Autonomous Medical Care for Exploration Class Space Missions

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Abstract:

The US-based health care system of the International Space Station (ISS) contains several subsystems, the Health Maintenance System, Environmental Health System and the Countermeasure System. These systems are designed to provide primary, secondary and tertiary medical prevention strategies. The medical system deployed in Low Earth Orbit (LEO) for the ISS is designed to enable a “stabilize and transport” concept of operations. In this paradigm, an ill or injured crewmember would be rapidly evacuated to a definitive medical care facility (DMCF) on Earth, rather than being treated for a protracted period on orbit.

The medical requirements of the short (7 day) and long duration (up to 6 months) exploration class missions to the Moon are similar to LEO class missions with the additional 4 to 5 days needed to transport an ill or injured crewmember to a DCMF on Earth. Mars exploration class missions are quite different in that they will significantly delay or prevent the return of an ill or injured crewmember to a DMCF. In addition the limited mass, power and volume afforded to medical care will prevent the mission designers from manifesting the entire capability of terrestrial care. NASA has identified five Levels of Care as part of its approach to medical support of future missions including the Constellation program. In order to implement an effective medical risk mitigation strategy for exploration class missions, modifications to the current suite of space medical systems may be needed, including new Crew Medical Officer training methods, treatment guidelines, diagnostic and therapeutic resources, and improved medical informatics.

Introduction

The US-based health care system of the International Space Station (ISS) contains several subsystems, the Health Maintenance System, Environmental Health System and the Countermeasure System. These systems are designed to provide primary, secondary and tertiary medical prevention strategies (see table 1) for the Crewmembers.

The bulk of the risk mitigation for medical maladies in LEO is placed on preventive medicine, as opposed to treatment. For ISS Operations two crewmembers are selected as Crew Medical Officers (CMOs) to receive 40 hours of dedicated training in the use of the on-orbit medical hardware and have the opportunity of additional 'hands on' training in an emergency and surgical operating room. For Shuttle two crewmembers are selected, by the Commander of each flight, to be CMOs. These crewmembers receive 18 hours of dedicated training in the use of the Shuttle medical equipment for the treatment of many types of illness and injury. The medical system deployed in Low Earth Orbit (LEO) for the ISS is designed to enable a "stabilize and transport" concept of operations. In this paradigm, an ill or injured crewmember would be rapidly evacuated to a definitive medical care facility (DMCF) on Earth, rather than being treated for a protracted period on orbit.

Insert table 1 approximately here

The medical requirements of the exploration class missions to the Moon are similar to Low Earth Orbit (LEO) class missions with the additional 4 to 5 days needed to transport an ill or injured crewmember to a DCMF on Earth. Mars exploration class missions are quite different in that they will significantly delay or prevent the return of an ill or injured crewmember to a DMCF. In addition the limited mass, power and volume afforded to medical care will prevent the mission designers from manifesting the entire capability (personnel and hardware) of a terrestrial DCMF (see table 2). In order to implement an effective medical risk mitigation strategy for exploration class missions the use of a preventive strategy is the single most important method to reduce risk. In addition several changes to the current suite of space medical systems are necessary, including new training practices for CMOs, treatment guidelines, diagnostic and therapeutic resources, and improved medical informatics.

Insert table 2 approximately here

Our current medical capabilities in support of ISS space crew represent a significant increase in medical compared to the Mercury, Gemini, Apollo, Shuttle, and Mir programs. A higher level of care is possible due to our increase in experience applying medical prevention strategies toward spaceflight induced changes in physiology and pathophysiology. Advances in terrestrial screening and preventive medicine allow disease processes to be identified early, mitigated for flight certification or screened out of the astronaut population.

Medical Care Mars Mission Requirements

The current mars exploration mission timeframe permits the phased development of a medical capability to meet the demands future deep space missions. In 2020 the first lunar missions are planned to deliver four astronauts to the surface of the Moon for short periods of time at the polar regions. Surface stays will gradually increase from two weeks to several months with the aim of establishing a permanent Lunar base with rotating crews in 2024, and a fully pressurized rover vehicle in 2027. NASA views the permanent lunar base as part of the critical path to accomplishing the validation and testing of the technology needed to explore Mars for surface stays of one year duration. The ability to rapidly evacuate a crew to Earth from the moon is possible should a catastrophic failure occur during the mission, however, this is not the case for a Mars mission once a transit vehicle leaves LEO. NASA is currently developing the Constellation (exploration) medical requirements, which will define the medical capabilities of the Crew Exploration Vehicle (CEV), Lunar Surface Access Module (LSAM), and the permanent Lunar Base.

