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Medical Event Management for Future Deep Space Exploration Missions to Mars

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ABSTRACT

Background: Long-duration exploration missions (LDEMs), such as voyages to Mars, will present unique medical challenges for astronaut crews, including communication delays and the inability to return to Earth early. Medical events threaten crewmember lives and increase the risk of mission failure. Managing a range of potential medical events will require excellent technical and nontechnical skills (NTSs). We sought to identify medical events with potential for rescue, range them according to the potential impact on crew health and mission success during LDEMs, and develop a list of NTSs to train for management of in-flight medical events.

Materials and methods: Twenty-eight subject matter experts with specializations in surgery, medicine, trauma, spaceflight operations, NTS training, simulation, human factors, and organizational psychology completed online surveys followed by a 2-d in-person workshop. They identified and rated medical events for survivability, mission impact, and impact of crewmember NTSs on outcomes in space.

Results: Sudden cardiac arrest, smoke inhalation, toxic exposure, seizure, and penetrating eye injury emerged as events with the highest potential mission impact, greatest potential for survival, and that required excellent NTS for successful management. Key NTS identified to target in training included information exchange, supporting behavior, communication delivery, and team leadership/followership.

Conclusions: With a planned Mars mission on the horizon, training countermeasures need to be developed in the next 3-5 y. These results may inform policy, selection, medical

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system design, and training scenarios for astronauts to manage in-flight medical events on LDEMs. Findings may extend to surgical and medical care in any rural and remote location.

Introduction

The National Aeronautics and Space Administration (NASA) is currently considering crewed missions to cis-Lunar space (the region between the Earth and the moon) and to the planet Mars over the next several decades.[1] These long-duration exploration missions (LDEMs) represent unique challenges from the current missions to the International Space Station.[2] Although astronauts represent a highly screened and physically fit population,[2] the physiologic changes that occur in microgravity, combined with the long-duration, isolation, background radiation, and uncertainties of space travel necessitate detailed and extensive planning for medical care (Fig. 1).[3,4] Spaceflight represents a significant risk of traumatic injury, either in flight or on planetary surface while performing extravehicular activities, such as space walks or lunar/Martian habitat exploration.[3,4] The deleterious effects of long-duration spaceflight, including living in confined environments, exposure to background radiation, and continuous exposure microgravity may also have debilitating effects that predispose astronauts to various illnesses and injuries. Effective management of in-flight medical events during space exploration is essential to protect crewmembers' lives and ensure mission success.[5,6]

In terrestrial settings, the nontechnical skills (NTSs), such as leadership, teamwork, communication, and situation awareness, play a crucial role in improving success in a range of complex work environments, including medicine.[7-9] Several surgical training program, such as simulation-based team training courses[10] and NTS coaching programs,[11] are designed to enhance leadership, diminish errors, foster team cohesion, and lead to better patient outcomes, especially during surgical crises.[12] In a recent investigation of outcomes in the Veterans Affairs Administration, NTS training was shown to reduce 1-y mortality rates by 18%.[14] NTS assessment tools such as Non-Technical Skills for Surgeons (NOTSS) have been found to be valid and reliable markers of behavioral skills for surgeons and related to patient safety outcomes from operating room video[15] and operating room simulation[16] exercises.

In spaceflight, superior NTS of the flight crew and mission control will lead to faster resolution, better outcomes, and increased odds of rescue during medical events. As is the case for technical skill acquisition, training medically focused NTSs requires deliberate practice and a valid assessment framework for medical events,[8] which does not currently exist for astronaut crews. Without prior experience and data from long-duration missions, it is challenging to form evidence-based countermeasures; however, our experience with developing similar assessment tools for surgeons in terrestrial settings provides a blueprint for innovation in space medicine. The aims of this investigation were to identify and rank potential medical events for survivability, mission impact, and role of specific crewmember NTSs on outcomes. To achieve this aim, we leveraged multidisciplinary expertise in the form of subject matter experts (SMEs) to develop a consensus on the design criteria, constraints, and behaviors for flight crew to effectively handle medical events on LDEMs.

Materials and methods

Study population

This study protocol was approved by the institutional review board at Partners Healthcare in Boston, MA, USA. Each subject provided informed consent before participating. Using a snowball sampling technique, we recruited a panel of SMEs to provide expert guidance (see Acknowledgments for roster). To ensure that the panel could provide a comprehensive view of the medical, behavioral, technical, and logistical aspects of the project, we recruited individuals with expertise in surgery, space medicine, emergency medicine, trauma, human factors, simulation, patient safety, training, and spaceflight. Experts came from academic, government, and business settings and represented a broad range of credentials and professional expertise (see Acknowledgments for a full list of SMEs). A total of 32 SMEs were recruited to participate in the process, with 28 able to participate in a 2-d consensus meeting that was held in Houston, TX, in November 2016. Those who were unable to attend were asked to provide input before the consensus meeting to ensure that their expertise and opinions were represented in the discussion.

