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A STRATEGIC APPROACH TO MEDICAL CARE FOR EXPLORATION MISSIONS

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Abstract

Exploration missions will present significant new challenges to crew health, including effects of variable gravity environments, limited communication with Earth-based personnel for diagnosis and consultation for medical events, limited resupply, and limited ability for crew return. Providing health care capabilities for exploration class missions will require system trades be performed to identify a minimum set of requirements and crosscutting capabilities, which can be used in design of exploration medical systems. Medical data, information, and knowledge collected during current space missions must be catalogued and put in formats that facilitate querying and analysis. These data are used to inform the medical research and development program through analysis of risk trade studies between medical care capabilities and system constraints such as mass, power, volume, and training. Medical capability as a quantifiable variable is proposed as a surrogate risk metric and explored for trade space analysis that can improve communication between the medical and engineering approaches to mission design. The resulting medical system design approach selected will inform NASA mission architecture, vehicle, and subsystem design for the next generation of spacecraft.

Keywords: exploration, medical system, risk mitigation, modeling, stakeholders

Acronyms/Abbreviations

Low earth orbit (LEO), National Aeronautics and Space Administration (NASA), Human Research Program (HRP), Lifetime Surveillance of Astronaut Health (LSAH), Integrated Medical Model (IMM), International Space Station (ISS), Life Sciences Data Archive (LSDA), Exploration Medical Condition List (EMCL), Medical Optimization Network for Space Telemedicine Resources (MONSTR), subject matter expert (SME), quality time lost (QTL), loss of crew life (LOCL), solar particle events (SPE), extravehicular activity (EVA), Exploration Medical Capability (ExMC), Design Reference Mission (DRM), evacuation of the space station (EVAC)

1. Introduction

1.1 Overview

Exploration class missions will present significant new challenges to crew health that will be unique from those experienced during missions conducted in low earth orbit (LEO). Crew will need to traverse the terrain of lunar, asteroid, or planetary surfaces during exploration and function in a variety of reduced gravity environments [1]. Limited communication with Earth-based personnel for the purpose of medical event consultation creates additional challenges. New mental and behavioural health needs will need to be carefully considered. Providing health care capabilities for exploration class missions will necessitate the definition of new medical requirements and

development of technologies to ensure the safety and success of exploration missions.

“Given that medical capabilities will be limited during human exploration missions, there is a possibility that in-flight medical events will lead to undesirable health and mission outcomes.” [2]

Planning for exploration requires understanding of the space flight environment, tasks that will be required to out carry a mission, and the potential effects on humans. Current and future medical data, information, and knowledge must be aggregated to facilitate querying and analysis. This data and information must be used to inform the medical research and development program through analysis of the trade-offs between medical care capabilities and system constraints such as mass, power, volume, and training.

Medical technology is a rapidly evolving field. The likelihood is low that a stable set of requirements can be established that exploits current technologies to provide a capable medical system for exploration missions not slated to fly for ten years. In order to address this reality, an incremental and iterative approach to system design is envisioned to incorporate the inevitable growth of technology. Additionally, since the human system is complex and effects of the space environment are not completely known, any system proposed should maximize flexibility to enable a care provider to address conditions that were not considered in the initial design.

1.2 Background

National Aeronautics and Space Administration (NASA) was prompted in 2001 to improve the integration of the vehicle and human systems through a very intentional and evidence based design of medical systems to support human spaceflight during exploration missions [3]. This has affected the structure of Space Medicine Operations as well as the Human Research Program (HRP) in how they both approach the problem of exploration medical needs in the context of a Mars mission. NASA has responded through both the implementation of an occupational health model that incorporates occupational surveillance principles and the structure and close tie between the elements of HRP to occupational surveillance.

The occupational surveillance work enables studies of astronaut health pre-flight, in-flight, and post-flight capture incidences of medical conditions during space missions. This enables ongoing compilation and tracking of common and high risk conditions that are likely to require medical attention during long-duration exploration missions. The NASA Lifetime Surveillance of Astronaut Health (LSAH) [4] collects data on astronaut medical care and workplace exposures, especially those occurring in the training and space flight environments, and conducts operational and health care analyses to look for trends in exposure and health outcomes. This data is used to feed quantitative risk tools described below including the Integrated Medical Model (IMM). NASA's Life Sciences Data Archive (LSDA) [5] also includes data from human subjects derived from both past and current space flight, as well as data from analogue studies. Several publications provide an overview of in-flight medical condition incidences [6-8]. Table 1 shows the occurrences of medical conditions experienced by NASA astronauts during previous space missions. The data obtained from LSAH records for medical conditions that occurred among United States astronauts during the Space Shuttle Program (through STS-114 in 2005), Mir, and International Space Station (ISS) (through Expedition 13 in 2006) missions are used to inform modelling estimates that are applied to current operations and future exploration missions. Data included from Apollo and Skylab missions are based on publications [9].