The following list provides examples of high level medical mission requirements which could be used determine the design of medical resources for an Expeditionary Mars Mission.

1. Fundamental mission priorities (in descending order of importance):
    a. immediate health and safety of the crew as a whole
    b. immediate health and safety of an individual crewmember
    c. long term health and safety of the crew as a whole
    d. long term health and safety of the individual crewmembers
    e. mission success
2. Mars surface stay will not exceed 400 days .
3. During a medical contingency on any exploration class mission, all medical resources will be available and functional.
4. Medical system capabilities mitigate the likelihood and/or severity of medical events based on a "best evidence" medical analysis techniques where possible.
5. Medical care for crewmembers includes primary and secondary prevention to mitigate the deleterious pathophysiological and behavioral health and performance effects of long duration space mission.
6. Dedicated mission control based flight surgeons shall provide telemedicine medical support during flight and bedside medical care during preflight and post flight mission phases.
7. For a Mars Mission there shall be at least one physician in the crew.
8. There will be only one seriously ill or injured crewmember per medical event.
9. There will not be continuous communication between the mission and the Earth support team, and as distance from Earth increases so will latency in communication. As a result, the crew shall be trained and equipped to provide autonomous medical care.
10. The lack of DCMF resources and the inability to immediately return to Earth during a Mars mission will increased the risk morbidity or mortality from illness and injury.

Occupational Medicine Prevention Strategies Applied to Exploration Class Missions

The approach to the care of a crewmember on an exploration mission follows the accepted pattern of Primary, Secondary and Tertiary intervention. (see Table 3). Therefore the occupational medicine approach of preventing illness and injury is focused on reducing the likelihood and/or severity of medical events occurring, or in other words, controlling a 'medical hazard'. This is usually accomplished by applying mitigation strategies or hazard controls to risk factors, where risk is defined as the likelihood of a medical event occurring with a certain severity. Humans are protected medically in extreme environments by taking a preventative approach to illness and injury, using progressive addition of levels of prevention (Primary, Secondary and Tertiary levels of care) until the risk is considered adequately mitigated by the mission designers.

Insert table 3 approximately here

The medical capability designed into any space mission should be focused at reducing the likelihood or severity of a medical event. For example, the risk of Acute Myocardial Infarction (AMI) is managed by applying primary and secondary prevention toward mitigating the risk factors of AMI, such as selection of crewmembers with low coronary artery calcium (CAC), low Framingham Risk scores (FRS), and by providing astronauts with the means to maintain cardiovascular fitness in reduced gravity environments. The medical prevention model therefore aims to reduce the risk by reducing its occurrence (likelihood or incidence) and/or impact (severity). The clinical presentation of AMI in the form of sudden cardiac death, myocardial infarction, unstable angina and most life threatening arrhythmias will cause an abrupt incapacitation or significant impairment of crewmember performance.[2,17,20] [9,21] AMI may result in the loss of life or mission, and therefore reducing its likelihood through appropriate primary and secondary prevention is the most effective mission enabling strategy.

The use of tertiary prevention to treat illness or injury is generally considered an emergency treatment and therefore not a desired means of managing medical events. Tertiary prevention should only be manifested on the vehicle under those circumstances where the incidence and severity of the medical hazard are high enough that it cannot otherwise be managed. This strategy involves a careful balance between the amount of risk the Agency and mission designers are willing to accept and the resources needed to reduce overall mission risk.

Prevention strategies to reduce the risk of idiopathic illness

The prediction of sub-clinical disease in a healthy cohort and its outcome with appropriate primary and secondary prevention is very difficult, even in populations where we have extensive experience. Predicting the incident and prevalence of disease in these healthy cohorts makes the Mars mission medical care system requirement definitions challenging to develop.

Example 1 Acute Myocardial Infarction versus Cancer:

The risk data derived from the analysis methods used by Gillis et al[8] is encouraging when applied to diseases like AMI since it estimates the incidence of 1 AMI induced sudden cardiac arrest every 33,000 person years for an astronaut analog subgroup with no CAC and a low FRS compared to an age matched population of 40 – 65 years.[3,11] The prevention of AMI by significantly reducing the prevalence of CAD in the astronaut corps seems to drive the overall risk of sudden cardiac death to mission acceptable levels.