Procedure

An electronic questionnaire was sent to each participant a week before the consensus meeting to gather initial individual rankings of event severity. Participants were asked to self-identify their expertise and then received instructions for ranking each of 30 potential medical events using a 100-point visual analog scale on the following criteria: (1) likelihood of survival, (2) impact on mission success, and (3) impact of NTSs on the outcome. See the following for details of the survey instrument. The conditions were presented in the alphabetical order, with a brief description of each condition that included symptoms, potential complications, and any relevant space-specific information. Participants could skip any questions or conditions that they did not feel qualified to answer.

The subsequent 2-d meeting was held at the Lunar & Planetary Institute in Houston, TX. The meeting location was chosen to maximize in-person attendance, as many of the participants were based in and around the adjacent NASA Johnson Space Center. This meeting followed the procedures for an NIH Consensus Development Conference.[17] It consisted of six facilitated discussions to better understand panel members' rating decisions on the following topics: (1)

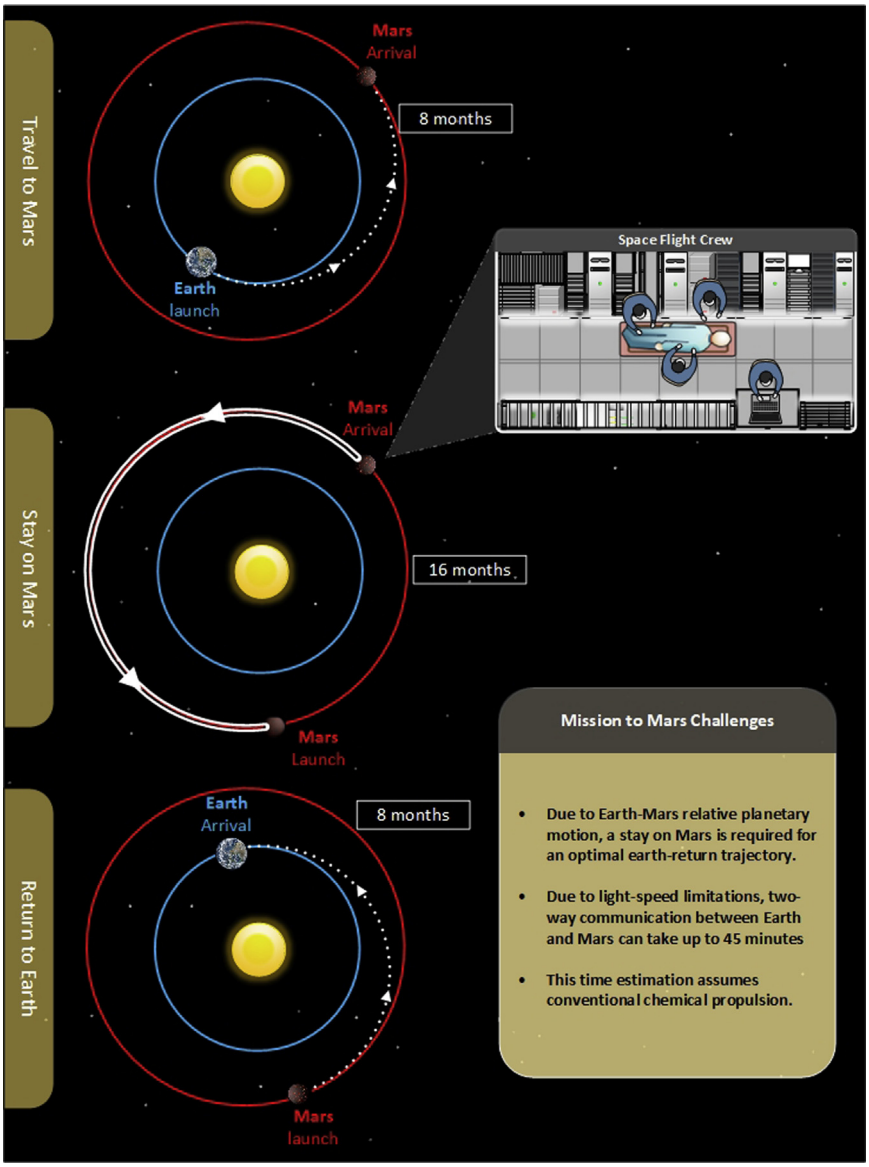

Fig. 1 – Challenges in managing medical emergencies during long duration space mission. (Color version of figure is available online.)

Likelihood and management of medical events in LDEMs, (2) NTS for astronauts to manage medical events in space, (3) Consensus on survivability of medical events in LDEMs, (4) Consensus on NTS for medical event management in space, (5) simulation for medical event management in space, and (6) behavior measurement scales and recurrent training in NTS. Panel discussions explored similarities and differences between the medical events, and the challenges associated with providing a rating for each one. Both large group (all participants) and small group (breakout groups) were employed during the discussions. Breakout groups were created by the research team before the meeting, and each group contained a multidisciplinary team of SMEs with diverse information on medical diagnosis and treatment of conditions, historical data from prior space and space-analog missions, current astronaut training in technical skills and NTSs, and the science of human behavior. Facilitators helped the SMEs reach consensus on the key features of medical events that may occur using an iterative process. Discussions were audio-recorded and transcribed for later analysis (Fig. 2).

