# Prototype Development of a Tradespace Analysis Tool for Spaceflight Medical Resources

Erik L. Antonsen; Robert A. Mulcahy; David Rubin; Rebecca S. Blue; Michael A. Canga; Ronak Shah

**INTRODUCTION:** The provision of medical care in exploration-class spaceflight is limited by mass, volume, and power constraints, as well as limitations of available skillsets of crewmembers. A quantitative means of exploring the risks and benefits of inclusion or exclusion of onboard medical capabilities may help to inform the development of an appropriate medical system. A pilot project was designed to demonstrate the utility of an early tradespace analysis tool for identifying high-priority resources geared toward properly equipping an exploration mission medical system.

**METHODS:** Physician subject matter experts identified resources, tools, and skillsets required, as well as associated criticality scores of the same, to meet terrestrial, U.S.-specific ideal medical solutions for conditions concerning for exploration-class spaceflight. A database of diagnostic and treatment actions and resources was created based on this input and weighed against the probabilities of mission-specific medical events to help identify common and critical elements needed in a future exploration medical capability.

**RESULTS:** Analysis of repository data demonstrates the utility of a quantitative method of comparing various medical resources and skillsets for future missions. Directed database queries can provide detailed comparative estimates concerning likelihood of resource utilization within a given mission and the weighted utility of tangible and intangible resources.

**DISCUSSION:** This prototype tool demonstrates one quantitative approach to the complex needs and limitations of an exploration medical system. While this early version identified areas for refinement in future version development, more robust analysis tools may help to inform the development of a comprehensive medical system for future exploration missions.

**KEYWORDS:** medical capability, exploration spaceflight, prototype, quantitative analysis.

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The risk of significant medical events and the inability to effectively manage clinical sequelae of such events represents a potentially serious limitation to human spaceflight, especially for exploration missions that will leave the relative safety of near-Earth operations. Current human spaceflight experience is measured in a time scale of months, with the longest missions to date having lasted for just over 1 yr.[6] The timeframe of future human spaceflight missions, potentially spanning many years, introduces higher risk to the crew and mission and increases medical operational needs.[2,7] Travel to increasing distances from the Earth will limit or eliminate evacuation capabilities, leaving a crew with only onboard resources and skills and limited communication with ground resources to address all health-related concerns that arise.[2,4,7] Limitations on vehicle design, including restrictions of volume, mass, and power, and of training time dedicated to medical capability will further affect the health maintenance and response capabilities that are available to crews.[7] In order to appropriately provide medical capabilities to minimize the risks of the crew, we must consider the following: first, what medical conditions are likely to occur on such a mission, and how often might they occur? Second, what would a physician want to be available, in both resources and skillset, to diagnose and treat the most likely and serious conditions?

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From the NASA Johnson Space Center, Houston, TX; the Department of Emergency Medicine and Center for Space Medicine, Baylor College of Medicine, Houston, TX; the Department of Preventive Medicine and Community Health, University of Texas Medical Branch, Galveston, TX; KBRwyle, Inc., Houston, TX; and GeoControl Systems, Inc., Houston, TX.

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Address correspondence to: Rebecca S. Blue, M.D., M.P.H., GeoControl, Inc., 2400 E. NASA Pkwy., Houston, TX; rblue.md@gmail.com.

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Accumulated records from prior human spaceflight provide some understanding of the types and frequency of medical events experienced in low Earth orbit (LEO) and, though experience is limited, during more distant lunar transit missions.[3,10,11] Using this historical precedence, NASA developed the Integrated Medical Model (IMM), a predictive mathematical tool designed to assess the risk of future medical events during spaceflight.[1,5,8] The IMM uses a probabilistic risk assessment approach via Monte Carlo simulation (mathematical modeling by probability distribution), drawing input from historical medical events during human spaceflight and analog sources to better understand potential medical risks for future crews.[8,9,13] The list of medical conditions considered within the model, known as the Integrated Medical Exploration Database (iMED), includes medical conditions identified by subject matter experts, further defined by each condition's best and worst case scenarios, and accepted by NASA as particularly concerning, due to incidence or severity, for long-duration spaceflight (**Table I**).[5,12]