With Cardiac risk becoming so low other risks may now become predominate in the mission design. Cardiac risk has now become very small when compared to, for example, the annual risk of cancer in the standard US population, reported by the National Cancer Institute[16] (age 20 to 54) being approximately 200 per 100,000 person years (or approximately 1 for every 625 person years or 0.6%/person/Mars mission). The approximate risk of breast and prostate cancer is 1 in 1,500 and 3,300 person-years respectively in this young cohort[16]. Both of these cancers are difficult to screen in young and middle aged astronaut populations and would have a significant impact on any long duration mission. With the expected 5 year cancer survival outcomes exceeding the 5% survival of a sudden cardiac arrest, in contrast to AMI, there is the possibility to effectively treat many cancers with chemo-therapy during a Mars mission, Breast cancer is the most common non-skin malignancy diagnosed in women and is the leading cause of cancer-related mortality in women aged 20-59 years.[1,7,12,19] The increased genetic susceptibility mainly from BRCA1 and BRCA2[5] genes, are risk factors which can also be selected out of an astronaut population.

Example 2 Spontaneous Pneumothorax:

The risk of spontaneous pneumothorax (SP) in the general population requiring hospital admission or physician consultation was published by Gupta et al[10], with rates generally reaching 1 per 5,000 person years in the typical age groups found in the astronaut corps (30 to 50 years). This low incidence of spontaneous pneumothorax in this cohort likely reflects the upper limit of risk for astronauts.

Prevention strategies to control occupationally induced medical events

The outcomes of idiopathic disease during space flight can be roughly estimated by observing incidence and response to treatment in analog populations, however this can be complicated by the limited treatment available during a space mission. The maintenance of human performance is influenced by the environment though air quality (headache – toxins or maladjusted atmospheric mixture), water and food quality (gastrointestinal distress – contaminated food or water system), radiation (degradations in the immune system and gastrointestinal distress), psychological factors (depression from crew interaction issues or news from Earth), and many other physiological, physical, and cognitive factors. Small changes in several of these factors may have a compounding effect and cause significant mission impact as they manifest as medical events. Many of these environmental factors may require secondary prevention in the form of countermeasures.

Example 3 Occupationally Induced Pneumothorax

Astronauts undergo a rigorous selection physical exam and are exposed to significant atmospheric changes during training which would most likely uncover a predisposition to pneumothorax further reducing the chance of a SP occurring during a mission. The only plausible risk factor for SP in reduced gravity space exploration environments is acute hypobaric exposure, such as during an EVA, which if it occurred would present a significant challenge to the CMO both in diagnosis and immediate treatment.

Thoracic injuries account for almost 25% of all trauma deaths; most of these injuries can be adequately treated by chest drainage with a tube thoracostomy alone[18]. Rib fracture is the most common thoracic injury and is present in at least 10% of all traumatic injuries of the thorax and in almost 40% of patients who sustain non-penetrating blunt trauma[13]. While rib fractures can produce significant morbidity and mission impact, the diagnosis of associated complications (such as pneumothorax, hemothorax, pulmonary contusion, atelectasis, flail chest, cardiovascular injury, and injuries to solid and hollow abdominal organs) may have a more significant clinical impact. Misthos et al[13] found that of 709 patients with a history of blunt thoracic injury who did not meet the criteria for intra-hospital management, almost 10% developed delayed pneumothorax 2 to 14 days later. Of these delayed pneumothorax 81% required chest tube thoracostomy. The low impact nature of blunt chest trauma most likely encountered during space missions might cause pneumothorax to present in a similar fashion.

Example 4 Treatment of Pneumothorax in Space

The management of pneumothorax on the ISS or the moon would require a tube thoracostomy which is presently considered a mission-terminating event. Should the treatment of SP or pneumothorax secondary to minor blunt trauma or hypobaric exposure become a requirement for exploration class missions, the insertion of a chest tube by the CMO will be a necessary component of medical care , which in the case of a Mars Mission will likely be a physician Under most circumstances, the morbidity of a tube thoracostomy usually outweighs the risk of untreated pneumothorax, and although a moderate pneumothorax is generally not acutely life threatening, a delay in diagnosis and treatment may eventually result in respiratory and circulatory collapse. Therefore the risk of a catastrophic, trauma induced thoracic injury in reduced gravity environments are very low, with on-board ultrasound serving as an effective tool in establishing the diagnosis, treatment, and return to duty status of an injured crew member.

Example 5 Decompression Sickness:

The risk of decompression sickness (DCS) during an ISS or Shuttle extravehicular activity (EVA) is considered to be adequately controlled by breathing 100% oxygen for an appropriate time prior to exposing the astronaut to reduced barometric pressures. Should the risk of DCS become unacceptable for exploration class missions, different prevention strategies may need to be applied to other DCS risk factors. In addition, should the mission designers decide that the risk of DCS is uncontrolled despite the optimization of all possible risk factors using primary and secondary prevention, tertiary prevention in the form of emergency hyperbaric therapy may need to be designed into the mission. Since some forms of DCS will incapacitate a crew member and require ALS, a hyperbaric chamber with advanced critical care may be needed. There are alternative DCS treatments which can be manifested, such as using the spacesuit itself as a "partially pressurized" hyperbaric chamber however this treatment presently cannot provide the equivalent standard of DCS therapy used on Earth.

