A Qualitative Investigation of Space Exploration Medical Evacuation Risks

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INTRODUCTION: Exploration beyond low Earth orbit requires innovative solutions to support the crew medically, especially as the opportunity for timely evacuation to Earth diminishes. This includes assessing the risks and benefits that a complicated medical evacuation (MEDEVAC) poses to the injured crewmember, the crew, and the mission. This qualitative study identifies common MEDEVAC risk assessment principles used in spaceflight and other extreme environments to better inform future risk assessment tools and exploration mission concepts.

METHODS: Semistructured interviews were conducted with subject matter experts in spaceflight and analog domains, including polar operations, undersea operations, combat medicine, and mountaineering. Transcripts were analyzed using the qualitative method of Thematic Analysis with the technique of consensus, co-occurrence, and comparison.

RESULTS: Subject matter experts described 18 themes divided into two main categories: Primary Risk Considerations (e.g., crew, mission, resources, time) and Contributing Factors (e.g., psychological considerations, medical preparation, politics).

DISCUSSION: Primary Risk Considerations can assess MEDEVAC risk across mission phases, with Contributing Factors acting as premission tools to adjust those risks. Inter- and intracategory connections identified medical support considerations, MEDEVAC support considerations, and philosophy as the most impactful Contributing Factors. Medical support considerations, psychological considerations, and political considerations were found to have unique aspects given the distances and societal impact of exploration vs. low Earth orbit spaceflight. The Contributing Factor theme of decision making was determined to be unique due to its impacts across both categories. These findings expand current considerations and are important inputs for exploration mission MEDEVAC Concepts of Operations.

KEYWORDS: medical evacuation, human spaceflight, Mars mission, Artemis, cislunar.

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Human spaceflight is inherently dangerous and may be one of the riskiest modes of transportation.[28] Despite the obvious risks, fatal incidents have occurred primarily from vehicle malfunctions, with only three medical evacuations (MEDEVACs) conducted from space, all by the Soviet space program.[29] Proximity to Earth and to a terrestrial definitive medical care facility (DMCF) while in low Earth orbit (LEO) provides important backstops for spaceflight medical care. Even if an astronaut becomes seriously ill or injured (which happens rarely), they can return to Earth relatively quickly, arriving at a DMCF within 24–48 h.[22] Future exploration beyond LEO to the Moon and Mars will present many challenges, including communication delays, minimal to nonexistent resupply, long transfer times to definitive medical care, and significant limits on mass, power, volume, and data.[16] These factors plus the extended durations of future missions to the more hazardous and less explored environments of cislunar space and beyond change the paradigm for medical risk and make medical evacuation simultaneously more likely and more challenging.[1] Future decision makers will need to weigh patient

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factors, crew risks, and mission factors before executing a MEDEVAC. Indeed, the evacuation of an ill or injured crewmember from the surface of the Moon or Mars could be the most expensive and public decision ever made in human history to save a single life.

For these reasons, it is important to develop an understanding of the factors that should impact an exploration mission MEDEVAC decision, which in turn can inform the development of Concepts of Operations for medical evacuation. Understanding the MEDEVAC Concept of Operations for exploration missions is vitally important, as it will strongly influence both medical risk and the clinical capabilities required for the mission. In addition, defining key MEDEVAC factors early will provide for improved probabilistic risk analysis for exploration missions.

This study seeks to fill this knowledge gap by drawing from the experiences of subject matter experts (SMEs) in spaceflight and other extreme environments to answer the main research question: what risk assessment principles must be considered in space exploration MEDEVAC scenarios? This question can be further divided into two objectives: 1) identify common principles used to assess risks and benefits of medical evacuations in extreme environments; and 2) identify common points of friction, complication, and challenges in extreme environment medical evacuations.

METHODS

For this study, 20 unique interviews were conducted with SMEs in spaceflight and analog domains. Analog domains were defined as environments with some overarching mission need that must be balanced against medical concerns that may arise, limited local ability for definitive medical care, and some complicating environmental factors for evacuation (e.g., terrain, weather, hostile actors, etc.). Given these criteria, six domains were identified from which to solicit SME input: wilderness/alpine exploration (wilderness), polar exploration and research (polar), military combat medicine (combat), civilian undersea operations/research (undersea), military submarine operations (submarine), and human spaceflight (space). For a description of study subjects, see **Table I**.

This study was reviewed by the National Aeronautics and Space Administration (NASA) Johnson Space Center Institutional Review Board and determined not to qualify as human subject research (exemption granted). Individuals with experience in medical care as well as evacuation planning, rehearsal, and execution in extreme environments were eligible for inclusion in the study. The decision was made to not collect/report several categories of data from subjects (e.g., age, sex, years of experience) in order to maintain anonymity in a relatively small community of extreme environment medicine.

After defining the major objectives of the study, an interview guide was created to focus the conversation rather than restrain it. Each interview was divided into two sections, with the first section asking subjects to describe a single or a few MEDEVAC experiences and the second querying the experts on their

Table I. Description of Study Subjects.