Several of these conditions are not high-risk or emergency in nature, requiring a relatively low level of treatment resources such as medication and crew medical officer input. Non-emergency conditions that have occurred during space missions include: dermatological, musculoskeletal, cardiovascular, and mild psychiatric conditions, as well as minor trauma and burns. Of greater concern, particularly for longer and more remote exploration missions, is the potential for more serious or life-threatening medical conditions

during a space flight mission. Both benign and more serious cardiac arrhythmias (supraventricular and ventricular tachycardia) have been reported during previous Mir, Skylab, and Apollo missions [10]. In cases that are emergent the option of evacuation of crews to provide the highest levels of medical care has been available to all human spaceflight missions to date. This is an option that may be unavailable on future long-duration exploration missions. Historically dental [11,12] and urological emergencies [13, 14] have been documented among astronauts and behavioural and mental health episodes have been successfully managed with near real-time psychological support during LEO missions [15]. Issues like these will require autonomous handling during exploration missions and provide a unique forward challenges.

1.3 Medical System Design Context

Current architectures for exploration call for long duration missions of 1-3 years [2]. These missions will face challenges not faced by prior programs. Uncertainties will be higher in the new environments, and resources will generally be more constrained.

The duration of these future missions exceed current spaceflight experience base. Current ISS operations baseline 6-month duration increments with half the crew rotating in and out approximately every three months. Worldwide, six Astronauts/Cosmonauts have exceed 1-year in microgravity, with the longest

Table 1. Number of occurrences of medical conditions that have affected NASA astronauts during previous space missions [9].

Medical condition	Number of events	Medical condition	Number of events
Allergic reaction (mild to moderate)	11		
Ankle sprain/strain	11	Mouth ulcer	9
Back injury	31	Nasal congestion (space adaptation)	389
Back pain (space adaptation)	382	Neck injury	9
Barotrauma (ear/sinus block)	31	Nose bleed (space adaptation)	6
Choking/obstructed airway	3	Otitis externa	3
Constipation (space adaptation)	113	Otitis media	3
Diarrhea	33	Paresthesias	26
Elbow sprain/strain	12	Pharyngitis	11
Eye abrasion (foreign body)	70	Respiratory/infection	33
Eye chemical burn	6	Shoulder sprain/strain	22
Eye infection	5	Sinusitis	6
Finger dislocation	1	Skin abrasion	94
Fingernail delamination (EVA)	16	Skin infection	13
Gastroenteritis	4	Skin laceration	1
Headache (CO2 induced)	20	Skin rash	94
Headache (Late)	49	Smoke inhalation	3
Headache (space adaptation)	233	Space motion sickness (space adaptation)	325
Hemorrhoids	2	Urinary incontinence (space adaptation)	5
Herpes zoster reactivation (shingles)	1	Urinary retention (space adaptation) - female	5
Indigestion	6	Urinary retention (space adaptation) - male	4
Influenza	1	Urinary tract infection - female	5
Insomnia (space adaptation)	299	Urinary tract infection - male	4
Insomnia (late)	133	Visual impairment and/or increased intracranial pressure (space adaptation)	15
Knee sprain/strain	7	Wrist sprain/strain	5

duration being 437 days. The current record for a female astronaut is 199 days in space [16]. The expectation for exploration missions is mixed gender crews. This limited evidence base results in higher

uncertainties for system design drivers. The medical system will need to address this uncertainty by providing additional flexibility to respond to unplanned events.

Because of the distances and mechanics involved, deep space missions will have a set of resource constraints which are not encountered in LEO missions [1]. Cis-lunar missions will require a minimum of 3 days for medical evacuation. Mars and other destinations will not have a capability for medical evacuation. Mars missions cannot expect resupply although some prepositioning of resources may be available. There will be periods of limited communications and extended transit times. With an expected 22-minute delay on one-way communications during some mission phases, a Mars medical system must be designed for considerable more autonomy than previous medical systems. Finally, due to the low margins available on these missions, we can expect increasing scrutiny and competition for resources across mission systems.

We can reasonably expect that future information processing and data handling capabilities will continue to expand. Additionally, lower mass and less power consuming medical technologies will become increasingly available as they are driven by a competitive marketplace.

2. Approach

2.1 Risk Reduction Strategy

“In this regard, although research in most fields may continue ad infinitum, the Bioastronautics Roadmap should attempt to identify what is good enough” for the launch of a given category of mission. Researchers in virtually all fields are reluctant to declare total success, since this would be tantamount to forfeiting future funding. In the conduct of exploration, leaders cannot wait until every detail is resolved definitively, but only until the collective risk is mitigated adequately or otherwise reduced to permit a high enough level of optimism to justify mission initiation.” [17]

The question in defining a medical system **is how can we leverage improving capability to minimize risk within the known constraints?** The resource limitations of exploration missions require proposed medical solutions that include consideration of mission constraints and architecture capabilities in medical risk assessments.

To address the problem of providing a medical system for extended exploration missions, a suite of medical capabilities will need be identified, developed, and integrated. Risk metrics need to be identified, and risk models will be developed to quantify outcomes for missions based on the proposed capabilities. Using

these models, design requirements can be identified that will reduce the system risk.