**Table I.** Medical Conditions Included in the iMED.

| **ENVIRONMENTAL** |
|---|
| Acute Radiation Syndrome |
| Altitude Sickness |
| Barotrauma (ear/sinus block) |
| Burns secondary to Fire |
| Decompression Sickness Secondary to EVA |
| Eye Chemical Burn |
| Headache ($CO_2$ induced) |
| Smoke Inhalation |
| Toxic Exposure: Ammonia |
| **INJURY/TRAUMA** |
| Abdominal Injury |
| Acute Compartment Syndrome |
| Ankle Sprain/Strain |
| Back Sprain/Strain |
| Chest Injury |
| Dental: Avulsion (tooth loss) |
| Elbow Dislocation |
| Elbow Sprain/Strain |
| Eye Irritation/Abrasion |
| Eye Penetration (foreign body) |
| Finger Dislocation |
| Fingernail Delamination Secondary to EVA |
| Head Injury |
| Hip Sprain/Strain |
| Hip/Proximal Femur Fracture |
| Knee Sprain/Strain |
| Lower Extremity (LE) Stress Fracture |
| Lumbar Spine Fracture |
| Neck Sprain/Strain |
| Neurogenic Shock |
| Paresthesias Secondary to EVA |
| Shoulder Dislocation |
| Shoulder Sprain/Strain |
| Skin Abrasion |
| Skin Laceration |
| Traumatic Hypovolemic Shock |
| Wrist Fracture |
| Wrist Sprain/Strain |
| **MEDICAL ILLNESS** |
| Abdominal Wall Hernia |
| Abnormal Uterine Bleeding |
| Acute Angle-Closure Glaucoma |
| Acute Arthritis |
| Acute Cholecystitis/Biliary Colic |
| Acute Diverticulitis |
| Acute Pancreatitis |
| Acute Prostatitis |
| Acute Sinusitis |
| Allergic Reaction (mild to moderate) |
| Anaphylaxis |
| Angina/Myocardial Infarction |
| **MEDICAL ILLNESS (CONTINUED)** |
| Anxiety |
| Appendicitis |
| Atrial Fibrillation/Atrial Flutter |
| Back Pain (space adaptation) |
| Behavioral Emergency |
| Cardiogenic Shock Secondary to Myocardial infarction |
| Choking/Obstructed Airway |
| Constipation (space adaptation) |
| Dental: Exposed Pulp |
| Dental Caries |
| Dental: Abscess |
| Dental: Crown Loss |
| Dental: Filling Loss |
| Depression |
| Diarrhea |
| Eye Corneal Ulcer |
| Eye Infection |
| Gastroenteritis |
| Headache (late) |
| Headache (space adaptation) |
| Hearing Loss |
| Hemorrhoids |
| Herpes Zoster Reactivation (shingles) |
| Hypertension |
| Indigestion |
| Influenza |
| Insomnia (space adaptation) |
| Medication Overdose/Adverse Reaction |
| Mouth Ulcer |
| Nasal Congestion (space adaptation) |
| Nephrolithiasis |
| Nose bleed (space adaptation) |
| Otitis Externa |
| Otitis Media |
| Pharyngitis |
| Respiratory Infection |
| Retinal Detachment |
| Seizures |
| Sepsis |
| Skin Infection |
| Skin Rash |
| Sleep Disorder |
| Small Bowel Obstruction |
| Space Motion Sickness (space adaptation) |
| Stroke (Cerebrovascular Accident) |
| Sudden Cardiac Arrest |
| Urinary Incontinence (space adaption) |
| Urinary Retention (space adaptation) |
| Urinary Tract Infection |
| Vaginal Yeast Infection |
| Visual Impairment and Increased Intracranial Pressure (VIIIP) (space adaptation) |

Of note, the Integrated Medical Exploration Database (iMED) was established for use in populating the Integrated Medical Model (IMM) and was not altered or further defined for use in the Medical Optimization Network for Space Telemedicine Resources (MONSTR) project.

EVA: extravehicular activity.

The IMM provides an understanding of medical risk and subsequent impact to both the crew and mission, but adjusts the predicted risk based on the availability of medical interventions, providing some estimation of baseline medical needs for future missions.[8,9,13] However, the IMM is limited by the assumptions and framework of the model. For example, the IMM incorporates only resources available in the medical kit currently onboard the International Space Station (ISS) and currently evaluates risk of medical events as though all potential events occurred on the first day of flight. While future versions of the model will address some of these limitations, the IMM, in its current form, is uniquely suited to help inform current operations in LEO. This limits its applicability to non-ISS, exploration-class missions outside of LEO or supported by alternative or additional medical resources. Despite these limitations, the IMM is currently the most robust modeling framework available to address predictive medical risk in spaceflight.