NOTABLE CHARACTERISTICS	SUBJECTS
Domain of Expertise (domain code)	
Wilderness (W)	2
Polar (P)	5
Combat (C)	4
Undersea (U)	2
Submarine (S)	3
Space (X)	4
Highest Level of Education*	
Professional degree (M.D./D.O.)	16
Graduate degree (Ph.D., M.S., MBA, etc.)	8
Undergraduate degree	3
Profession*	
Physician (M.D./D.O.)	13
Medical provider (nonphysician)	1
Military officer	9
Flight surgeon (NASA/military)	5
Dive medical officer	1
Logistics operations	1
Spaceflight flight director	1
Astronaut - Active (NASA/CSA)	2

Each domain was given a letter designator shown in parenthesis that was used for anonymous labeling of subjects.
*Several experts hold multiple degrees and/or professions.

opinions about higher level principles that might guide future spaceflight MEDEVACs. Accordingly, this work represents what these experts described and is not an official NASA position. This was modeled after similar research undertaken by Eiding et al. in their investigation of interhospital transfers.[13]

SMEs were recruited within a domain until there was saturation of the overall research questions, a common endpoint in Thematic Analysis, which is reached when additional interviews no longer yield new insights or themes, typically at two to five subjects per domain.[6,24] Interviews took place via video teleconference, voice calls, or via email exchange. Interviews were recorded, the audio anonymized, then transcribed by the NVivo automated software program (QSR International, Burlington MA, United States). Records of interviews were stored securely and stripped of identifying information. All interviews were conducted by 1 of 2 interviewers, with a single interviewer conducting the majority of the interviews (18 of 20). A common interview guide, pre-interview training, and post-interview debriefs were used to help minimize variability between the two interviewers. Following each interview, the team compared the information and major topics discussed with prior interviews using a constant comparative method.[15]

Data analysis was performed by a single researcher using the Thematic Analysis approach. Due to the knowledge gap associated with this research topic focused on a historically rare event, Thematic Analysis was selected for its inductive or "bottom-up" approach.[7] Briefly, this method consists of identifying essential ideas, statements, or phrases within the text and labeling them with a summative description to create a "code." Similar or related codes are then grouped together and labeled to create a "theme." Associated or related themes can then be grouped further into "categories."[31] Final themes and categories were defined with their respective key points, and representative statements were extracted from the data.

A modified version of coding via "consensus, co-occurrence, and comparison" was employed to ensure external validity and credibility, with two additional researchers serving as reviewers of the results and analysis.[27,33] Methodological rigor was applied as follows using the criteria suggested by Nowell.[27] Transferability was sought through the application of results to past events as seen in the discussion section. Confirmability and dependability were sought through the presentation of excerpted quotes and the retention of raw and complete anonymized transcripts, respectively.[27] Similar versions of Thematic Analysis have been used to explore other emerging and less-defined spaceflight issues.[2,20,31]

RESULTS

Data collection yielded 20 SME interviews, totaling over 22 h of audio and over 250,000 words of transcription. Analysis of the data resulted in 18 themes expressed by the SMEs. These 18 themes were broken down by researchers into two main categories: 1) Primary Risk Considerations, and 2) Contributing Factors. These results can be seen in **Table II**.

Here the themes expressed by SMEs are listed and defined. Bullet statements below each definition explain the main aspects of each theme using both summative statements and direct SME quotes, focusing on unique, opposing, and even contradictory concepts expressed by multiple SMEs. There is considerable overlap and interplay between the themes, yet each attempts to describe and categorize only one domain of the complex problem.

Nine distinct themes from the SME interview data were categorized as Primary Risk Considerations. Researchers determined that SMEs expressed and emphasized these nine themes as the most important to consider when making a MEDEVAC decision. These themes, with definitions, summative analysis, and representative statements, are presented below and in consolidated fashion in **Table III**.

Table II. Results Overview.

CATEGORIES & THEMES	PERCENTAGE*
Primary Risk Considerations	
Crew	4.9%
Environment	3.7%
Execution	5.1%
Experience	5.1%
Mission	5.8%
Patient(s)	17.8%
Provider	2.3%
Resources	15.8%
Time	2.9%
Total	63.4%
Contributing Factors	
Communication	5.1%
Crew Cohesion	1.3%
Decision Making	11.7%
MEDEVAC Preparation	7.0%
Medical Support Planning	2.9%
Offsite Support	2.4%
Philosophy	4.0%
Political Considerations	1.5%
Psychological Considerations	0.8%
Total	36.6%

*Percentage of all codes that are grouped into each specific theme (or category).

Crew

Members of the mission or activity who are immediately impacted by a MEDEVAC, not including those being considered for MEDEVAC due to injury or illness:

- "Don't create more people needing to be rescued."
- "The needs of the many outweigh the few," while the crew themselves may take an "all for one" mentality.
- Delayed risks to the crew should be considered such as: increased workload (through assumed duties and patient care) and limited resources available for future medical or MEDEVAC contingencies.

Environment

The natural and constructed surroundings and how they impact the crew, patient(s), medical care, and modes of MEDEVAC:

- The natural and built environments (including countermeasures) can impact or limit medical care (e.g., surgery in a microgravity environment, patient monitoring in body armor, a spacesuit, or while strapped into the crew restraints of a spacecraft).
- The environment can drive operational decisions that lower risk tolerance thresholds (e.g., specific MEDEVAC windows driven by polar climates or orbital mechanics).
- The environment can have direct impacts on the patient's medical condition and the provider (e.g., the microgravity environment can have many effects on body systems).
- The environment may need to be modified or controlled prior to providing medical care (e.g., toxic atmosphere in spacecraft, warfare).

Execution

The steps, settings, and processes required to transport a patient from the point of injury to a DMCF:

- The method of execution matters clinically (e.g., a fast aircraft with little medical capability vs. a slow but more medically capable ship).
- "[Try] not to have the level of medical care deteriorate in any way while you're evacuating."
- Waiting a short time to initiate a MEDEVAC can save total time by optimizing later steps in the overall execution.
- How the provider integrates into the execution matters, particularly in maintaining continuity of care.