The generalized elements of a system level approach to medical risk include the following considerations:

1. Development of risk metrics.
2. Development of assessment tools to allow quantification of risk.
3. Identification of risk drivers or influential capabilities.

Identification of risk metrics allows prioritization of risk mitigation approaches within the medical system, which will drive the solution space available to influence these metrics. Typical risk metrics used for spaceflight at the program level include loss of crew and loss of mission. For medical system optimization, these metrics do not provide the level of discrimination required for some systems trades. In particular, a medical system is judged by its ability to provide a crew fit for duty when called which will require the ability for general prevention, screening, diagnosis, and treatment. This suggests the need for crew performance metrics. Inclusive of this is the need for long-term treatment, as manifested by rehabilitation and palliative care. One other difficulty in determining medical risk metrics is a reticence to establish a baseline risk acceptance criteria in the face of rapidly evolving capability. We do not expect definitive risk acceptance levels to be established until an exploration mission has been baselined.

“A sustained human exploration program beyond LEO, despite all reasonable attention paid to safety, will almost inevitably lead to multiple losses of vehicles and crews over the long term. For each step along the pathway, it will be important for NASA leadership and other stakeholders to discuss risk honestly and to establish acceptable levels of risk to missions and crews for deep-space missions. At the Agency level, the risk discussion will be more detailed and will use relative or probabilistic levels to define the risk threshold, inform the design, and set priorities.” [18]

With this constraint in mind, we chose to compare exploration medical capability against a measurable baseline – the terrestrial standard of care. By comparing capability against a common standard, progress towards reducing the medical risk could be measured. NASA currently estimates risk in terms of likelihood and consequence. In the medical domain the likelihood of any particular event can be estimated from either known spaceflight events in the past or from appropriately generalizable populations in terrestrial medicine. Neither of these are perfect, but given the lack of data on medical events in the exploration domain beyond LEO, these are the best that can be expected at this time. The consequence side of medical risk is more difficult to quantify. Medical

consequence is assessed through decrements in crew performance or morbidity but cannot be well measured in that definition.

“Consequence can be a mission level effect or an individual crew morbidity or mortality. In both these approaches, consequence requires a means of assessing the expected effectiveness of a medical capability in mitigating the effects of a medical condition occurring. It is impossible to predict the effectiveness of all possible medical treatments given an assumed resource set. However it is possible to measure a proposed resource set against a gold standard. If the gold standard resource set is defined as resources available to a US based tertiary care hospital, then the preventive, diagnostic, treatment, and rehabilitation capabilities of a proposed medical system can be measured against that gold standard as a measure of medical readiness rather than predictable effectiveness. Since even the relatively unlimited capability of a tertiary care hospital cannot provide perfect outcomes, it is considered that medical readiness as measured by capability provision is a viable risk metric.” [19]

By using medical capability as a demonstration of medical readiness, a metric for consequence can be tabulated and calculated. At the time of program implementation a decision regarding required capability can then be made.

The Human Research Program has developed several assessment risk tools to assist in quantifying risk. The Exploration Medical Condition List (EMCL) provides a list of conditions of concern for exploration missions. The IMM uses historical information to estimate medical event occurrence. The Medical Optimization Network for Space Telemedicine Resources (MONSTR) is designed to catalogue the current terrestrial standard of care as a documented baseline of human health care.

The EMCL provides a framework to organize the results of medical systems needs analyses. IMM can be considered as a provider of incident rates for a medical event. MONSTR can be considered as the source for resource requirements for medical events. By integrating the resource calls across all conditions, an initial set of influential medical capabilities can be defined.

2.2 Risk Measures and Tools

2.2.1 Exploration Medical Conditions List

Early in the planning for exploration missions, the need for a list of medical conditions of interest was

identified. JSC-65722 EMCL was created to address this need drawing on spaceflight experience to document the set of medical conditions of primary interest for medical system development [20].

“The purpose of the list is to serve as a foundation for identifying medical conditions of interest which could affect a crewmember during a given mission profile, which of those conditions would be of concern and require treatment, and for which conditions a gap in knowledge or technology development exists. This information will be used to focus research efforts and technology development.”

The EMCL (Table 2) is applicable to medical conditions that could occur in several exploration mission profiles. The intent of this list is to identify conditions that occur as a consequence of human space flight and human habitation of space, in addition to injuries that result from hardware or vehicle failure. A condition was listed as “not addressed” if it is highly unlikely to occur, is expected to be engineered out, or limitations in medical training/hardware/consumables preclude its treatment.

The EMCL is expected to be an evolving document as our evidence base for spaceflight grows, it will be updated accordingly.

2.3 Integrated Medical Model

For quantitative evidence based decision support, the IMM combines organizational knowledge, published literature, and in-flight medical event data in a statistical modeling tool to produce simulations of medical scenarios that may impact astronaut health during a mission [21]. The output of IMM provides comparative estimates of in-flight risk and medical resource utilization based on specifications of mission parameters, including crew profiles and mission length and availability of medical resource options.