In addition to risk prediction tools, there is a need for a medical system designed specifically for exploration missions with appropriately targeted resources and crew capabilities. However, it is difficult to identify the ideal resources and training needed by exploration crews for appropriate response in the case of a medical event outside of LEO. A quantitative approach to this problem requires, first, defining an ideal set of terrestrial capabilities that would enable optimal physician management, to which mission planners and medical system architects can aspire, and, second, identifying the capabilities that would be required to meet such a standard. While the immaturity of exploration mission design limits these efforts, the NASA Human Research Program Exploration Medical Capability Element sought to develop an early pilot application designed to identify ideal onboard medical capabilities to support the health and wellbeing of the crew within an exploration medical context. This led to the creation of a repository of capabilities addressing the conditions identified in the iMED with a searchable architecture designed to help identify most commonly and most critically needed elements of a future exploration medical capability.

## METHODS

A pilot effort, entitled the "Medical Optimization Network for Space Telemedicine Resources" (MONSTR), was developed to catalog diagnostic and treatment resources required to address conditions identified in the iMED and to provide a framework for the weighting of resources by relative importance. The project was developed in the context of the iMED and IMM using the IMM's predictive model to provide estimations of the probability of occurrence and severity of various medical conditions during a crewed mission of 2.5 yr. For each medical condition in the iMED, we identified the requisite components of medical care to meet an idealized terrestrial capability. These include Prevention/Screening, Diagnosis, Treatment, and Long-Term Management. Only Diagnosis and Treatment components were explored as part of this pilot project. Here, Diagnosis is defined as the ability to determine which condition has occurred, differentiate clinical presentation from other conditions, and identify the severity (with a bimodal designator, defined by the IMM, of Best or Worst Case) of the condition. Treatment is here defined as any intervention designed to either monitor or mitigate the condition; this component is further delineated by treatment of either the Best or Worst Case of a given condition. Definitions for model terminology are provided in **Table II**.

Five physician subject matter experts were selected for their qualifications based upon medical training and board certification in the specialties of Aerospace Medicine, Emergency Medicine, Internal Medicine, Family Medicine, and Physical Medicine and Rehabilitation, as well as their familiarity and experience in operational aerospace medicine practice and the exploration mission concept. For each medical care Capability (Diagnosis: Best Case, Diagnosis: Worst Case, Treatment: Best Case, Treatment: Worst Case) identified, Actions (procedures or tasks to be performed by a caregiver) required to implement the Capability, either in Diagnosis or Treatment of the Best or Worst Case, were defined by subject matter expert consensus. Subject matter experts were explicitly directed to base decisions on an estimation of the expectation of a high-quality terrestrial tertiary care capability within the context of the U.S. healthcare system. For each Action, experts then identified Resources (assets defined as tangible, such as hardware or pharmaceuticals, or intangible, such as skillsets, training, and support) required to perform the Action. All Capability, Action, and Resource data were entered into the MONSTR database.

**Table II.** Model Definitions for Condition-Related Terminology.

| TERM | MODEL DEFINITION |
|---|---|
| Condition: Best Case | All interventions and treatments are successful and the patient recovers in the best manner possible. |
| Condition: Worst Case | The condition is complicated by poor response to treatment and failed interventions. |
| Diagnosis: Best Case | All interventions required to Diagnose the Best Case of a given condition |
| Diagnosis: Worst Case | All interventions required to Diagnose the Worst Case of a given condition |
| Treatment: Best Case | All interventions required to Treat the Best Case of a given condition |
| Treatment: Worst Case | All interventions required to Treat the Worst Case of a given condition |
| Capability | All Diagnosis and Treatment medical care interventions (individually associated with Diagnosis Best Case, Diagnosis Worst Case, Treatment Best Case, and Treatment Worst Case conditions) |
| Action | Procedures or tasks to be performed by a caregiver to Diagnose or Treat a given condition (Best or Worst Case) |
| Resource | Assets defined as tangible, such as hardware or pharmaceuticals, or intangible, such as skillsets, training, and support, needed to perform Actions to Diagnose or Treat a given condition. |

Following population of all data elements into the database, a scoring scheme was instituted to help prioritize Actions and Resources associated with each medical condition. The physician subject matter experts ranked the medical criticality of each Action and Resource on an ordinal scale of 0–3, where medical criticality was defined as the physician's estimate of impact on the Diagnosis or Treatment of the condition, ranging from entirely unnecessary to critical (where the lack of the Action or Resource would render the condition untreatable). **Table III** provides an example of the scoring approach for Resources. Finally, the IMM was used to generate incidence rate estimates for each of the possible medical conditions established by the iMED.