Experience

Training and exposure of medical providers and crew to medical skills, MEDEVACs, and risk trade-offs:

- The more experienced a crew or provider is, the more likely they are to be successful in medical treatments, interventions, and making correct risk trade-off decisions.

Table III. Consolidated Results—Primary Risk Considerations.

THEMES	DESCRIPTION	REPRESENTATIVE STATEMENTS*		
Crew	Mission members immediately impacted by MEDEVAC, not including those injured or sick.	Don't create more people needing to be evacuated -W2	The needs of the many outweigh the needs of the few. -C3	The rest of the crew covers down for as long as they can on the taskings at hand. -X4
Environment	The natural and constructed surroundings and how they impact the crew, patients, medical care, and modes of MEDEVAC.	Don't poke the bear. They're not deteriorating, just let them float there with no stress and get treated. -X4	You may not be able to help anybody…you're just trying to survive…. -X4	About 30 min after they left, they hit [a mine], and we saw all of them again…the risk is just ever present. -C1
Execution	The steps, settings, and processes required to transport a patient from the point of injury to a DMCF.	[You] try not to have the level of medical care or conditions deteriorate while… evacuating. -X1	The stresses of entry and landing…then they're hours away from care…what can we treat [in space]? -X1	Can you get them in a suit, strapped down…maybe? I can't provide any care… maybe talk to them, that's it. -X3
Experience	Training and exposure of medical provider(s) and crew to medical skills, MEDEVACs, & risk trade-offs.	Here, I've got no shortage of help. I don't have to ask the janitor to scrub in, but…that may be the case. -C4	We were less willing to tolerate medical risks with more advanced [MEDEVAC] capabilities. -P2	You need real experience of doing trade-offs of sick people…and balancing impact versus patient outcome. -W2
Mission	The explicit or implied purposes for the undertaking and the things required to achieve those purposes.	How do you evaluate the importance…a mix of how hard it was to get there and how likely we are to come back? -W1	We're going to shut down most of the station to make sure this person gets on a plane to safety. -P5	Once you launch to Mars, you've already made that decision…the mission is more important than the people. -X3
Patient(s)	The person(s) who have become sick or injured for whom a MEDEVAC is being considered.	Casualty status dictates everything. -C4	The [first patient] was getting better…now we have two patients, do we take two? -P1	If it could go either way, what does the patient want to do? -P5
Provider	The person(s) providing medical care to the patient(s) regardless of training.	We make recommendations, but they're going to listen. -X2	You've got to preserve your provider at all times…. -P5	They're the eyes and ears on the ground, but ultimately the decision isn't for the doctor on the ground. -P5
Resources	Local and remote workforce, consumable and durable goods for the mission, or providing medical care.	The crew will have to decide: do you use all your consumables on one person? -X4	OK, so we do this Hail Mary surgery…what do we do now? -P2	We'll modify the standard treatment so we don't use as many resources or people. -C1
Time	Duration of medical stability, procedures, MEDEVAC, resources, and decision space.	Most of the time you don't have to make a split-second decision…now you've got to talk to people. -X1	Could I wait 24–48 h to spin up my nominal landing site? -X1	If you put a [patient] in the back of an open-bed truck for a 4-hour drive, they're going to die. -C1

*Alpha-numeric code denotes domain and subject number per Table I.
MEDEVAC: medical evacuation; DMCF: definitive medical care facility.

- Increased MEDEVAC experience can decrease threshold to execute a MEDEVAC as the risk of treating locally can quickly exceed the risk of a MEDEVAC executed by an experienced crew.
- Increased MEDEVAC experience can increase threshold to execute a MEDEVAC as crews are more comfortable with a delayed and possibly more complicated or urgent MEDEVAC.
- Experience develops temperance, as no information "that initially [comes] out [is] better than 50 percent" accurate.

Mission

The explicit or implied purposes for a given undertaking and the things required to achieve those purposes:

- Level of prioritization is often explicitly prioritized in slogans like NASA's "Crew-Vehicle-Mission" or the military's "Mission first, people always."
- The mission is commonly prioritized below the crew or patient.
- Some missions are automatically prioritized over the crew upon launching given their inherent risks (e.g., military combat missions or a human mission to Mars).
- The value of a mission can potentially be assessed by the resources allocated and the likelihood of a repeat attempt.
- The patient(s) should get a vote in how important they are vs. the mission.

Patient(s)

The person or persons who have become sick or injured and for whom a MEDEVAC is being considered:

- The severity of the patient's injury or illness and the expected clinical course through the execution of a MEDEVAC are the most important things to consider as "…the casualty status dictates everything…."

- Prioritization of the patient varies between medical and operational personnel.
- Assessments should include how many "years of life" would be saved and whether they knowingly volunteered to accept risk of injury or death.
- The patient(s) should get a vote in how important they are vs. other priorities (i.e., the principle of patient autonomy).

Provider

The person(s) providing medical care to the patient(s) regardless of training:

- The provider's first priority should be to the patient, and they simply advise decision makers.
- Provider proficiency may degrade over the course of a mission, increasing the risk presented by local medical care.
- The provider is a resource and asset to be conserved and supported, often over the patient.
- Provider input weighs heavily on operational decision makers, who usually have the final say, unlike traditional medical settings.