Currently, the medical condition input data represents 100 medical conditions that have occurred in space or concern the space medical community. Baselined to the ISS, space flight health studies provide the data for conditions that have occurred during space flight (Table 1). Analog studies, general population data, SME opinion, and data derived from specifically constructed Bayesian statistical analyses serves to provide incidence estimates for conditions that have yet to occur, or have occurred infrequently.

Table 2. EMCL Medical Conditions

Abdominal Injury	Dental – Filling Replacement	Indigestion	Seizure
Abdominal Wall Hernia	Dental - Crown Replacement	Insomnia (Early/Late)	Sepsis
Acute Arthritis	Dental - Exposed Pulp/Pulpitis	Intra-Abdominal Infection (Diverticulitis, Appendicitis, Other)	Shoulder Dislocation
Allergic Reaction (Mild to Moderate)	Dental - Abscess	Lumbar Spine Fracture	Sinusitis
Altitude Sickness	Dental - Avulsion/ Tooth Loss	Malignancy	Skin Abrasion
Anaphylaxis	Depression	Medication Overdose/Adverse Reaction	Skin Laceration
Anxiety	Diarrhea	Mouth Ulcer (aphthous ulcer; Herpes Simplex Virus – cold sore)	Skin Rash
Back Injury	Dysfunctional Uterine Bleeding	Nasal Congestion (Space Adaptation)	Small Bowel Obstruction
Back Pain (Space Adaptation)	Elbow Dislocation	Nausea/Vomiting	Smoke Inhalation
Barotrauma (Ear/Sinus Block)	Eye Abrasion (Foreign Body)	Neck Injury	Space Motion Sickness (Space Adaptation)
Behavioral Emergency	Eye Chemical Burn	Nephrolithiasis	Extremity Sprains/Strains
Burns	Eye Corneal Ulcer	Neurogenic Shock	Stroke
Cardiogenic Shock	Eye Infection	Nosebleed (Space Adaptation)	Sudden Cardiac Arrest
Cellulitis	Eye Penetration (Foreign Body)	Osteoporosis	Surgical Treatment
Chest Injury/Pneumothorax	Finger Dislocation	Otitis Externa	Toxic Exposure
Chest Pain/Angina	Fingernail Delamination (EVA)	Otitis Media	Upper Extremity Fracture
Choking/Obstructed Airway	Glaucoma – Acute	Palliative Treatment	Urinary Incontinence (Space Adaptation)
Compartment Syndrome	Head Injury	Paresthesias/Hot Spots (EVA)	Urinary Retention (Space Adaptation)
Constipation (Space Adaptation)	Headache (CO ₂ , Space Adaptation, Other)	Pharyngitis	Urinary Tract Infection
De Novo Cardiac Arrhythmia	Hemorrhoids	Prostatitis	Vaginal Yeast Infection
De Novo Hypertension	Herpes Zoster Reactivation	Radiation Sickness	Visual Impairment/Intracranial Hypertension
Decompression Sickness	Hip/Lower Extremity Fracture	Respiratory Infection	
Dental - Caries	Hypovolemic Shock	Retinal Detachment	

The IMM uses the input data to produce estimates of crew health, resource utilization, and mission outcomes. IMM estimation of the outcome of a given medical condition requires consideration of a number of factors, including the severity at presentation, defined as either the best or the worst-case scenario. IMM expresses the models findings in the form of output measures such as the quality time lost (QTL) to an astronaut due to medical events, the probability of the need to consider evacuation of the space station (EVAC), and loss of crew life (LOCL) resulting from inability to sufficiently address a medical event. Of note, the model accounts for the degree of functional impairment of the crew medical officer(s) due to the particular medical condition.

IMM achieves these estimates through intelligent implementation of Monte Carlo probabilistic techniques, implementing a randomly generated mission with each model trial and accounting for the medical condition treatment and clinical outcomes based on resource availability. An IMM trial consists of applying the medical condition probability profiles and specific mission scenario variables, such as crewmember attributes, extravehicular activities and mission duration to generate the mission medical event and outcome events. The IMM also accounts for events unique to the spaceflight environment, such as solar particle events (SPE) and extravehicular activities (EVAs) that may lead to the presentation of associated medical conditions. Primary outcomes describing the impact of medical events on the missions are described in terms of the QTL, probability of EVAC, and probability of LOCL. Subsequent to the probabilistic modeling aspects of IMM, IMM optimization routines allow for trades between medical resource mass and volume and the one of the IMM risk metrics [22], providing an initial, evidence based assessment of the mission medical resources for mission designers and decisions makers.

2.4 Medical Optimization Network for Space Telemedicine Resources

The ability to evaluate the resource trade space for prevention, screening, diagnosis, and treatment of medical conditions is essential during the development of an exploration mission medical system. MONSTR is a decision support system that is being designed to provide users the ability to assign resources required for medical intervention and relative importance to those resources. The MONSTR is a data repository to catalogue treatment resources required for conditions identified in the EMCL. Tangible items such as equipment, medication, and medical procedures required to respond to a condition are identified, along with non-tangible items such as the clinical skillsets required to execute the procedure. Figure 1 shows an example of the data types and categorizations that are

expected in MONSTR. Because of the complexity of the data structure, it is important to capture a complete data array and retain those relationships to the condition.