Example 6 Radiation:

The risk of a fatal dose of radiation has always been a concern of the space program and acute radiation sickness has always been considered an uncontrolled hazard for Lunar and Mars surface EVA.[6] Recent data has shown that during a 180 day lunar surface mission performing 65 EVAs, the incidence of very large Solar Particle Events (SPE) with maximal doses of approximately 1 Gray to blood forming organs is between 0.2 to 0.3 % .[4] This calculation assumes that the crew will be exposed for the 3 hours it will take to get back to the pressurized habitat module. An acute dose of 1 Gray will not pose a life threatening risk to the crew in the form of acute radiation sickness with bone marrow suppression, but may cause some prodromal symptoms (> 10% probability, presenting as nausea and emesis).[4] This represents a significant reduction in the severity of the effects of an SPE on a crew performing an EVA on the lunar surface as compared to what was previously believed. The lunar EVA presents a much higher radiation risk compared to Martian EVAs due the greater distance from the sun and atmospheric attenuation. The acute radiation event however does not address the increase risk of long term carcinogenesis effects of the individual.

Which Medical Conditions could be disqualifying?

Even the most common and treatable illness and/or injury become a challenge in extreme environments such as those found during space travel and planetary exploration. The challenge for Space Medicine is to determine the selection criteria and performance requirements of crewmembers for a lunar or Mars Mission. Examples of crewmembers which may not be considered for selection for a Mars Mission might be candidates who:

1. Have chronic conditions that require regular dosing of life-sustaining medication for the purposes of secondary or tertiary prevention (i.e. thyroid hormone replacement or anticoagulation).

2. Have conditions that will be worsened by spaceflight exposure, placing them at additional personal health risk though not necessarily increasing mission risk (i.e. previous radiation exposure or preflight osteopenia/osteoporosis)
3. Require specialized medical devices for monitoring or treatment of a medical condition, including conditions that require special provisions to conduct routine required countermeasure activities (i.e. blood glucose meter or heart rate monitor).
4. Have a disease or requires treatment for same, and for which the effects of space travel may be deleterious to the short or long term health of the individual.
5. Have medical risk factors which raise individual or mission risk to unacceptable levels (i.e elevated CAC scores, genetic markers for neoplasia)
6. Have a medical condition which would prevent participation as a candidate in any scientific and medical operational research studies, as their underlying condition would confound the collected data.

One class of candidates the previous list does not include is the crewmember requiring primary prevention to manage a chronic condition which does not pose an increase in mission risk. These chronic disease risk factors are being mitigated in a manner which makes them acceptable to the civilian and military aviation community as well as long duration ISS crewmembers. The question remains “which diseases when combined with their primary prevention strategies will present an acceptable risk for a lunar or Mars Missions?”

Levels of Care

In the 1980’s NASA wrote its first version of the Manned Systems Integration Standard (MSIS), which specified how to design systems to support human health, safety, and productivity in space flight. However, this was too specific towards existing space programs and NASA recently decided to write a set of human factors and medical standards using more general terms that would apply to all present and future systems with human crews. The result is an agency-level two-volume document that addresses the human needs for space flight, called the NASA Space Flight Human Systems Standards. Volume 1, “Crew Health”[14] covers the requirements needed to support the astronaut health and Volume 2, “Habitability and Environmental Health”[15] covers the requirements for a system design that will maintain astronaut safety and performance .

NASA has as part of this process defined five levels of medical care to address medical support for Exploration Missions ranging from LEO missions of less than 8 days to a Mars Expedition Mission lasting several years. (See table 4) These levels of care identify the types of medical threat faced by crewmembers and the interventions needed to address those concerns. The levels focus on classes of missions, ranging from Level 1 which would be LEO missions to the ISS, and Level 5 which refers to Mars-type exploration class missions.

Mass, power, and volume constraints for Mars missions are significant: i.e., a ten pound piece of medical equipment could require 400 pounds of Earth launch mass (vehicle structure, propellant, etc.) for a long duration Mars mission. The launch phase for return from distant exploration destinations are, pound for pound of mass, even more challenging. (See figure 1)

Insert figure 1 approximately here

NASA recognizes that there is a significant risk that crewmembers may have a serious medical event during a mission an exploration class missions, and the fifth level of care was designed specifically to address this challenge. Space Flight Human Systems Standards documents the need for preventive strategies to mitigate risk factors and adequately control medical hazards, but also provides treatment capability for any critical or catastrophic medical event that is reasonably expected to occur. The standards also document that, in a Mars exploration mission, extensive medical training is required which can be met with the addition of a specially trained physician to the crew compliment.