Resources

Local and remote workforce, consumables, and durable goods for the mission or for providing medical care:

- Restricted resources limit possible diagnostics, interventions, and treatments.
- Offsite resources and flexible standards of care can expand available capabilities.
- Having a capability does not mean you should use it depending on the long-term impacts and follow-on care available (i.e., "if you're bridging to an intervention you can't give, you better be moving").
- A MEDEVAC can conserve local resources by avoiding prolonged on-site care.

Time

The duration of medical stability, procedures, MEDEVAC, resources, and decision space:

- Time in spaceflight is often determined by the consumption rate of resources and orbital dynamics.
- Time to a DMCF and in what environment needs to be considered.
- Most of the time, a split-second decision does not need to be made, and other decision makers at different levels with different information and considerations can be involved.
- Delays can expand decision space and improve MEDEVAC execution.
- "…time is a precious commodity. But I think if you can seek out more time to allow the decisions…to flourish, to grow, and eliminate avenues that now don't make sense or provide more avenues that might give you a better answer. That's good. But then you run into some of those hard balls of consumables that [don't] allow you to expand your decision space time."

Nine distinct themes from the SME interview data were categorized as Contributing Factors in a MEDEVAC decision. Researchers determined that SMEs expressed and emphasized these nine themes not to be of primary importance when making a MEDEVAC decision, but rather concepts that can both reduce risk and shape the environment for those decisions. These themes, with definitions, summative analysis, and representative statements, are presented below and in consolidated fashion in **Table IV**. Decision making is discussed separately.

Communication

The transmission, receipt, and understanding of information regarding medical issues, assessments, treatments, and MEDEVAC execution:

- In spaceflight, communications delays are particularly difficult and stressful but can be made more manageable with skill practice and event rehearsals.
- Communication in both crisis and medical scenarios leads to an inherent loss of information.
- Communicating medical information can be difficult due to its sensitive or complicated nature, requiring cross-training for both medical and operational personnel.

Crew Cohesion

The level of camaraderie, bonding, and integration the crew has achieved before the mission begins or in mission:

- The relationship between providers, particularly the Crew Medical Officer (CMO), and the rest of a team is critical for them to provide accurate assessments and quality care.
- Cohesion is important among crewmembers and between the crew and offsite support personnel, particularly given the underlying perception that flight surgeons "have two patients…[and] their main patient is the national space program."
- Cohesion between medical and nonmedical personnel facilitates better understanding, communication, and decisions.

MEDEVAC Preparation

Prior considerations, planning, and rehearsals for MEDEVAC execution through both training as well as mission and vehicle design:

- All SMEs considered preparation important, but approaches varied from deliberate rehearsals, to flexible templates, to limited rehearsal, with a "we're smart enough to figure it out" approach.
- Competing training priorities limited time and resources available for rehearsal in many environments.
- Preplanned and rehearsed MEDEVAC scenarios can help identify stress points and practice complicated "stacked failures" scenarios.

Table IV. Consolidated Results—Contributing Factors.

THEMES	DESCRIPTION	REPRESENTATIVE STATEMENTS*		
Communication	Transmission, receipt, and understanding of information regarding medical issues, assessments, treatments, and MEDEVAC execution.	It really degrades communication. It takes longer. It increases frustration. It makes everything harder. -X4	And I had to explain why, because these are engineers and they [don't] understand …the medical issues. -X2	With every handoff, there's some deterioration, and it's just like playing telephone. -C1
Crew cohesion	The level of camaraderie, bonding, and integration the crew has achieved before the mission begins.	Crews on a deep space mission will be very, very close… they're not necessarily all good friends…more like siblings. -X5	As a crew medical officer, that's your main goal…do the people trust you. -X5	We've established that trust and we were able to communicate with them. -X2
MEDEVAC preparation	Prior considerations, planning, and rehearsals for MEDEVACs through both training and mission/vehicle design.	You won't get more training hours. -X4	[MEDEVAC] is not a pickup game. -C3	That's why we train for the things that we do…hoping that the scenario we meet on the real day is not nearly as tough…. -X1
Medical support preparation	Prior consideration, planning, and rehearsals for medical scenarios through both training and mission/vehicle design.	I will tell you the medical team, the hours we get for medical training are few and far between. -X4	It's about $6k a year to support...We just made the call like we're not going to do it. -W2	Common things happen commonly…you have to think about high consequence, low incidence…as well. -W2
Offsite support	The availability for remote resources, consultation, and guidance to be provided to the crew.	Whoever the lead surgeon is in Houston, it's that chief physician who makes the recommendation. -X2	…my team has been activated and they are available to provide full support…. -P3	…if you're having a bad day… talk to your buddy…call your wife…if you're calling NASA…there's something weird. -X5
Philosophy	The underlying culture, approach, and acceptability for risk, casualties, and MEDEVAC planning.	…we're smart enough to figure it out. -X4	Either fully prepare them to be autonomous or just ask them to be careful and accept that they might die. -X5	…it all goes back to that priority scheme of crew safety, vehicle safety, mission. -X1
Political considerations	Broad organizational, national, and international impacts from the success or failure of a mission, crew injury, or loss of life.	…paratroopers die in a helicopter crash…it's tragic but that risk is part of their job…the public doesn't think like that for astronauts… -X5	…we don't want any narcotics because of the risk of diversion…that seems very shortsighted…. -W2	…if an astronaut dies, it's bad for them…but also for national prestige…that drives the resources put into saving someone. -X5
Psychological considerations	The mental health support, training, and assets provided in case of injury or the death of a crewmember.	…human spaceflight has to be the strongest link of the operation…resiliency, even for the most dedicated. -W2	When you put people in those amounts of pressure…it's impossible to predict…the ones who are going to fold up. -P5	…being in the same camp where now there's people missing from seats, that's a different experience. -C2

*Alpha-numeric codes in statements denote domain and subject number per Table I.
MEDEVAC: medical evacuation.