MONSTR is a pilot research project currently designed to show whether the specific approach of this type of relational database can provide value to mission planners who have a need to explore the medical capabilities trade space. MONSTR is populated with resources that are considered typical for a health care facility in a first world nation to be used as the “Terrestrial Standard of Care”. By populating each condition with nested resources required to implement a diagnosis or a treatment for that condition retains the relationship between the full set of resources needed to intervene on a potentially ill crew member. The project and its outcomes are described briefly here. A follow up version is currently being researched to improve upon lessons learned. Data shown here should be considered notional and representative of the potential of the tool but not a final product.

Figure 1. Typical MONSTR Data and Criticality

Condition	Use Case	Resource Type	Resource	Criticality	
Abdominal Injury	Diagnosis	Procedure	Vital Signs	3	
			Physical Exam - Abdominal	3	
			Physical Exam - Trauma Survey	2	
		Imaging	Ultrasound - AC	2	
			CT - Torso	3	
		Lab	BMP	2	
			CBC	3	
			LFT	2	
			Lactate	3	
			Lipase	1	
	Treatment (Best Case)	Procedure	IV Access - Minor	2	
			IV Fluids	1	
			Monitoring - Standard	2	
		Medication	Analgesics	3	
		Treatment (Worst Case)	Lab	IV Access - Minor	3
				IV Access - Major	3
				IV Fluids	2
				Blood Products	3
				Monitoring - ICU	3
				Advanced Airway	3
Palliative Care	1				
Surgery	Surgery - Trauma		3		
Medication	Antibiotics		1		
	Analgesics		3		
	Antifibrinolytics	2			

The prototype version of MONSTR consists of a SQL database that interfaces with business analytics software for data visualizations/reporting. It is currently populated with information provided by six board certified physicians in Aerospace Medicine, Emergency Medicine, Family Medicine, Internal Medicine, and Physical Medicine and Rehabilitation.

Definitions of the medical condition and their best and worst case scenarios are taken from the IMM definitions [21]. Rankings of each of the resources with regards to ‘medical criticality’ are given by consensus among the physicians informing the model. Medical Criticality in the prototype version is on a scale from zero to three. Zero is not applicable, three is a resource critical to the intervention, one is a resource that would be nice to have but is not critical, and two is anything in-between a one and a three. Figure 1 shows an early breakdown of this from a prototype database.

Deconstruction of medical resources required for a given intervention allows development of relative weighting for those resources not only by medical criticality but also by the probability of occurrence for any given condition. Probability of occurrence is calculated by the IMM and easily exported for each condition to the MONSTR database to further weigh the estimated relative ‘value’ of each resource. This approach attempts to create a ‘level playing field’ by which the relative utility of resources can be compared. For example, mission planning decisions that may hinge on deciding whether to include an ultrasound, an Automatic External Defibrillator, or an increased volume of high use medications such as Ibuprofen currently have no quantitative method for weighing the ‘value’ of these items to a specific mission scenario. The relative value is some combination of how often conditions are expected to occur that might need the resource as well as the utility of the resource in different scenarios when called on. This approach is directed toward providing a ‘ballpark estimate’ of these values to mission planners and SME who then will need to exercise discretion in interpreting the results applicability. Expert evaluation is critical as MONSTR is populated with information from terrestrial medical experience and interpretation is for the context of spaceflight. For example, if an MRI were to be found highly valuable, that particular output could be downgraded by an SME who understands the low likelihood of implementing that type of technology in spaceflight. On the other hand, if a capability like X-ray shows high value, then the Exploration Medical Capability (ExMC) element may elect to invest in research that would seek to minimize mass and optimize integration capability with a medical system to determine if it is a viable exploration medical capability. This highlights the value of a quantitative approach to capability and resource ‘value’ in informing an applied research pathway.

3. Results

Initial analysis of from these two tools will be facilitated through the use of Centrifuge Systems (McLean, VA, USA) and Tableau® (Seattle, WA, USA) visualization software. These tools are being used to integrate the application of resources across the

medical condition space prioritized by resource call rate and criticality.

The IMM outputs provide incidence rate estimates for medical events per mission. MONSTR catalogues the resource requirements for each condition in an idealized Terrestrial Standard. MONSTR also provides a criticality weighting to the resource which provides an initial assessment of the importance of a resource to a treatment plan. Total resource calls per mission can be calculated by integrating the resource calls across all events for a mission. Utilizing the criticality estimates to modify the weighting of each resource call can further modify the estimate of call rate to better reflect the relative importance of a particular resource to the mission of interest.

Multiple visualizations may be performed to identify relationships to suites of treatment capability. Figure 2 shows a broad spectrum of potential output formats available through the use of Centrifuge. This one sample can be used to illustrate the need for software tools to retain multiple data relationships which may be displayed in multiple ways depending on the analytical need. In this case multiple graphics, numbers, and color provide insight into a highly networked data set.