As Actions and Resources are scored on the same ordinal 0–3 scale, it was likely that many different Actions or Resources would have identical scores despite intuitive differences in the overall clinical utility of each. There was consideration given to the issue of comparing Resources across different Actions and across all Capabilities—for example, how might we compare 1) a noncritical Resource that might be desired (though not required) to complete a critical Action for one Capability to 2) a critical Resource required to complete a noncritical Action in another Capability? In this case, Resource and associated Action scores were used in conjunction to provide a composite criticality score for each Resource-Action pairing. This composite criticality score was a product of the Action score and the Resource score in question as demonstrated in **Table IV**.

**Table III.** Scoring Definitions for Resources Identified for Diagnosis or Treatment of Various Conditions.

| SCORE | DEFINITION |
|---|---|
| 0 | Resource is irrelevant to Diagnosis or Treatment |
| 1 | Helpful but noncritical Resource |
| 2 | Highly desirable Resource, could be excluded with detriment to Diagnostic or Treatment capabilities |
| 3 | Critical Resource that, if excluded, would dictate that the condition in question would be undiagnosed or untreatabl.e |

**Table IV.** Criticality Score Calculations for Associated Actions and Resources.

| | RESOURCE SCORE | | |
|---|---|---|---|
| **ACTION SCORE** | **1** | **2** | **3** |
| **1** | 1 | 2 | 3 |
| **2** | 2 | 4 | 6 |
| **3** | 3 | 6 | 9 |

"Aggregate criticality" was defined as the sum, across all 100 medical conditions, of the criticality of all Resources and Actions as applied to Diagnosis of the condition as well as the Best or Worst Case Treatment scenarios. "Aggregate weighted criticality" merged the product of the aggregate criticality and the condition probability of occurrence as identified by the IMM across all 100 conditions. This formula allowed for a logical, if simple, mathematical comparison of desired Actions and Resources, as well as the ability to compare the relative need for various Resources and Actions across conditions.

Following development of a comprehensive database of Best and Worst Case conditions, Capabilities, Actions, and Resources, incidence rate estimates, and criticality scores, analysis and visualization software was sourced to visualize and present Resource and Action needs, as well as identifying limitations of medical Capabilities subsequent to exclusion of any Actions or Resources. Final outputs were generated using Tableau$^{TM}$ software.