Medical Support Preparation

Prior consideration, planning, and rehearsals for medical scenarios through both training and mission and vehicle design. This differs from MEDEVAC preparation in that medical support preparation focuses specifically on the diagnostic, intervention, and treatment functions, often executed along with the operations of a MEDEVAC:

- Medical training time for spaceflight Crew Medical Officers (CMOs) and crew is very limited given competing duties and training priorities resulting in heavy use of just-in-time training.
- Using past data and population analyses to plan and resources for likely and high-consequence medical conditions can increase local medical capabilities and thus decrease MEDEVAC likelihood.
- Equipment and resources for medical support can be limited by mass-power-volume constraints as well as technical and political approval processes.

Offsite Support

The availability for remote resources, consultation, and guidance to be provided to the crew:

- Offsite resources are often used to expand medical diagnostic, consultation, and decision-making capabilities of a remote crew, with final decisions often formally made offsite.
- Utilization of offsite resources can be heavily impacted by communications (with usage complicated by delays), underlying philosophy, and cohesion between the crew and ground support (especially regarding the use of psychological support resources).

Philosophy

The underlying culture, approach, and acceptability for risk, casualties, and MEDEVAC planning:

- Broad philosophical approaches varied from "we're smart enough to figure it out," to "[the] system above the need of an individual," to "enable them to be autonomous" to simply asking that the crew "…be careful and accept that they might die."
- SMEs expressed the need for a paradigm shift with exploration missions to more acceptance of harm, akin to "…when humanity started to venture across oceans."
- Explicit philosophies included decision firewalls between operational and medical personnel, "load-and-go" versus "stay-and-play" medical approaches, and prioritizations of "crew-vehicle-mission" or "mission first."
- "…it would take a lot for you to…abandon your crewmates…it's unfathomable. Your crewmate is the rest of humanity."

Political Considerations

Broad organizational, national, and international impacts from the success or failure of a mission, crew injury, or loss of life:

- Concerns over consequences and negative public relations can impact decisions for medical resourcing, treatment, and MEDEVAC.
- National prestige, public perception, and acceptance of failure can drive overall resource and funding decisions more than actual outcomes.

Psychological Considerations

The mental health support, training, and assets provided in case of injury or the death of a crewmember:

- Successful psychological screening and selection was credited by many, particularly in the military domain, for enabling teams to be successful.
- Psychological considerations were deemed important given the stressful environments, but few organizations focused on it outside of operational rehearsals and family preparation for a loss of life due to limited training time and competing priorities.
- Psychological support was usually provided via offsite resources with significant impacts from communication delays as well as cohesion between the crew and ground teams.

Decision Making

The theme of "Decision Making" was described by SMEs as having effects on both Primary Risk Considerations and Contributing Factors. This theme is concerned with how a MEDEVAC decision is made, by whom, at what level of an organization, and with what information. This theme was found to not only be necessary to consider when making a MEDEVAC risk decision, but also to impact how future decisions are made through organizational structure, decision making delegation, and the existence of standing guidelines (i.e., spaceflight "flight rules") and rehearsals. Summative analysis and representative statements are presented below and in consolidated fashion in **Table V**:

- MEDEVAC decisions are often made with medical and operational inputs considered separately with a "firewall" between them.
- In organized structures, final decisions often rest offsite in the operational realm.
- Decision are made at higher levels if time allows.
- SMEs described that medical providers have significant influence over final decisions.

DISCUSSION

The main objective of this research was to determine what unique risk assessment principles are used to make MEDEVAC decisions in space and analog domains to better inform risk decisions and planning considerations for future space exploration missions. Through analyzing interviews with subject matter experts, 18 risk assessment themes were expressed, many with important and consequential connections, and several with unique applications for space exploration missions, illuminating the complex decision landscape.

To better prepare for future MEDEVAC scenarios, the 18 themes identified in this project (Table II) can serve as a starting point for establishing a MEDEVAC Concept of Operations and could aid in real time decision making. Currently, MEDEVACs in space are rare occurrences which SMEs described as generally considered on a case-by-case basis with little rehearsal or detailed planning. These emergencies are currently backstopped with ample offsite support, extensive resources, and the understanding that a DMCF can be reached from LEO in 24–48 h in a worst-case scenario. However, deliberate MEDEVAC decisions are difficult and become even more complex as human spaceflight transitions from LEO to the

Table V. Consolidated Results—Decision Making.

THEME	DESCRIPTION	REPRESENTATIVE STATEMENTS*		
Decision making	How a MEDEVAC decision is made, by whom, at what level, and with what information.	Make your recommendations, but it's up to the commander. -C1	You never tell the pilot it's a 3-year-old who's going to die if you don't go out. -P2	You need roles, responsibilities, and decisions made at the right places…the lowest possible level. -X2

*Alpha-numeric codes in statements denote domain and subject number per Table I.
MEDEVAC: medical evacuation.

exploration of cislunar space and beyond.[19] Therefore, new tools are needed to assess the MEDEVAC risks in future exploration missions.