Materials

To create a questionnaire to identify medical events likely to affect crewmembers during LDEMs for preconsensus meeting data collection, we used the Space Medicine Exploration Medical Conditions List.[13] This NASA-developed document includes 84 probable medical conditions that have been identified and prioritized by a team of flight surgeons, physician astronauts, engineers, and scientists. This list is based on historical data from previous missions;

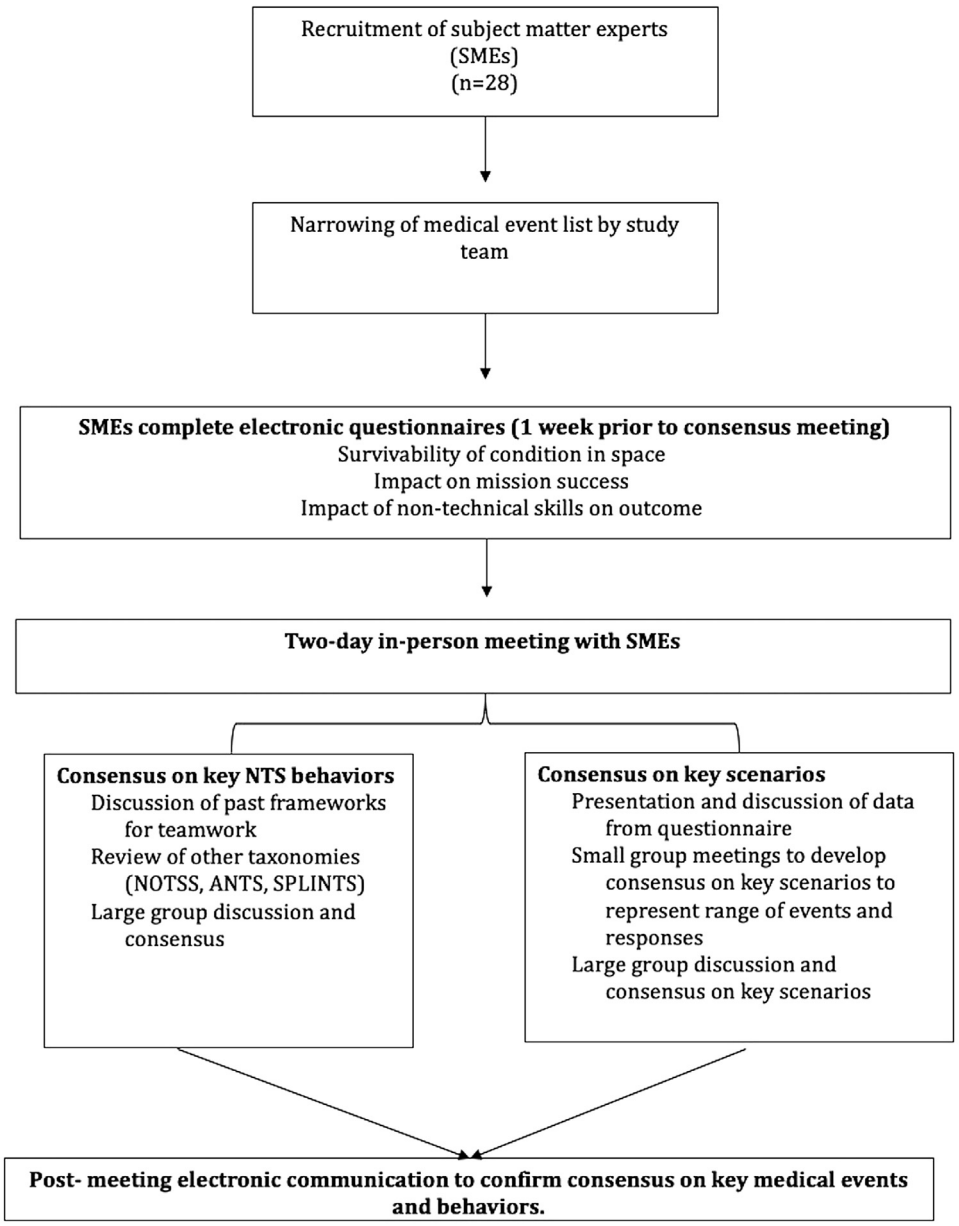

Fig. 2 – Subject matter expert recruitment and consensus flow chart.

data from high-stakes remote environments, such as Antarctica; statistical probability; and expert opinion. Designed to serve as a reference document for activities related to medical planning for upcoming LDEMs, the list serves as a living document that is continually updated as new screening, diagnostic and treatment capabilities are identified. To limit this list to events most likely to significantly impact crewmembers and mission success during LDEMs, the study team (J.M.R., S.Y., D.M., C.P., R.D.) removed expected minor ailments, such as indigestion and skin abrasions, as well as common crew complaints during acclimation, such as nausea and nosebleeds, as these were likely to neither impact mission success nor require extensive team skills and coordination to successfully manage. This created a reduced set of 30 medical events for ranking and deliberation of the SMEs during the consensus meeting (Table 1).