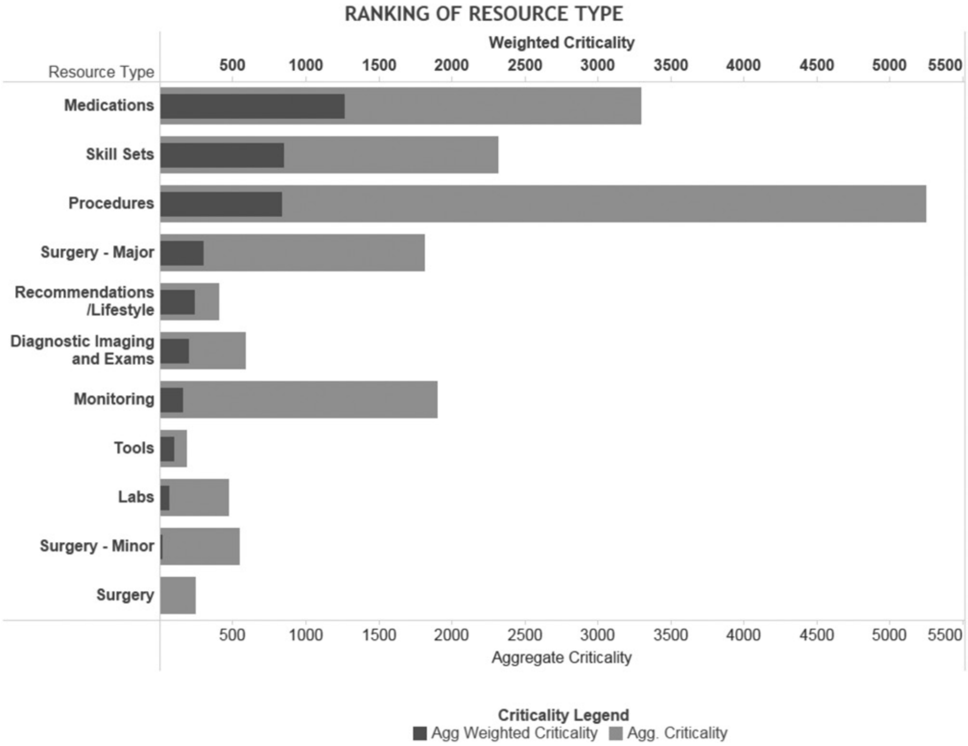

**Fig. 1.** Sample output of weighted medical capability categories for a Mars transit mission (duration 2.5 yr). Light bars indicate aggregate criticality scores; darker bars indicate weighted scoring of Action and Resource criticalities. Note the variability between weighted and unweighted criticalities. The unweighted criticalities highlight the overall frequency that the capability is desired, where the weighted criticalities provide some indication of the necessity of the capability to treat a specific condition.

## RESULTS

The subject matter expert inputs to the application resulted in a database of Capabilities, Actions, and Resources for medical response based on terrestrial standards. This database was then populated by criticality scores and data regarding probability of occurrence of each condition. Application outputs were generated to present the relative utility of tangible and intangible inclusions in a medical system. Specific outputs were generated for demonstration purposes, visually displaying the relative need for various Actions and Resources as identified by the MONSTR database. Example outputs are provided for consideration (See **Fig. 1**, **Fig. 2**, and **Fig. 3**).

## DISCUSSION

The pilot project demonstrated an ability to generate outputs for comparison of the weighting of Actions and Resources needed for the management of the Capabilities defined. At a superficial level, the MONSTR tool generates a simplified comparison of the relative need for various Actions and Resources for the management of in-flight medical conditions. In this regard, the project was successful.

As with any demonstration of early or pilot capability, there are multiple limitations to the application as presented. First, MONSTR is designed as a tradespace analysis tool, to help prioritize research investment and medical resource inclusion by identifying the most flexible and intersecting elements that will maximize exploration medical capability available to a crew while minimizing mass, volume, and crew burden. As the MONSTR database is based on terrestrial medical capabilities, subject matter expertise is required to interpret and apply the output in the context of spaceflight applications. This database is not designed to be used without this critical interpretation. Even superficial scrutiny demonstrates a disconnect between relative ranking of some Actions and Resources as provided by the application and the true value of such assets based on actual clinical and spaceflight experience. For example, the Action of "Major Surgery" received a weighted score greater than that of "Monitoring" or "Laboratory" Resources (see Fig. 1). In reality, major surgical interventions are