The Primary Risk Considerations themes have the greatest impact on a real-time MEDEVAC risk decision. When analyzing a mission concept for MEDEVAC risk, each phase of the mission could be assessed or quantitatively scored against these themes given some predefined objective criteria for each theme. Consider a hypothetical scenario with conflicting themes of Patient(s) and Mission. During the lunar surface phase of an Artemis mission, the MEDEVAC of an injured astronaut from the surface of the Moon to the Lunar Gateway station could present relatively high risk to the Mission if it means an end to the mission before the objectives were complete. However, the MEDEVAC could be relatively low risk for the Patient if there is increased diagnostic and treatment capability on the cis-lunar space station vs. the lunar surface. MEDEVAC to a DMCF on Earth from the Moon could also be assessed and compared. Weighting of each theme relative to the others according to some broader institutional guidance could enable even more critical analysis. In this way, MEDEVAC risk across multiple phases of a complex exploration mission could each be quantified and assessed prior to a mission's execution.

With this approach, the Contributing Factors themes can be seen as the dials that can be turned which alter the Primary Risk Considerations within any given mission phase. Continuing the example, if the risk to the Patient(s) was determined to drive the MEDEVAC risk beyond some acceptable level, Medical Support Planning could be addressed through the addition of expanded treatment capability on the lunar surface vehicles.

Connections and overlaps between the emerging themes were common. Some of these connections were direct and logical (e.g., more patients require more resources), while others were determined to be causal through analysis of SME inputs. When considering the risks associated with any single principle or theme, it is also important to consider the connection and drivers behind those principles.

While it may seem duplicative to enumerate the connections between the two categories, the impacts that Contributing Factors themes have on Primary Risk Considerations are a fundamental result from this study. While the Primary Risk Considerations may prove to be a helpful context for assessing MEDEVAC risk in an exploration mission, they alone are likely not enough to help adjust that risk. Pairing the Primary Risk Considerations with the Contributing Factors provides a basis for adjusting MEDEVAC risks, ideally prior to a mission, and helping reduce the overall risk an exploration mission may present. In other words, the connections make the results of this work not only explanatory, but actionable. Below is a discussion of those principles with significant or unique connections between the premission Contributing Factor themes and real-time Primary Risk Consideration themes as illustrated in **Fig. 1**.

The Contributing Factor with the most connections to Primary Risk Considerations is Medical Support Preparation. Since this theme is defined as the "prior considerations, planning, and rehearsals for medical scenarios through both

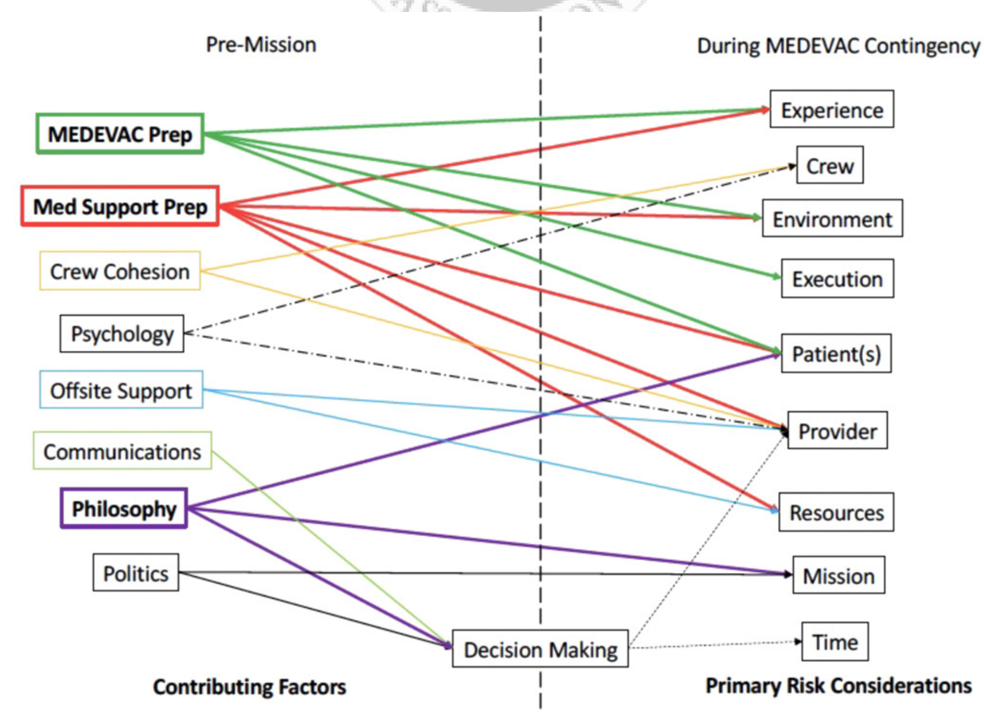

Fig. 1. Inter-category connections. The arrows from the Contributing Factors themes indicate that connections or driving factors exist between that theme and the corresponding Primary Risk Considerations. Themes determined to have especially significant or unique connections are bolded. The varied colors and patterns have no significance beyond distinguishing each group of arrows from each other.

training and mission/vehicle design," some connections are clearly logical. The amount of planning and rehearsals for medical contingencies directly influences the Experience of the crew, risk to the Patient(s) through treatment or MEDEVAC, and the skills of the Provider, including the risk they incur if they themselves are the patient and need to be treated by the other crewmembers. Less obviously, medical support preparation, particularly when considering the design and functionality of a vehicle or medical support system, can impact the constructed Environment. Finally, the considerations for what medical conditions are worthwhile to plan and resource has an obvious and direct impact on the Resources available. Through these connections, Medical Support Preparation is the most impactful Contributing Factor and, therefore, one of the most important principles for affecting the risks associated with a MEDEVAC.