NASA Levels of Care (see figure 2) describe the 3 categories of tertiary prevention, which are broadly categorized into 3 areas:

1. Advanced Life Support
2. Transitional Care
3. Ambulatory Care.

These tertiary prevention treatment capabilities are required for Mars missions to bring major and minor medical events to some form of medical stability to ensure mission success. The integration of all levels of prevention will describe the requirements for the total mass, power, volume, and training (MPVT) needed to reduce overall medical mission risk to an acceptable level. A Mars mission will need significant MPVT to support primary and secondary prevention (exercise countermeasures, environmental monitoring, etc.) and tertiary prevention (resuscitation, acute and chronic treatment, etc) for major/ minor illness or injury. An ISS LEO mission requires little tertiary prevention MPVT due to its evacuation capability to Earth and the secondary prevention (countermeasures) MPVT is also minimal because faulty equipment can be replaced with regular re-supply.

Advanced Life Support Care:

The Society of Critical Care Medicine and the Institute of Critical Care Medicine, defines the requirement for "critical care" (also known as "advanced life support" care) for cases in which a patient's life is in jeopardy or is at risk of sustaining failure of one or more organ systems.[1] These patients require constant, intensive care, including continuous physiological monitoring over a period of time. Tertiary prevention also requires "emergency care" which refers to the care needed in the immediate aftermath of an illness or injury but does not encompass the sustained care provided to these patients in the ensuing hours or days.

In terrestrial settings, "critical care" or "advanced life support" (ALS) is generally provided in intensive care units (ICUs) by specialist caregivers such as physicians with critical care training, critical care nurses, respiratory therapists, etc.. Although different hospitals have different criteria for ICU admission, based upon the hospital's size, staff, and capabilities, common criteria include:

- Use of a ventilator or other respiratory support
- Unstable vital signs (as defined by the attending physician or nurse)
- Need for close medical supervision
- Use of drug infusions (drug specifics vary by hospital but may include anti-dysrhythmics and/or pressor agents)
- Recent or anticipated use of defibrillator, cardioversion, or transcutaneous pacing
- Multi-organ system failure

Examples of conditions which might be categorized as requiring ALS for spaceflight will includes severe infection, toxic inhalation, 3rd degree thermal burns, anaphylaxis, DCS etc.. Risk factors underlying events which require ALS should be controlled by proper mission design and effective primary and secondary prevention strategies.

The major medical challenge to designing a mission to Mars is the inability to return a crewmember to DMCF. Therefore, mission designers need to consider the consequences of

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[1] Society of Critical Care Medicine website, "About Critical Care Medicine", http://www.sccm.org/about/about.html, and Institute of Critical Care Medicine website, "The Institute's Story", http://www.911research.org/intro.html .

treating certain illnesses and injuries from which the crewmember may not survive or more importantly, will survive, and which could deplete irreplaceable consumables and place the remaining crew at additional risk. It may be possible to resuscitate or stabilize a crewmember with a significant medical insult, however if they require ventilation or fluids without the possibility of return to a DMCF, consideration must be given as to whether initializing or sustaining treatment under such circumstances is ethically appropriate and mission enabling. Unfortunately the primary medical provider in the crew may need to make such an autonomous decision, real-time with incomplete data and limited resources.

Transitional Care

For exploration class missions, “transitional care” is needed for those conditions which impair the crewmember’s ability to perform his or her scheduled tasks, yet are not so incapacitating as to require ALS. These conditions do not need continuous, close observation but do require care beyond what the crewmember can self administer. Transitional care may also be required for the period after ALS until full recovery.

Criteria for “transitional care” would include:

- Provision of intermittent parenteral medication, such as intramuscular or intravenous injections
- Use of a splint or other device that limits mobility or activity level
- Assistance with the activities of daily living, such as catheterization in order to void
- Inability to perform the majority of scheduled mission tasks
- Inability to maintain a normal nutritional status.
- Need for intermittent physiological monitoring and/or assessment
- Need for frequent private medical or psychological conferences

Examples of conditions which might be categorized as requiring transitional care would include: diverticulitis, kidney stone, severe gastroenteritis, abdominal pain (of unknown etiology), or a fractured wrist. Obviously, many medical maladies which require transitional care may deteriorate into acute conditions such as nephrolithiasis induced sepsis.

Ambulatory Care

For exploration class missions, "ambulatory care" is defined as that level of medical care which a crewmember can independently self administer. While the flight surgeon on Earth might be consulted, no complex interventions or assistance from other crewmembers are needed. The majority of conditions which require ambulatory care are minor ailments which would be likely to resolve eventually even in the absence of treatment, but may in the interim have significant mission impact.

