality of life.

In this mission profile, the large quantity of capabilities and resources that manage these types of symptoms likely reflects the prevalence of non-life-threatening conditions. Of the 298 medical events that occurred on average per mission, 154 of them were related to lunar dust exposure and the medical system optimized by the IMPACT tool reflects this. Empiric research on the effects of lunar dust on human health is limited, especially at longer durations, [16], [30], but there are significant concerns about repeated exposure on missions that require frequent EVAs like those proposed in the mid to late Artemis program. Engineering solutions that reduce exposure or more substantive research on the pathophysiological effects of lunar dust will allow us to update IMPACT and more accurately quantify this risk.

Future Directions

As a tool, IMPACT is most useful when comparing missions of similar profiles but with different constraints. In this mission profile we set the maximum system size to 50 kg and let the IMPACT tool optimize the medical system to reduce risk. A smaller or larger system would not only result in different calculated risk metrics but also a different set of resources and capabilities included. Similarly, we can model the resources needed to meet desired risk metrics if the calculated values above are too high (or too low). IMPACT can be used to compare how increasing or decreasing the mission duration affects medical risk or how the number and cadence of EVAs might increase the risk of certain musculoskeletal conditions and therefore require more medications and devices to treat sprains or fractures.

The medical risk profile of this notional long duration Artemis mission was driven in large part by the number of anticipated EVAs performed by the crew. Unlike the ISS, crews on lunar missions will be exploring and field-testing equipment outside of the vehicle or habitat which introduces several medical conditions that may need to be addressed. Solutions may include having crew perform fewer EVA and instead use machines to perform surface tasks, or design spacesuits and vehicles that prevent against predicted injuries. However, every design decision needs to be balanced with others as the goal in using modeling tools is not to reduce medical risk but instead to reduce overall mission risk for astronaut crews. In this way, IMPACT can be used to extensively quantify risks and help make informed tradespace decisions.

Future iterations of this tool aim to have more operational applications. By identifying medical conditions with the greatest contribution to risk, research, training programs, and inflight resources can be tailored to the specific needs of a mission. In this analysis, for example, improving training for the crew to manage DCS and wrist fractures would likely substantially reduce actual mission medical . Additionally, IMPACT may be operationally useful in real-time, helping a Crew Medical Officer pick the optimal antibiotic to treat a given infection by comparing bacterial coverage and medication stores available aboard the vehicle. In this way, probabilistic risk assessment and tradespace analysis tools like IMPACT can transform the way medical systems are developed and improve human health and performance on future exploration missions.

Conclusion

The IMPACT tool was able to model a long duration lunar mission profile that represents a notional long duration Artemis mission to calculate medical mission risk and propose an optimized medical system to treat relevant conditions. This tool uses the best available medical evidence to quantify risk and inform mission planners who can combine this quantitative approach with operational spaceflight experience to create the most optimized medical system possible for astronauts on long duration missions beyond low Earth orbit. A system that meets the needs of our astronaut crews by providing necessary medical resources and reducing medical risk, but contributes the least amount of mass, volume, and power to the vehicle as possible.

The long duration lunar mission presented is a conceptual demonstration of IMPACT applied to a notional Artemis mission, but it is important to reemphasize that the power of this tool is its customizability to a broad set of mission profiles. Mission length, crew composition, past medical history, system size, and many other factors that influence medical system design can be adjusted and compared to reduce medical risk on exploration missions. Given its utility, NASA aims to continue updating and improving the IMPACT model to broaden its functions and improve its fidelity for missions to the Moon, Mars, and beyond.

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