Analysis protocol

All statistical analyses were conducted using Stata 14.2 (StataCorp). Box and whisker plots were created for each of the three rating criteria (survivability, mission impact, NTSs) for each of the 30 medical conditions under consideration. Median scores for each of the three criteria applied to a given event were used to create quartiles to classify the medical events into categories ranging from minimal to high impact. These classifications were used to create a standard risk matrix, in line with standard industry risk management processes used by NASA, and to identify medical events with

Table 1 – Thirty medical events rated by subject matter experts, listed alphabetically.

Abdominal injury	Intra-abdominal infection
Anaphylaxis	Lumbar spine fracture
Burns	Malignancy
Cardiogenic shock	Neurogenic shock
Chest injury/pneumothorax	Radiation sickness
Chest pain/angina	Seizure
Choking/obstructed airway	Sepsis
Compartment syndrome	Shoulder dislocation
Decompression sickness	Skin laceration
Elbow dislocation	Smoke inhalation
Eye chemical burn	Stroke
Eye penetration (foreign body)	Sudden cardiac arrest
Head injury	Surgical treatment
Hip/lower extremity fracture	Toxic exposure
Hypovolemic shock	Upper extremity fracture

the highest likelihood of negatively impacting overall crew wellness and mission success. Qualitative analysis of facilitated discussions added context and regarding the factors influencing medical event management in space and identification of the critical behaviors necessary to mitigate these events.

Results

A total of 28 SMEs were recruited for the consensus meeting. Eight were female (28.6%) and 20 (71.4%) were male. The majority were from academic settings ($n = 18$; 64.3%), followed by government ($n = 7$; 25.0%) and private industry ($n = 3$; 10.7%). Twenty-three of the 28 SMEs completed the online survey (82.1%). Thirteen respondents (56.5%) selected that they had expertise in medicine, 13 (56.5%) in simulation, nine (39.1%) in space, nine (39.1%) in Human Factors, and five (21.7%) in psychology. Four respondents (17.4%) chose that they had other expertise, with one response each for nursing, training, bioethics, and planetary geology. SMEs could select multiple areas of expertise. We present the results according to study aims to rank potential medical events for (1) survivability, (2) mission impact, and (3) role of specific crewmember NTSs on outcomes.

(1) Survivability: The top three medical events with the highest median likelihood of survival were identified as shoulder dislocation (99.0% likelihood of survival), skin laceration (98.5%), and upper extremity fracture (97.0%). Cardiogenic shock (8.0%), sudden cardiac arrest (14.5%), and neurogenic shock (14.5%) were rated as least likely to be survived (Fig. 3).

(2) Mission impact: The conditions determined to have the greatest negative impact on mission success were sudden cardiac arrest (88.0%), sepsis (89.0%), and cardiogenic shock (91.5%). The conditions determined to have the least negative impact on mission success were skin laceration (10.5%), upper extremity fracture (58.0%), and choking/obstructed airway (59.0%) (Fig. 4).

(iii) Crewmember NTSs: Choking/obstructed airway (88.0%), sudden cardiac arrest (87.0%), and chest injury/pneumothorax (79.5%) were rated as the top three conditions, respectively, where excellent NTS could have a significant impact on the outcome. The three conditions where crew NTS were rated to have the least impact were skin

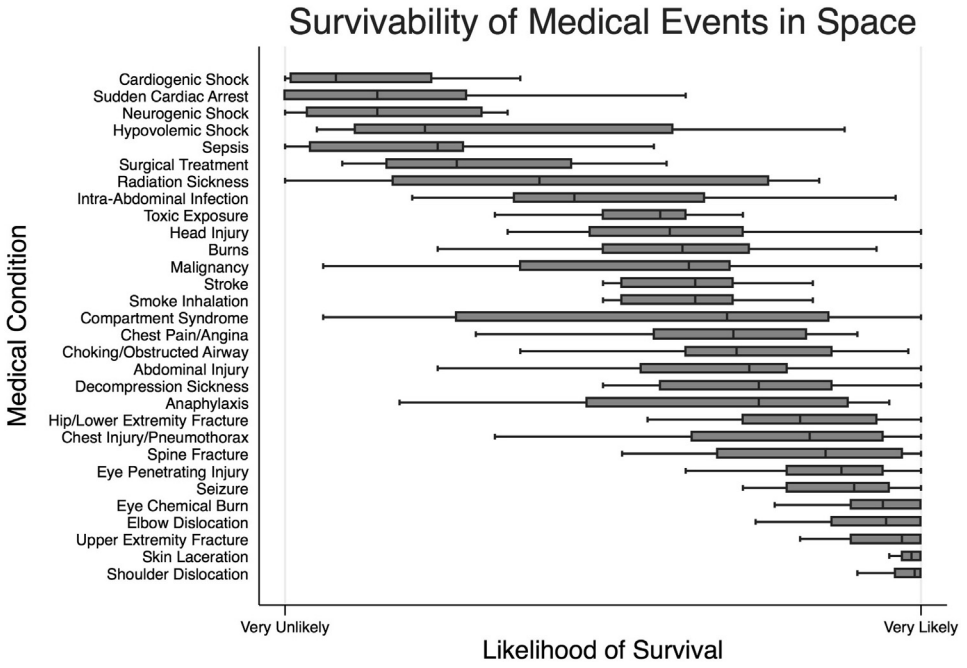

Fig. 3 – Survivability of 30 likely medical events in space. Boxes represent interquartile range, with median designated by a vertical line.