Once the dataset has been accumulated, specific questions can be asked and subsequently visualized. Figure 3 shows a particular slice of the dataset, the relative importance of laboratory assays that might be called in a Mars design reference mission (DRM). In this example, the resource weighted criticality, total of resource calls adjusted for incidence (blue), versus unweighted criticality, total of calls (grey) shows the importance of considering incidence when assessing the importance of a given resource for a mission.

Unweighted criticality is defined as the physician’s estimate of medical criticality of a particular resource to a particular condition summed over all conditions. Weighted criticality is the unweighted criticality multiplied by the probability of occurrence. This weighting preference is utilized in the pilot demonstration and is not the final algorithm for interpretation. However, it does enable an assessment of the utility of this approach.

Figure 3 shows laboratory assays that would be called upon in a terrestrial medical case are weighted according to the above formulas. This highlights the critical evaluation of these starting results by SME’s for interpretation. For example, the top three laboratory panels include complete blood count, basic metabolic panel, and a urinalysis. These likely have high value in helping with diagnosis in both domains. However, laboratories further down the list might be pared from consideration This provides a starting point to understand how much value these particular resources have in the terrestrial environment when weighted by how likely they are to occur in the spaceflight environment.

Figure 2. Sample MONSTR Outputs

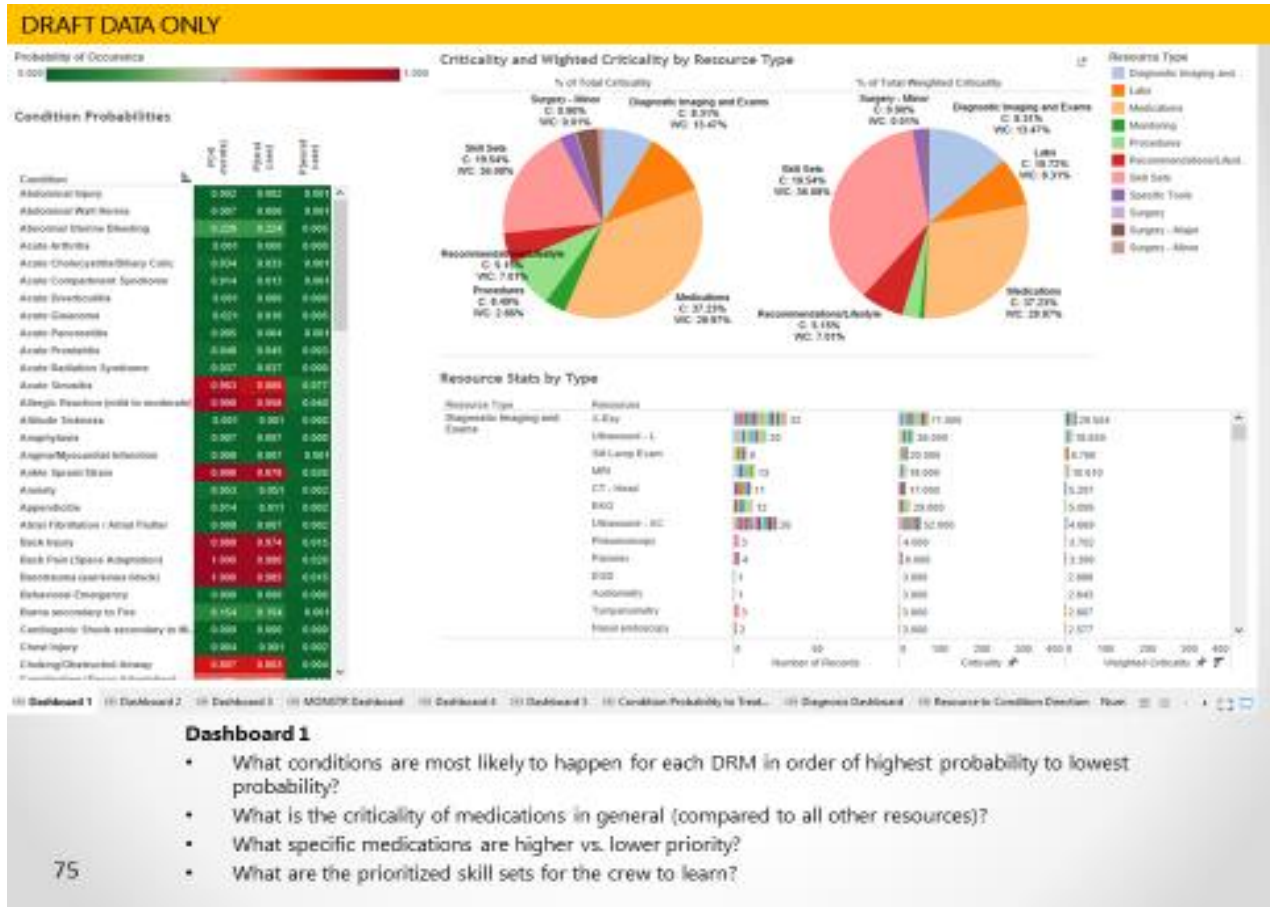
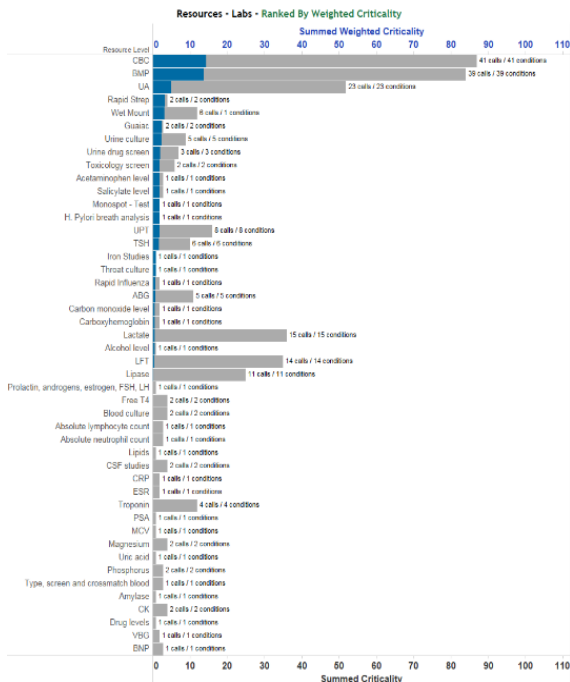