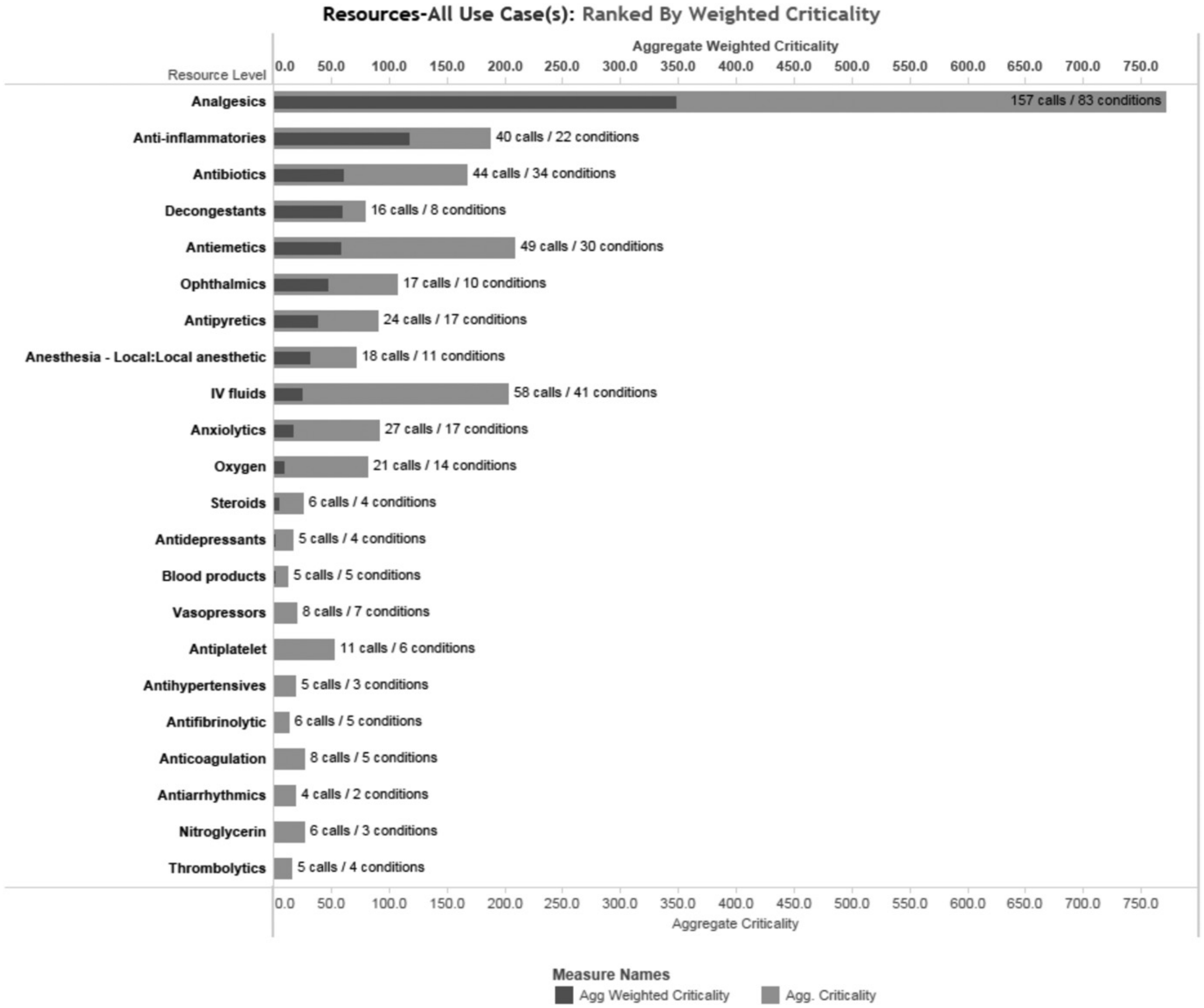

**Fig. 2.** Sample output of relative tangible asset utility. Results presented are specific to pharmaceutical resources. Light bars indicate aggregate criticality scores; darker bars indicate weighted scoring of Action and Resource criticalities. Here, note the specific case of intravenous fluids: the weighted criticality for fluids for any given condition is not necessarily as high as other medication criticalities, but note that the overall need for onboard intravenous fluid capability is higher, as represented by the unweighted call for fluid resources in multiple conditions.

unlikely to be successful without a means of monitoring patient hemodynamics and laboratory values are generally used to guide treatment parameters, including indications for, and evaluation of outcome following, any surgical intervention. Further, the inclusion of a surgical capability onboard an exploration vehicle would necessitate dedication of significant mass, volume, power, and technological resources, as well as crew time dedicated for training, and the tradeoffs for such a capability would likely render a mission unachievable. Thus, the relative scoring scale includes inadequacies that limit its application in its current form, as does the aspiration to an idealized terrestrial medical capability.

The MONSTR database uses a bimodal evaluation, defined by the iMED, of only Best and Worst Case scenarios for any given condition as well as defined and limited elements required for each scenario. In reality, the broad spectrum of condition manifestations may require a vast number of resources, skills, and capabilities for the diagnosis and treatment of an ill or injured crewmember. As a result, the Resources and Actions identified for inclusion for the Diagnosis or Treatment of a modeled medical event may be under- or over-estimated by this limited framework. Further, the database does not consider the relative severity of any given condition. For example, the MONSTR database does not have a means of capturing the intrinsic severity differences between a cardiac arrest and space motion sickness; while these two conditions are quite different regarding the likely prognosis of the afflicted crewmember, MONSTR, by design, treats both conditions equally with regards to scoring associated Actions and Resources for relative importance. This limitation was accepted for simplicity in the development of this pilot capability; in future versions, input from medical subject matter experts and bio-ethicists could