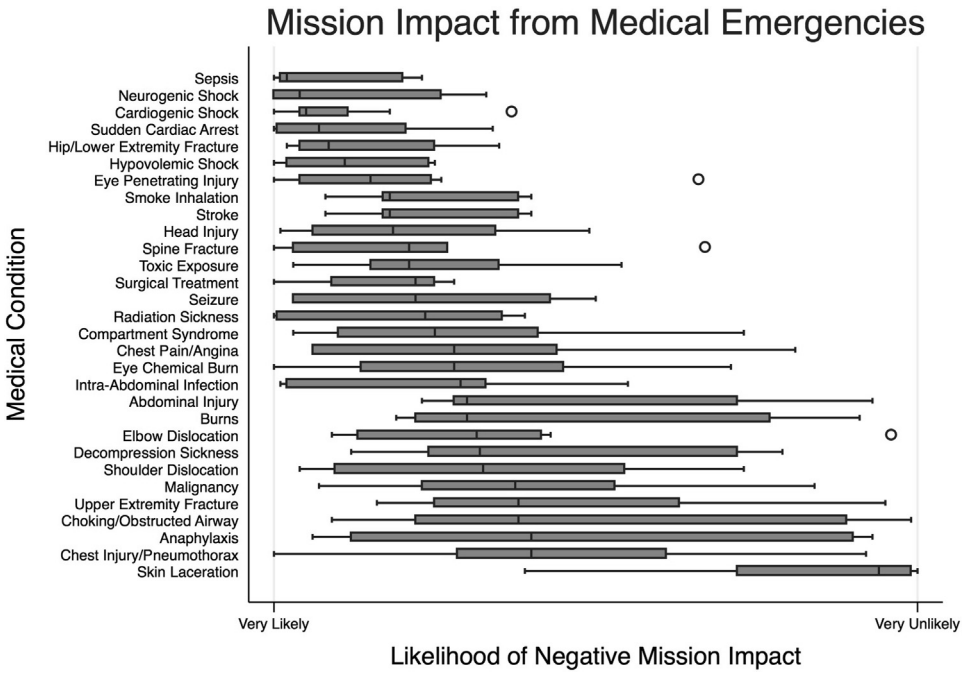

Fig. 4 – Mission impact of 30 likely medical events in space. Boxes represent interquartile range, with median designated by a vertical line.

laceration (42.0%), radiation sickness (54.5%), and abdominal injury (62.0%) (Fig. 5).

Using the data from the questionnaires, median scores for likelihood of negative mission impact and the impact of NTSs on their management were calculated for each of the 30 medical events based on the ratings of the entire expect panel. Discussions in breakout groups throughout the 2-d meeting with SMEs were used to clarify and confirm the data and rankings for each of the medical events. The results for each measure were then stratified into quartiles and placed into a risk matrix (Fig. 6). The red and yellow areas of the matrix