Figure 3. Relative importance of laboratory analyses for Mars DRM



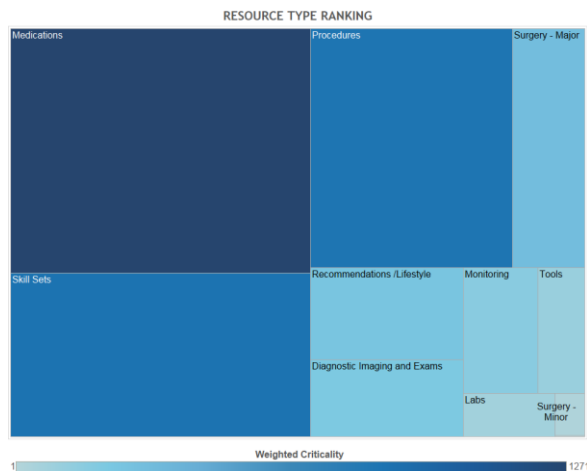
Alternately, we can probe the dataset for categories of resource calls. Figure 4 is a visualization of this question to graphically show the resource type relative rankings. This could form the basis for the first step in a Pareto analysis.

The category definitions are not final, but give insight into the relative value of different treatment needs. The largest category value is medications here, which is not unexpected in the context of space medicine needs. However, the calls for major and minor surgery may be more insightful. Major surgery is defined as a tissue-cutting intervention that would require an operating room to implement. Minor surgery is defined as a tissue cutting intervention that can be performed in an emergency department in completeness. When visualized for relative value the need for major surgical capabilities applies mostly to worst case scenarios in medical situations. Not shown here are the sheer volume of resources required to implement a major surgery. In that context this could inform decisions on how much capability is warranted in the face of significant resource limitations.

It is critical to recognize the model limitations and output must be interpreted by SMEs, but this approach

allows for the organization of a complex data set to facilitate understanding the relationships across the

Figure 4. Relative importance of resource types for Mars DRM



entire set of possible risk mitigations. Visualization is an approach that can allow intuitive insight, which may then be subjected to more rigorous analysis [23].

4. Discussion and Future Work

Categorization and quantification of medical capability is a promising approach to measuring progress in medical risk reduction. The success of the approach will be dependent on establishing an accepted risk framework and developing validated data sources for decision support.

During the initial assessment of results, it became clear that further work needs to be done in resource weighting and integrating across the event space. In particular, the relative weight of resources used for low probability/high impact conditions against high probability/low impact conditions can affect results. A specific example would be the relative importance of Sepsis treatments, which are highly unlikely to be used, but absence will result in death vs accommodation of topical ointments, which a nearly certain to be used and depletion will result in crew discomfort and possibly significant reduction in crew/mission performance measures. These risk trades are not unique to the medical system; however, this approach has highlighted some of these trades early in the design process.

Future work in this area includes developing an architecture of tools for systems evaluations. A notional representation is shown in Figure 5 Medical system design evaluations must include the risk metrics and clinical value of system capabilities as described in this paper, however, additional aspects must be included in more mature and comprehensive evaluations over time. For example, medical system functional and performance requirements will be derived from a concept of operations currently in work.

Medical system design options must then be assessed for their ability to meet these requirements. In addition, as communication with mission operational and vehicle design engineering SME's increases, additional interface requirements and constraints will be identified for further design option evaluation. Feasibility of the medical system volume and layout within a vehicle or habitat must also be considered. The suite of tools to accomplish these evaluations will be architected to support medical system evaluations that respond to evolving requirements and technologies as exploration mission scenarios are being defined.