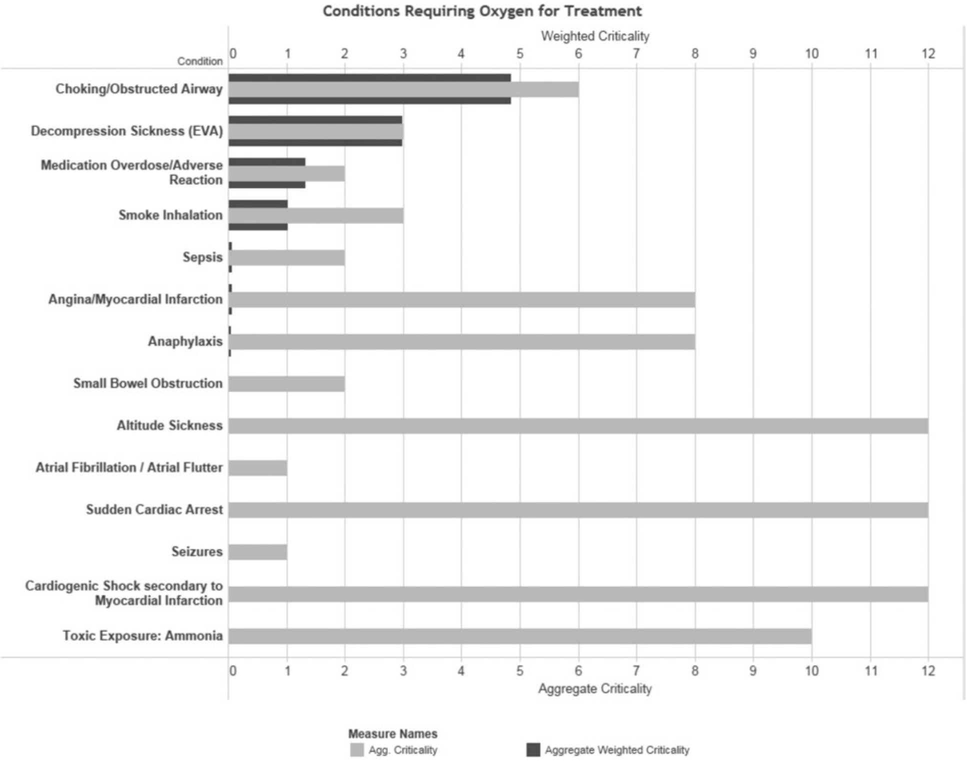

**Fig. 3.** Sample output of weighted utility of a single onboard resource (oxygen). Light bars indicate aggregate criticality scores; darker bars indicate weighted scoring of Action and Resource criticalities. Note a demonstration of the inadequacies of the scoring schemata: here, the Diagnosis of "Small Bowel Obstruction" appears to require significant oxygen resources, which is not particularly intuitive to clinical needs. This requirement in fact stems from the "Major Surgery" action required to treat the Worst Case scenario of Small Bowel Obstruction in the database, thus lending the higher criticality score for oxygen resources associated with surgical intervention.

help refine scoring schemata to provide improved indicators of relative importance for a given Resource or Action (or, potentially, in limiting heroic measures in conditions of likely poor prognostic outcome).

Similarly, the ordinal scoring approach for medical criticality was implemented to provide simplicity for the physicians providing input data, but became a source of inaccuracy. This approach, like the Best/Worst Case parameters and the inability to compare condition severity, introduced limitations into the application and should be changed in future versions to a more robust and iterative approach. As the lines delineating different levels of medical resource criticality are rarely as sharp as those defined in the application, a better approach could have been the use of a sliding scale or more complex modeling of relative need of a Resource, or allowance for potential substitution of other onboard assets in lieu of an unavailable Resource. Further, limiting application inputs to only a few expert opinions introduces inaccuracies related to the experiences, specializations, and clinical practices of the physicians included. Outsourcing for more robust input, inclusion of specialist opinions, and scoring based on a scale established upon more realistic parameters would improve the applicability and utility of this approach.

Finally, MONSTR is not designed for use as a dataset to support predictive medical algorithms, as inputs are based upon established medical conditions rather than symptomatology or practitioner skill. While MONSTR is designed to help identify Capabilities required for Diagnosis of various modeled medical conditions, it does not have any intrinsic diagnostic capability as a medical resource. In the development of this tool, the accepted paradigm was that an onboard practitioner could make use of all Resources and Actions listed in the database tool; in reality, diagnostic and treatment capabilities will be limited by the core medical knowledge, experience, and skill retention of the treating medical officer.

The limitations described highlight a need for a more robust approach for the inputting of database parameters, incorporation of expert medical opinion, and application of relative weighting schemata. While these limitations are extensive, they are not unexpected for an early prototype application. The approach presented here provides an early framework and potential approach for quantitative analysis and comparative evaluation of various factors that will impact a future medical system capability. Quantification of elements of a medical capability allows a focused discussion of the merits of research investments, particularly regarding the cost/benefit ratio of various resources and skills. At the same time, this method provides a tangible approach to trading system assets to optimize vehicle design across medical, engineering, and system needs. Further development of this approach and closer evaluation of comparative criticality of conditions, resources, and skillsets may help to inform the development of a robust and comprehensive medical system for enhanced crew protection in future exploration missions.