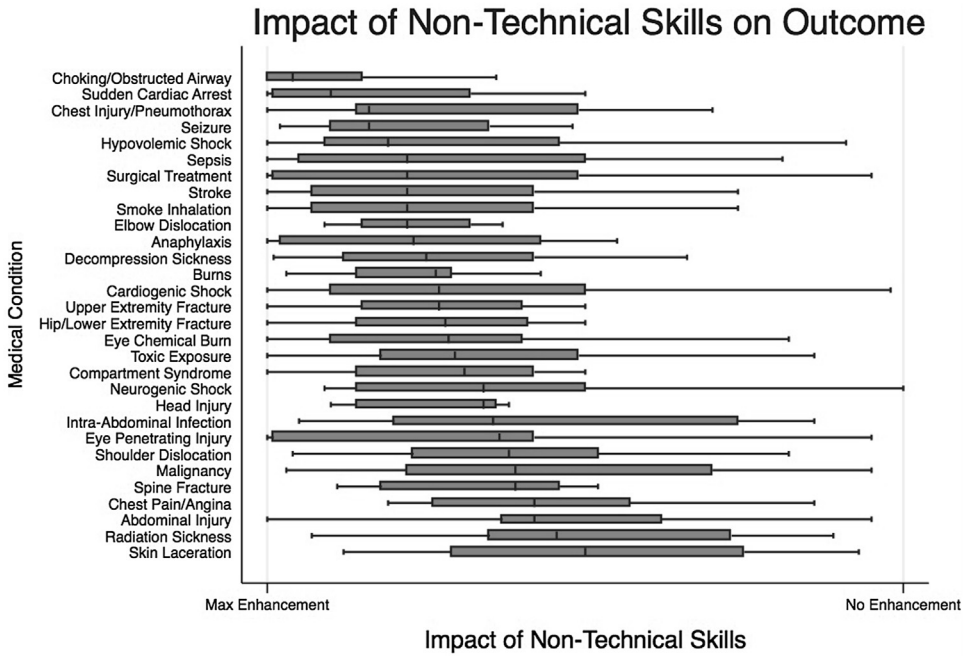

Fig. 5 – Role of nontechnical skills in effective management of 30 likely medical events in space. Boxes represent interquartile range, with median designated by a vertical line.

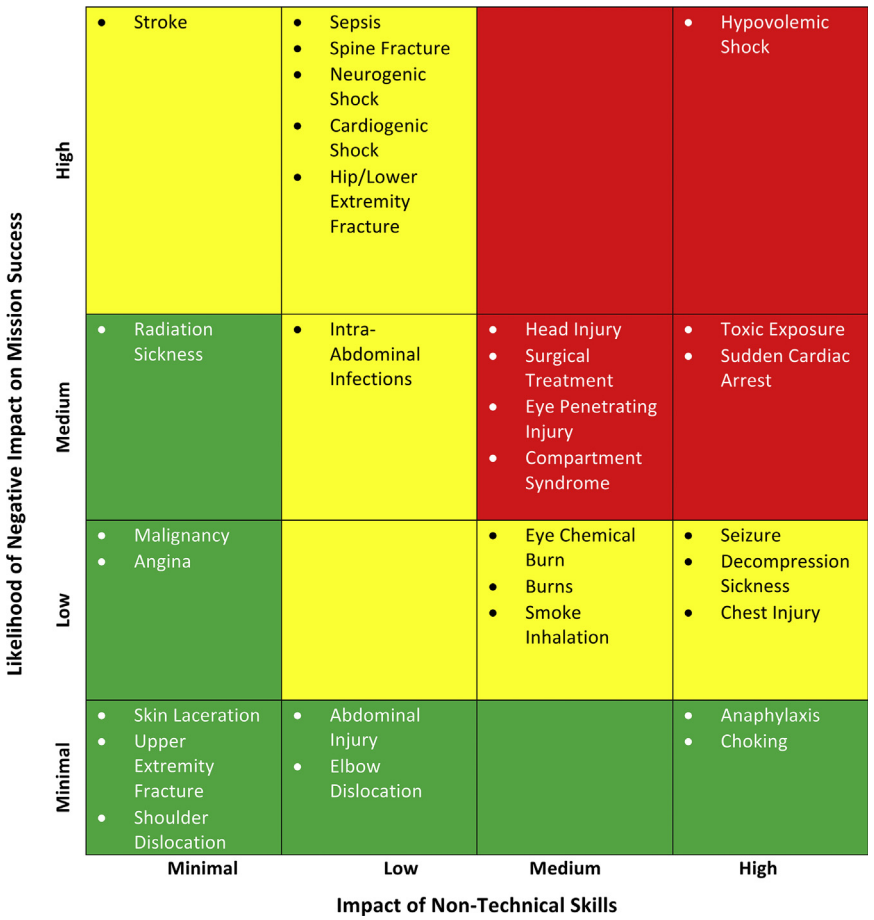

Fig. 6 – Risk matrix of 30 medical emergencies broken into quartiles for likelihood of negative impact on mission success and impact of nontechnical skills on the outcome. Areas shaded yellow and red are those where there is the highest likelihood for mission impact and where good nontechnical skills could make a difference in the outcome. (Color version of figure is available online.)

highlight events where a combination of effective crew NTS during medical event management could avoid a potentially devastating impact on mission success. Analyzed survey data were presented on the first day of the panel meeting. After presentation, SMEs engaged in discussions to come to a consensus on the top conditions to provide training in NTSs for astronaut crews. Four breakout groups were asked to consider both the individual aspects of each potential condition, as well as how it fit within the larger set of conditions chosen. Each group was asked to come to a consensus on the top conditions that together would represent a range of crew coordination, mission control interaction, urgency, and survivability. The breakout groups used data from the questionnaires, large group discussions during presentation of data, risk matrix, and prior knowledge of past medical events in space and space-analog settings to come to a consensus on the top conditions that would represent desirable variability around issues of crew coordination, need for interaction with mission control, urgency, and survivability.

The panel's selected medical events that provided for a range of options representing both ends of the spectrum for each of the previously stated categories. This consensus discussion identified sudden cardiac arrest, toxic exposure, smoke inhalation, penetrating eye injury, and seizure as key conditions to focus on to develop training programs and countermeasures. These acute medical events are broadly classified in two ways:

- Single crew member affected (sudden cardiac arrest, penetrating eye injury, seizure)
- Multiple crewmembers affected (toxic exposure, smoke inhalation)

In addition, toxic exposure, smoke inhalation, and penetrating eye injury require concurrent management of the medical event and nonmedial operations to contain an ongoing technical emergency that may affect mission success. The reasons for the selection of these specific conditions included variations in the severity, immediacy, number of crew lives in danger, length of concern, and required medical knowledge.