Criteria for "ambulatory care" are defined as:

- Resolution expected with the administration of oral or topical medications
- No more than one procedure required for resolution of condition (example: single dose of intravenous medication or reduction of dislocation)
- Ability to perform the majority of scheduled mission tasks

Examples of conditions which might be categorized as requiring ambulatory care would include: abrasion, rash, frostnip, or upper respiratory infection.

Duration of therapy

Ideally, provision of the appropriate level of care during an exploration mission will resolve a condition; either completely or to the point that it requires a less intensive level of care. The following durations of care for Mars missions need to be defined for all probable medical illnesses or injuries requiring treatment:

1.) Number of hours/days of ALS care capability
2.) Number of days of transitional care capability
3.) Number of days of ambulatory care capability

Given that the crewmembers are presumed to be in good health prior to the inciting injury or illness, it is anticipated that after a short period of critical care, the crewmember's condition will improve and only transitional care will be required. A Lunar mission may require an ALS capability to sustain the life of a crew member for the length of time it takes to return to a DCMF on Earth. This represents a significant MPVT for any Lunar short or long duration mission. Therefore ALS care should be provided for a limited period of time with subsequent triage to determine whether additional resources are needed, or whether the intervention should be terminated.

In addition, ALS care should be able to:

- improved diagnosis – more time to follow signs and symptoms and to perform the available diagnostic tests, as well as time to create and consult with an earth-based team of medical specialists with the appropriate knowledge base(s)
- provide a trial-of-therapy – the ability to attempt treatment and to observe the crewmember's response
- improved patient outcome through more accurate diagnosis
- optimize the balance between patient outcome and mission impact

In the event that provision of ALS care allows the crewmember to improve sufficiently such that transitional care is subsequently required, resources will be required to support transitional care resolution of the original medical condition, plus resources to manage any secondary complications. Although it is conceivable that some conditions might require transitional care for an extended period, the goal of treatment is to improve the condition, and it is therefore reasonable to assume that with appropriate care most conditions will shift from requiring transitional care to needing only ambulatory care.

An ambulatory level of care would be available for the duration of the mission. This is meant to address not only conditions that had been more serious but are improving, but also the routine minor conditions that are frequently encountered, which, given adequate supplies, can safely be managed permanently or treated to resolution in-flight. ISS experience has shown that the most common conditions seen during missions have been self-limiting illnesses and chronic problems which only require an ambulatory level of care.

The occurrence of illness or injury during an exploration mission may result in several outcomes depending on the patient's response to therapy. The ability to predict how any particular illness or injury will progress from ALS care through ambulatory care is quite difficult on Earth, and the unique characteristics of a Lunar or Mars mission may further complicate this task. There may be insufficient data to drive an illness or injury specific model, yet a generalized approach may not identify essential requirements for specific medical events. A comprehensive risk analysis of all possible medical hazards would be one approach to drive the definition of exploration class medical systems.

Failure of Therapy

The possibility of permanent impairment or death exists during any remote mission to an extreme environment and exploration missions are no different. Accordingly, it is necessary to prospectively identify procedures to be followed in such a case. This is important so that all stakeholders (flight surgeons, crew and families, flight directors, public affairs, etc.) are familiar with procedures in the event of a death. Similarly, the criteria for a considering a "do not resuscitate" status on a fatally ill or injured crewmember should be established prospectively for all possible medical conditions during a Mars mission.

In addition, criteria should be established prospectively for those conditions for which descent to the Martian surface for one year is inappropriate. This could include those conditions which are intolerant of the necessary seat position, the G forces (including descent and impact), other forces (spin, swing, etc.), or those which have a need for continual assessment and/or intervention which may embarrass mission success. Some examples of these conditions, albeit very rare for a Lunar or Mars mission, include spinal injury, femur fracture, or cardiovascular compromise.

Engineering Requirements for Space Medical Hardware and Procedures

All space flight hardware is designed, manufactured, tested and certified to meet its mission critical functional requirements. In addition the hardware can't be easily returned to Earth for upgrades, repair, or replacement. Due to the challenges imposed by the requirement for autonomous medical care, coupled with the limited MPVT associated with a Mars mission, a requirement for advance medical technologies which have no Earth medical analog may need to be developed by NASA. An example of this is the promising recent work funded by NASA's Smart Medical Systems project to validate closed-loop algorithms used to control oxygenation/ventilation and fluid resuscitation in an acutely ill patient which represents a change the current paradigm for medical care in extreme environments. The paradigm shifts in medical policy require that:

- certain aspects of medical care for the patient be adequately managed by the medical device in question in an autologous fashion with minimal physician oversight.