Finally, it is worth mentioning that true medical ingenuity often arises from situations of limited resources. Medical practitioners that find themselves in need of unavailable resources often resort to work-arounds and innovative management techniques that, while not ideal, may offer some ability to manage an "unmanageable" condition. By providing insight into the relative value of capabilities, actions, and resources that have utility across many different conditions, this approach may give some insight into tools that are more likely to have broad applicability. In this sense it may support the concept of medical flexibility. Even so, human-driven inspiration is impossible to capture in an algorithmic method as described here. While reliance upon human ingenuity should not be incorporated in the design of an exploration medical capability, modeling resources such as MONSTR will never be capable of accounting for human resourcefulness that manifests in time of need.

The ability to categorize and quantify, on a meaningful scale, available medical skills, training, and resources provides a useful framework in which to consider future exploration medical capabilities. MONSTR outputs demonstrate a rudimentary, but promising, approach for such categorization; improved modeling capabilities could assist the development of medical capabilities for exploration missions in a meaningful way. While limited, this pilot project successfully demonstrates one approach to the weighting and integrating of various aspects of a medical system, and highlights a means of evaluating the risks and benefits of inclusion or exclusion of medical resources in future exploration-class spaceflight missions.

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*Authors and affiliations:* Erik L. Antonsen, M.D., Ph.D., Michael A. Canga, and Ronak Shah, M.D., M.P.H., NASA Johnson Space Center, Houston, TX; Erik L. Antonsen, M.D., Ph.D., Department of Emergency Medicine and Center for Space Medicine, Baylor College of Medicine, Houston, TX; Robert A. Mulcahy, M.D., M.P.H., Department of Preventive Medicine and Community Health, University of Texas Medical Branch, Galveston, TX; David Rubin, M.S., KBRwyle, Inc., Houston, TX; and Rebecca S. Blue, M.D., M.P.H., GeoControl Systems, Inc., Houston, TX.

## REFERENCES

1. Antonsen E, Hanson A, Shah R, Reed R, Canga M. Conceptual drivers for an exploration medical system. Guadalajara, Mexico; 67th International Astronautical Congress; 2016. Paris (France): International Astronautical Federation; 2016. No: IAC-16,A1,3,9,x35689.
2. Baisden DL, Beven GE, Campbell MR, Charles JB, Dervay JP, et al. Human health and performance for long-duration spaceflight. Aviat Space Environ Med. 2008; 79(6):629–635.
3. Berry CA. Medical legacy of Apollo. Aerosp Med. 1974; 45(9):1046–1057.
4. Bridge L, Watkins S. Impact of medical training level on medical autonomy for long-duration space flight. Hanover (MD): NASA Center for Aerospace Information; 2011. No: NASA/TP-2011-216159.
5. Canga M, Shah R, Mindock J, Antonsen E. A strategic approach to medical care for exploration missions. Guadalajara, Mexico: 67th International Astronautical Congress; 2016. Paris (France): International Astronautical Federation; 2016. No: IAC-16,E3,6,11,x35540.
6. Grigoriev AI, Bugrov SA, Bogomolov VV, Egorov AD, Polyakov VV, et al. Main medical results of extended flights on space station Mir in 1986–1990. Acta Astronaut. 1993; 29(8):581–585.
7. Hamilton D, Smart K, Melton S, Polk JD, Johnson-Throop K. Autonomous medical care for exploration class space missions. J Trauma. 2008; 64(Suppl.):S354–S363.
8. Minard CG, de Carvalho MF, Iyengar MS. Optimizing medical resources for spaceflight using the integrated medical model. Aviat Space Environ Med. 2011; 82(9):890–894.
9. Nelson ES, Lewandowski B, Licata A, Myers JG. Development and validation of a predictive bone fracture risk model for astronauts. Ann Biomed Eng. 2009; 37(11):2337–2359.
10. Stewart LH, Trunkey D, Rebagliati GS. Emergency medicine in space. J Emerg Med. 2007; 32(1):45–54.
11. Summers RL, Johnston SL, Marshburn TH, Williams DR. Emergencies in space. Ann Emerg Med. 2005; 46(2):177–184.
12. Watkins SD. Space medicine exploration: full medical condition list. Washington (DC): National Aeronautics and Space Administration; 2010. No: NASA/TP-2010-216118.
13. Weaver AS, Zakrajsek AD, Lewandowski BE, Brooker JE, Myers JG. Predicting head injury risk during International Space Station increments. Aviat Space Environ Med. 2013; 84(1):38–46.