Once the SMEs selected targeted medical conditions, breakout sessions and large group discussions at the meeting focused on NTS behaviors that SMEs re-recognized as essential to providing medical care in space during an acute situation. These discussions, as well as continued consensus

Table 2 – Identified nontechnical skill behaviors mapped to selected medical events.

Medical event			
Cardiac arrhythmia	Eye injury	Pneumothorax	Toxic exposure
• Gathering information • Recognizing that something is wrong • Providing situation assessment updates • Communicating with mission control center • Calling for health • Sharing mental models • Deploying checklists • Using closed-loop communication • Transitioning leadership	• Gathering information • Recognizing that something is wrong • Providing situation assessment updates • Calling for health • Sharing mental models • Managing competing priorities	• Gathering information • Recognizing that something is wrong • Providing situation assessment updates • Communicating with mission control center • Involving others in decision making • Calling for help • Using closed-loop communication • Dealing with diagnosis uncertainty	• Gathering information • Recognizing that something is wrong • Providing situation assessment updates • Communicating with mission control center • Regulating stress and emotional responses • Reconciling patient *versus* mission goals • Sharing mental models • Handling role conflict • Managing competing priorities

gathering discussions via electronic communication after the meeting, identified a list of key behaviors to include in scenarios. These included information exchange, supporting and followership behaviors, communication delivery, leadership, and followership. Behaviors were mapped to the medical events previously selected to ensure that the selected scenarios provided opportunities for demonstrating all of the identified NTSs (Table 2).

Discussion

Main findings

Medical events represent a serious threat to crew well-being and survival, as well as to mission success during LDEMs. In this study, a panel of SMEs rated survivability, mission impact, and role of crew NTSs in management of 30 potential in-flight medical events. We were able to successfully rank the events according to these criteria, leveraging the considerable variability in ratings for survivability, mission impact, and role of NTS management between experts.

Much of the variability in ratings was driven largely by the actual range of potential severity around each event. For example, hip/lower extremity fracture could range from stress fractures to crush injuries,[13] with resulting variability in estimations of survivability and mission impact. We also found that events thought not to be life-threatening in terrestrial settings could pose serious risks to mission success (e.g., upper extremity fracture, eye injury). Other variables, including time to diagnosis and availability of medical supplies (significantly different in spaceflight compared with terrestrial medical settings) also influenced the ratings. In addition, there is no current policy on the equipment that will be available to crew during an LDEM or what the number or makeup of the crew will likely be, including whether a physician will be onboard. Despite this variability, we were able to differentiate between events based on severity and identify a subset of medical events that represent a serious threat to overall crew cohesion, health and safety, as well as to the continued success of the mission. Many of these conditions and the postulated outcomes in space have been discussed in prior literature.[5,6,18]

Based on this analysis, we were able to identify a subset of events including sudden cardiac arrest, toxic exposure, smoke inhalation, eye penetrating injury, and seizure where survivability and impact on mission could be significantly improved by effective NTSs of the crewmembers. Of the 30 events rated by the expert panel, hypovolemic shock, head injury, surgical treatment, penetrating eye injury, compartment syndrome, toxic exposure, and sudden cardiac arrest fell into the red area of the matrix, indicating that they would present a serious threat to the success of the mission, and furthermore that the result of each event could be positively impacted by excellent NTS performance by the crewmembers.

The present study was able to categorize events based on the likelihood of mission impact and potential impact of crew's NTS to develop a risk matrix. The subset of medical conditions chosen by the SMEs includes conditions from both the red and yellow sections of the risk matrix. For conditions representing both the greatest threat and potential for countermeasure development (in the red area of the matrix), SMEs identified penetrating eye injury, toxic exposure, pneumothorax, and sudden cardiac arrest as exemplary events representing a range of severity. Four other conditions (hypovolemic shock, head injury, surgical treatment, and compartment syndrome) are also found in this area of the matrix. However, some of these conditions, such as surgical treatment, require a skill level that will likely be beyond that of a standard spaceflight crew. Other conditions, such as hypovolemic shock, are likely to exhaust resources with little chance of survival. As such, these conditions were felt by the SMEs to be less critical for astronaut crew training. The events identified represent a desirable diversity in severity, immediacy, crew danger, number of crew affected, and coordination with mission control. Sudden cardiac arrest, penetrating eye injury, and chest injury/pneumothorax each represent a circumstance in which one crewmember is affected. There are already cardiac arrest protocols in place, but performing cardiopulmonary resuscitation in limited gravity conditions is