The Contributing Factor MEDEVAC Preparation also impacts many Primary Risk Considerations. Defined as "prior considerations, planning, and rehearsals for MEDEVAC execution through both training and mission/vehicle design," it also has many connections that are clearly logical (e.g., Experience, Environment, etc.). MEDEVAC Preparation also has a direct impact on the risk the actual Execution of a MEDEVAC presents. SMEs described how practice and rehearsal mitigates risks through identifying "stress points" and exploring the impact of "stacked failures" until the dangerous activities are "muscle memory." Together, the Medical Support Preparation and MEDEVAC Preparation contributing factors have large impacts on the ultimate risks associated with a MEDEVAC.

Several of the themes are notable for having unique aspects when considering exploration missions vs. LEO spaceflight. These unique aspects are driven by both the physical differences in traveling beyond LEO and the broad societal impacts such missions are likely to have.

Longer times for Patient(s) transport to a DMCF will require expanded CMO training in prolonged care, more onboard resources, and autonomous decision making compared to the current LEO paradigm.[32] Any medical contingency will also likely place an increased burden on the Crew to care for a patient and assume their critical duties, as well as introduce the possibility of continuing a lengthy mission after the loss of a crewmate.[18] The delayed physical and possible psychological impacts on the crew must be considered in any exploration MEDEVAC decision as well as when designing exploration medical support systems.

Exploration missions to cislunar space and beyond involve increased distances that directly impact the themes of Time (via increased travel times) and Communication (via the introduction of extended latencies).[12] Increased communication latencies have been shown to complicate the use of Offsite Support, as was also highlighted in conversation with spaceflight SMEs.[14] The current paradigm for LEO medical support relies heavily on offsite support with CMOs explicitly assisting ground-based flight surgeons in evaluating and treating medical problems.[32] Increased communication times will uniquely hinder, or outright prevent, exploration CMOs from utilizing offsite support in this way, requiring adjustments to the Medical Support Considerations Contributing Factor in the form of increased training or decision support tools to help mitigate the risks associated with the Provider. Indeed, Medical Support Considerations in the form of increased medical training for the entire crew will likely be needed. The current paradigm relies heavily on ad hoc and just-in-time training, with one SME describing having to create "cheat sheet[s] for the rest of the crew" when they themselves became the patient, to handle the crew's concerns of "what do we do, or how do we know if this gets worse?"

Finally, exploration missions are likely to differ from current LEO spaceflight in their impact on society at large. An estimated 650 million people worldwide watched the first steps on the lunar surface in 1969, and it is likely that a return to the Moon will again raise excitement and interest in human spaceflight, to say nothing of a mission to Mars.[8,21,26] Furthermore, any contingency scenario will likely draw even more attention, with popular culture having shown enthusiasm for tales of astronauts stranded or injured far from home.[30] This anticipated public visibility and the objectively high resource costs of such a mission highlight the impact the theme of Political Considerations will have as a Contributing Factor to any MEDEVAC decision.[4] These unique political pressures impact the Decision Making and Philosophical approaches organizations should take when handling MEDEVAC risk decisions and dictate the need for a methodical approach to these difficult calls.

Taken as a whole, this study finds future exploration missions beyond LEO will require unique MEDEVAC risk assessments. The Primary Risk Consideration themes identified in this study, along with the Contributing Factors, offer an organizational framework to plan for and execute exploration spaceflight MEDEVACs. The unique distances and impacts associated with these missions also require increased focus on medical and psychological autonomy and training provided to CMOs and the crew. These distances and impacts also require advanced development of deliberate philosophies that pertain to how prioritizations are made and the acceptability of risk and mission loss.

The applications of this study are limited principally by the qualitative nature of the research. The research team has significant prior knowledge about extreme environments (including human spaceflight) and medical evacuations, which may have shaped the results. Furthermore, SMEs were recruited in a stepwise fashion, with many being known to the research team or other subjects. Although attempts were made to ensure saturation of each domain, there are undoubtedly opinions and experiences that were not captured.

The three prior medical evacuations from space offer the opportunity to check the face validity of the framework described herein by retrospective application. Each scenario will be presented with a vignette followed by a brief discussion of the relevant themes from the MEDEVAC framework.

The first scenario involved a MEDEVAC from Salyut 5 in 1976 due to toxic environmental exposures. A summary of the mission and MEDEVAC is reproduced from the "Handbook of Bioastronautics":

> *The crew was exposed to acrid odors apparently caused by nitric acid fumes leaking from propellant tanks. There were also reports the crew didn't follow their exercise program and were sleep deprived. Mission psychologists felt there were "interpersonal issues" between the crew. Vitali Zholobov had space motion sickness as well as the aforementioned psychological issues. The crew returned on day 49 of a planned 54-d mission. Because of the early return, the recovery conditions were not optimal, and included strong winds, which caused uneven firing of the braking rockets, resulting in a hard landing at night.*[10]

Several Primary Risk Consideration themes from this study are apparent in this vignette. Here the medical incident (an environmental exposure) put the Patient(s) at risk during the time between the exposure and the eventual MEDEVAC. The theme of Execution also contributed significantly, with the decision to evacuate before the planned return [Patient(s) over Mission], resulting in executing the MEDEVAC in suboptimal return conditions, increasing the risk to the Crew. Adjusting the Contributing Factors of Medical Support Preparation (through increased toxic exposure prevention or treatment capability), Team Cohesion (hopefully mitigating the "interpersonal issues"), and Psychological Considerations (through increased sleep planning and support) prior to launch could potentially have changed the scenario, possibly alleviating the need for what was ultimately an off-nominal, and possibly more hazardous, return to Earth. This vignette also presents interesting parallels for a future lunar mission. Here a toxic exposure rendered the entire crew as Patients with no true "healthy" Provider or Crew while nevertheless requiring the entire Crew to act as Providers for themselves and each other. This is similar to what will be encountered by long-duration lunar exploration crews inevitably dealing with chronic lunar dust exposure.[9]