- the use of these algorithms minimizes the consumption of critical mission resources (such as fluids or oxygen) by optimizing what is medically needed for medical event stabilization.

The provision of a reasonable and prudent duration of ALS for a Mars Mission would require the following resources be manifested:

- A means of securing and maintaining the airway
- A means of oxygenating and ventilating the patient
- A means for the patient to resume unassisted respiration
- A dedicated location for the provision of medical care and ready access to other requisite resources
- A means of providing continuous physiological monitoring
- Adequate supplies of pharmaceuticals, including anti-dysrhythmics, fluids, systemic and local analgesics, sedatives, and antibiotics, any of which can be administered parenterally or orally
- A means of providing parenteral medications at specific rates (such as syringe drivers or infusion pumps)
- A means to relieve a hemo-pneumothorax, effusion, or pericardial tamponade
- A means of emptying the stomach, colon and bladder
- A means to stop external bleeding, protect wounds, and promote their healing
- Adequate pre-flight training of the crew medical officer (CMO) in the requisite skill sets, with sustainment training during the mission
- Diagnostic imaging system(s)
- The ability to perform basic laboratory studies
- Digital scopes (stethoscope, ophthalmoscope, otoscope) that permit downlink of images and/or sounds
- The ability to splint or otherwise stabilize orthopedic injuries
- A dental care kit, eye care kit

Once the requirements for these devices are integrated into a medical care system design, reliability becomes a significant engineering challenge. Questions remain as to whether medical devices which were designed for terrestrial use will provide the same functionality and relaiability during exploration missions. Most medical devices used in current medical environments on Earth have been validated by daily clinical use and have been regulated for their intended use by several government agencies. These devices are regularly maintained in a manner which makes them cost effective, accurate, and safe.

Mission critical hardware for space flight is designed with strict material and design constraints. The current off-the-shelf medical technology used in most primary, secondary and tertiary medical care environments would not meet these design and test criteria, nor would it meet the material limitations for critical mission space hardware. Some medical devices may only meet these strict requirements for mission critical reliability if they are made redundant by manifesting a backup capability. This would increase the mass, power, and volume of vehicle design. Most commercial medical equipment is used continuously, and therefore durability/reliability is tested thousands of times everyday. Mission designers will need to combine operational experience gained from using commercial-of-the-self medical devices with the reliability and ruggedness of space hardware design and testing practices.

Conclusion

The primary objective in sending humans to Mars is to explore and perform science. The maintenance of human health and performance, using appropriate medical care, is essential to meet these mission objectives. This is particularly true for missions which, by the nature of its inherit hazards, place the crew at increased risk for illness and injury. The medical support required for the exploration of the solar system would include a multi-tired medical prevention and intervention approach. The evidence based use of tertiary prevention for treatment of stochastic or unpreventable illness or injury is difficult to accomplish even on remote terrestrial outposts where operational data is becoming abundant. Medical planning for a surface mission to Mars must address the expected hazards secondary to the mission profile in addition to the stochastic medical events inherent in any population of healthy humans. The 1/3 gravity environment enables a much simpler design of medical hardware and procedures when compared to the microgravity of ISS. Nonetheless, the voyage to and from Mars will occur in a microgravity environment barring the deployment of large scale artificial gravity on transfer vehicles. Medical systems designed for these disparate gravitational fields may require unique hardware and procedural solutions to handle samples and waste under varied environmental conditions.

Medical hazards for space exploration are diverse in their incidence, severity, and outcome. The ability to maintain current standards of care for exploration missions over the next 25 years will be complicated by the lead time of 5 to 10 years it takes to design, build, validate and certify a medical support system for flight, while terrestrial medical standards of care continue to evolve. The medical support of a Moon mission in 10 years and a Mars mission in 20 years may require a different paradigm as it pertains to maintenance of the appropriate medical standards of care, given that these standards advance daily on Earth.

Most medical provider organizations rely on an evidenced-based approach to deriving standards of care. Exploration medicine will to some extent be able to call on the experiences of past and current spaceflight , in addition to advances that have occurred in medicine in extreme environments However, Lunar and Mars missions may represent a "new frontier", where we may find ourselves in a situation similar to the 1960's lunar missions…. inventing a space medical risk mitigation strategy based on "a whole bunch of smart people thinking hard in absence of experience and data" … yet they have to get it right the first time.