Finally, an unexploited area for work alluded to in this paper is stronger analysis of medical system design on health and performance of crew. Results from this analysis can be used to drive architecture design to reduce crew medical risk caused by the mission systems.

5. Conclusions

The complexity of the medical decision space is such that a rote approach to system design through prioritization is doomed to failure. At best, these tools can be used to organize a large networked data set to support decision making and understand the implications of design choices.

For the exploration medical systems, a requirement for medical autonomy will become a driving factor as time to definitive care increases. Considerations around autonomy and medical system design are well described in A Risk Reduction Strategy for the Human Exploration of Space [17].

“Both the biological and the operational research issues are aimed not at fundamental science, but at support of the specific health care delivery issues that are focused on crew health and mission success. What to treat? What not to treat? What to take in the vehicle’s medical supply manifest?... limitations imposed by upload volume and mass may preclude the availability of many techniques and impose a limited selection of options based on risk assessment and logistics.”

The National Academy of Sciences Committee on Aerospace Medicine and the Medicine of Extreme Environments recommended [17]:

“The committee recommends that a system be developed for quantitatively evaluating the mental and physical health risks that could affect mission success and crew health and that priorities for countermeasure development (i.e., definitive treatment vs. palliation) be established for the most likely conditions to be encountered during each reference mission. A panel of outstanding medical clinicians should be used to assist NASA medical operations staff in characterizing the likelihood, importance, and “treatability” of each condition.”

The approach describes nascent steps towards building a quantitative approach to medical system

design requirement identification and trade space evaluations that will guide research investments.

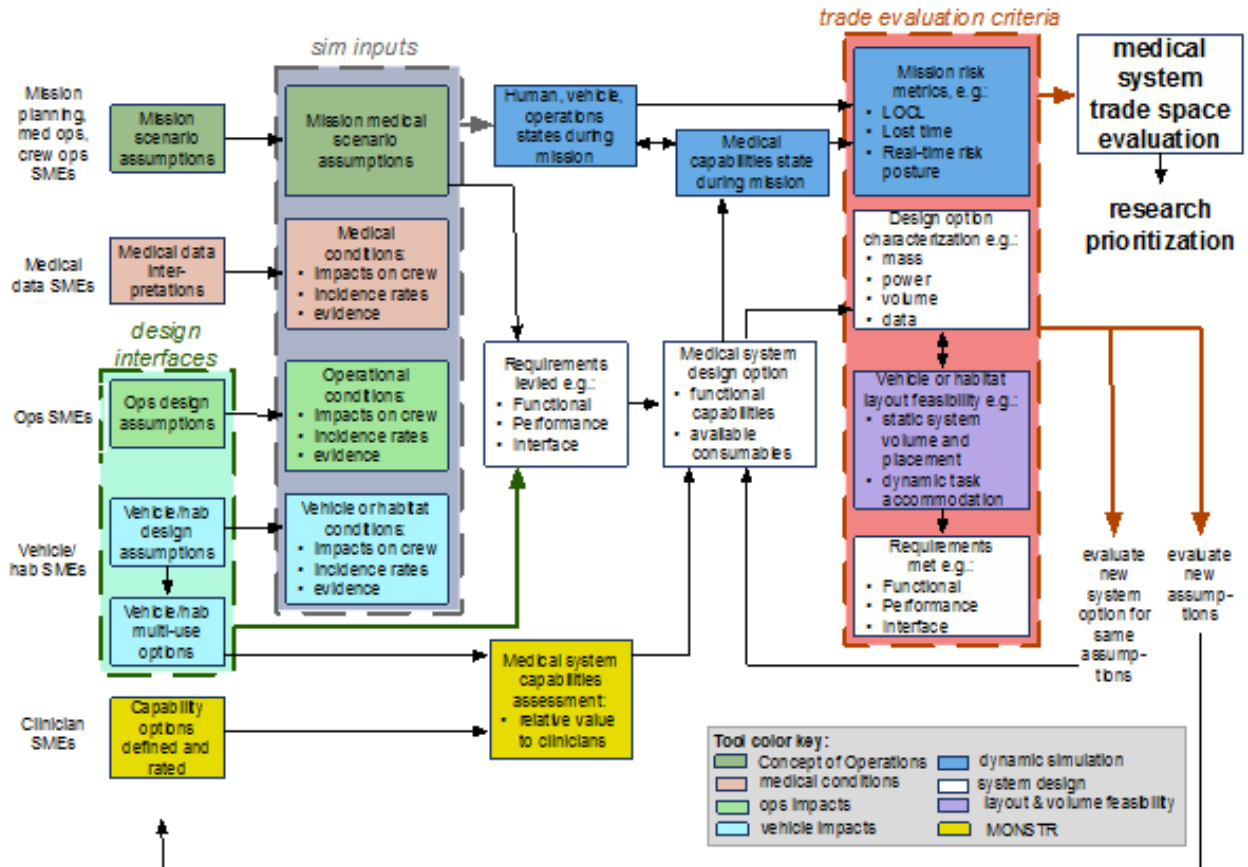


Figure 5 Notional System Evaluation Flow/Tools

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