The second scenario is from Salyut 7 in 1985 which involved a crewmember with a urinary and prostate infection. A summary of the mission and MEDEVAC is reproduced from the "Handbook of Bioastronautics":

> *[Vladimir] Vasyutin fell ill soon after arriving at the station and was unable to perform his duties as station commander. The mission was originally scheduled for a 216-day stay, but his illness forced an early mission termination. The illness was probably prostatitis, and he had pain and a fever as high as 104 degrees F. Savinyikh, Vasyutin, and Volkov returned to Earth on 21 November 1985 after 65 days. Vasyutin spent a month in hospital on return to Earth.*[10,17]

Here again, the Principal Risk Considerations of Mission and Patient are in tension with the ultimate decision to return, prioritizing the Patient over the Mission. The Crew also likely experienced increased risk during the time the Patient was unable to execute his duties as station commander. An increased focus on the Medical Support Considerations Contributing Factor theme could have adjusted the risk a prostate and urinary infection posed to the Patient and perhaps enabled the Mission to continue to its planned duration.

The third scenario is from Mir EO-2 and involved a crewmember with a cardiac dysrhythmia. A summary of the mission and MEDEVAC is reproduced from the "Handbook of Bioastronautics":

> *[Aleksandr] Laveykin performed a strenuous EVA and developed a cardiac tachyarrhythmia that persisted for several days before returning to normal. The dysrhythmia recurred and mission control recommended he return before the planned December 1987 return date. He was replaced by Aleksandr Aleksandrov and returned on 30 July 1987, having spent 174 days 3 h 25 min in space. He was later returned to flight status.*[10]

This vignette shows how risk assessments can change as a situation develops. Initially, the risk a cardiac dysrhythmia posed to the Patient was apparently deemed below the risk a MEDEVAC would pose to the Mission. As Time continued the condition apparently did not completely resolve and the risk to the Patient rose to outweigh the Mission, resulting in an early return. However, the manner of MEDEVAC Execution likely helped reduce the risk to the Mission, as the choice was made to evacuate the Patient in conjunction with a flight to bring a replacement crewmember. Also interesting in this vignette is the role Offsite Support and the context around Decision Making played in the eventual MEDEVAC. Had no Offsite Support in the form of cardiac monitoring and evaluation been in place, the dysrhythmia might never have been discovered, leaving the Patient at risk during the execution of the Mission. While it is possible that the crew could have discovered and diagnosed the dysrhythmia themselves, it was the Decision Makers on the ground that apparently made the call to have the crewmember return. Had the ultimate decision rested with the crew, the outcome could have been quite different.

It is also important that this framework be applicable to scenarios where MEDEVAC is considered even if not ultimately undertaken. A dental abscess nearly caused the return of a cosmonaut; however, appropriate Medical Support Considerations enabled his treatment with analgesia.[10] Another cosmonaut's ingestion of toxic ethylene glycol resulted in facial and upper-airway dermatitis, with the onboard Provider treating the cosmonaut in flight.[10] A case of abdominal pain caused the planning of an early return for fear of an acute appendicitis which might require a surgery that was outside the Resources and Provider capability onboard. However, the Patient's illness subsided and was found to be a case of nephrolithiasis.[10]

Within the U.S. space program, an astronaut was discovered to have a deep vein thrombosis in their internal jugular vein.[5] The diagnosis and treatment of the Patient was done through extensive use of Offsite Support with experts on Earth providing diagnosis, prognosis, treatment plans, and even remotely guiding diagnostic use of the ultrasound.[5]

Appropriate Resources also had to be flown to the International Space Station in the form of anticoagulants.[5] These close calls and vignettes above show how themes from this study can be used to analyze medical events and MEDEVAC risk assessments.

This qualitative survey of spaceflight MEDEVAC principles is well suited to aid future mission planning by pairing with quantitative risk assessment tools. One such tool, NASA's Informing Mission Planning via Analysis of Complex Tradespaces (known as IMPACT), is designed to estimate medical risk and generate recommendations for medical system resource sets within user-specified inputs and constraints (e.g., mission duration, number of crew, system mass).[3,23]

IMPACT can identify phases of exploration missions with high likelihoods of a medical event or evacuation, driving a detailed MEDEVAC risk assessment.[25] The themes detailed herein can then serve as the basis for objective criteria to break down these risks, perhaps in a manner similar to the creation of likelihood vs. consequence risk matrices used by the Department of Defense and NASA.[11] Mission phases with a resulting MEDEVAC risk assessment above a predetermined threshold could then be assessed for adjustment of one or more of the associated Contributing Factors to mitigate the likelihood or consequence of a medical event or evacuation.

Ultimately, this work enumerates the specific themes that should be considered in MEDEVAC planning for human space exploration. Although the results are generalized, defining them in a rigorous fashion is a necessary precondition for development of objective and quantitative criteria for specific missions. Future work using these results as a basis for analysis can lead to the development of high-level consensus recommendations for medical evacuation in spaceflight as well as the creation of specific guidelines for particular mission profiles. Indeed, a clear understanding of all the factors to be considered in a spaceflight MEDEVAC decision will decrease the risk faced by exploration crews and enable even greater discoveries for all of humanity.

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