challenging. Penetrating eye injury presents dangers both to the crewmember affected and to first responders because of the potential for floating debris. Identifying and resolving pneumothorax with needle decompression requires heightened situation awareness and decisiveness. Similar to out of hospital emergency situations experienced by fire ground commanders and mass casualty events, space crews will be required to handle both the injured crewmember and potential ongoing safety threats (e.g., fire, floating debris) to prevent further casualties. Toxic exposure and smoke inhalation represent emergent situations that require leadership "trade-off" decisions to prioritize care for sick individuals and essential technical tasks to protect the integrity of the spacecraft and mission. The chosen events align with the red or yellow highlighted section on the risk matrix and therefore are prime candidates for protocol development that will reduce the risk of these events affecting mission success according to NASA. As crewmembers on LDEMs may have limited medical knowledge and because there will be limited onboard resources and an inability to return to Earth ahead of schedule, training for medical events will be an essential part of mission preparation. Although previous research has characterized the risk of a medical event and the probability of various conditions occurring during spaceflight,[5] to our knowledge, no studies have yet identified a subset of conditions that would allow generalizable training in skills necessary to manage unforeseen medical events. Given limited training time and competing demands, the identification of a small but optimized set of scenarios is helpful to ensure maximum benefit for a medical NTS training program.

We also identified a subset of associated crew behaviors to guide the identification of training priorities. Identified behaviors included information exchange, supporting and followership behaviors, communication delivery, leadership, and followership. Mapping these behaviors to each of the identified medical events allowed us to confirm that the medical events selected by SMEs would provide training scenarios that encompassed the most critical NTSs. As excellent NTSs of in-flight crews may improve survivability and limit mission impact during an acute event, targeting training programs before missions to allow for practice and refinement of these skills is key to ensuring that astronauts are prepared for the serious but unlikely risk of a medical event during a mission. Understanding the shared features of these conditions allowed us to investigate management of medical events to create a focused list of medical conditions that would represent variability in the severity and approach by the team of astronauts. The results of this study extend current knowledge by creating an understanding of the shared features of these conditions to create a focused list of medical conditions on which to base a robust training curriculum in space medicine.

Strengths and limitations

As with any applied medical study, we identified a number of limitations. There was the considerable variability in ratings within each of the medical conditions. At the 2-d panel meeting, we were able to elicit some of the reasons for the range, which was largely driven by the potential variation in severity. The manner in which individual panelists viewed these conditions resulted in variability in estimations of survivability and mission impact. However, panel members were selected to represent a diverse number of governmental, academic, and research organizations with varied educational and experiential backgrounds. The range of expertise and experience, as well as the level of on-going commitment, which we were able to harness to conduct this program of research greatly contributed to the success of the rating process. This created a rich discussion that provided more insight into the topic than could have been gained through single discipline groups of engineers or clinicians. In addition, combining individual questionnaire and group discussions allowed us to "sense check" key findings and ensure the research met the needs of the population of astronauts and space medicine community.

Other variables, including time to diagnosis and availability of medical supplies, also influenced the ratings. As there is currently no consensus on the medical supplies that will be available during an LDEM or the professional makeup of the crew, SMEs found it difficult to determine whether a given condition would be diagnosable or treatable using the onboard resources. However, basing data collection on the Space Medicine Exploration Medical Conditions List, a validated list of potential medical conditions in space, with NASA definitions was a strength of this study.

Conclusion

The success of the next phase of space exploration is dependent on the ability of training programs to prepare crews to manage a range of events, medical and technical, which may occur during spaceflight. LDEMs will require crewmembers to be more autonomous than on previous missions, making the development of countermeasures to allow for crewmembers to mitigate the effects of in-flight medical events essential to both survival and mission success. In this study, we ranked for the first time probable in-flight medical events that may jeopardize LDEMs and identified specific crew behaviors that may mitigate the consequences of unanticipated medical events in space. This new knowledge is the first step in creating successful countermeasures in the form of training programs to prepare astronauts to manage medical events on LDEMs, increasing crew safety and improving the likelihood of success of the first crewed missions to Mars over the next 20 y. As the potential risks of in-flight medical events to both the well-being of the crew and to the success of the mission are high, identifying ways to mitigate those threats and prepare crews to handle these high stress situations is essential.

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Authors' contributions: This study was conceived and designed by S.Y., D.M.M., T.E.D., and J.M.R. The data were analyzed by J.M.R., D.M.M., S.R.L., and S.Y. The first draft of the manuscript was prepared by J.M.R. and S.Y., which was then edited by D.S.S., R.D.D., A.G., C.N.P., and T.M. All authors provided critically important intellectual content for the revision of the manuscript. All authors gave final approval of the version to be published and have contributed to the manuscript. J.M.R. and S.Y. are guarantors.

Disclosure

All authors have completed the ICMJE uniform disclosure form at www.icmje.org/coi_disclosure.pdf and declare: Dr Musson reports personal fees from The Canadian Space Agency, outside the submitted work. All other authors declare no undeclared support from any organization for the submitted work, no financial relationships with any organizations that might have an interest in the submitted work in the previous 3 y, and no other relationships or activities that could appear to have influenced the submitted work.

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