Figure 1

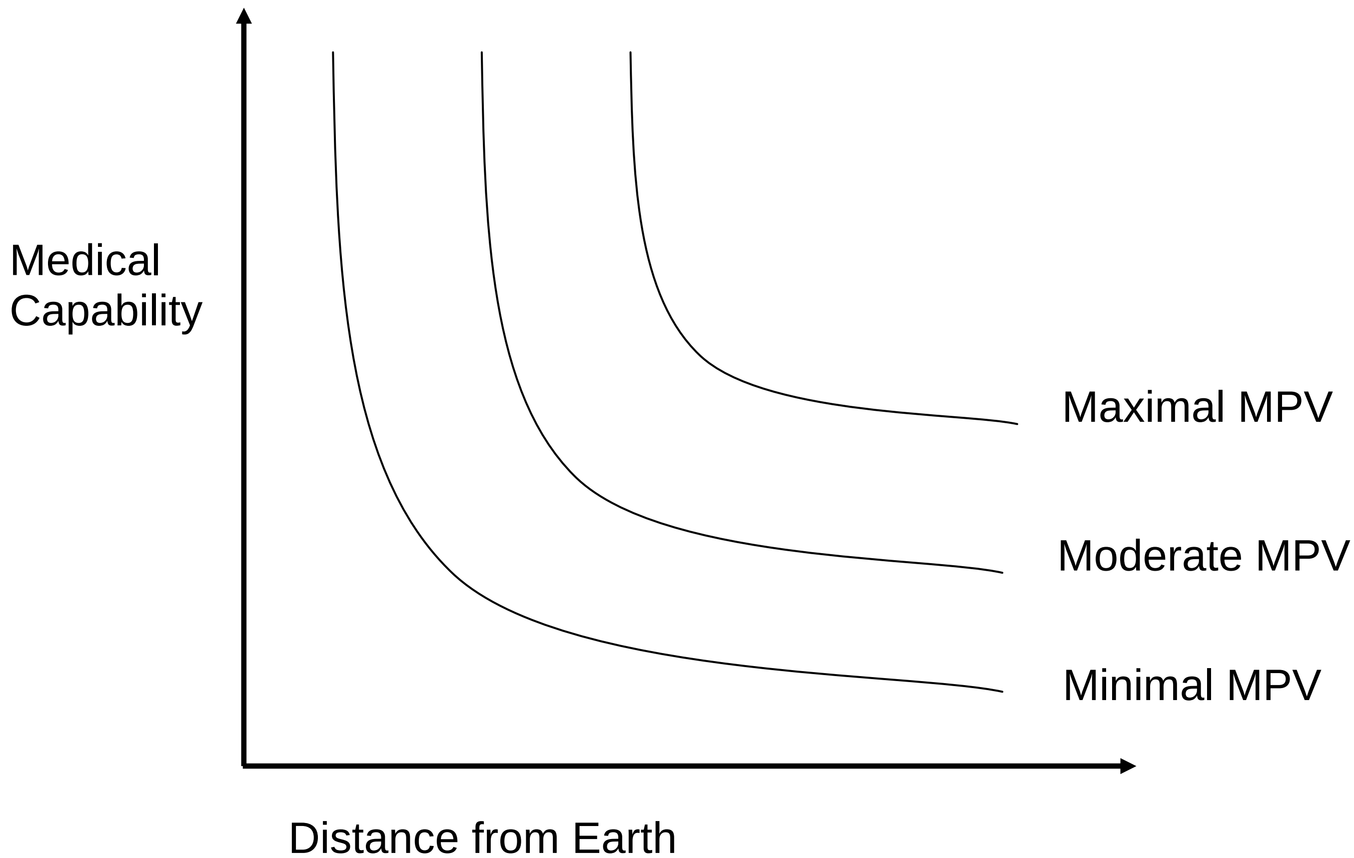

Figure 1.

Constraints must be considered in the mission optimization process including mass, power, and volume (MPV), and the medical capability that will be required for adequate hazard control and emergency procedures. Launch weight and volume constraints exist both on Earth and for return from lunar and planetary missions, potentially requiring forty pounds of vehicle launch weight per pound of medical payload for a long duration Mars mission. The launch phase for return from distant exploration destinations are even more challenging from a mass standpoint. Thus the relative importance of primary and secondary prevention strategies increases as mission duration, distance of destinations, number of surface launches required, hazard likelihoods, and number of crew increase.

Table 1 - Medical Capability on Shuttle and the ISS

Shuttle	SOMS	• Airway Subpack (Resuscitator / Ambu bag valve mask) • Trauma Subpack • EENT Subpack (contains general diagnostic and therapeutic items) and TONO-PEN Kit • Drug Subpack (contains oral, topical and injectable medications.) • Saline Supply Bag • IV Administration Subpack (plus blood pressure cuff used to move the IV saline fluid through the IV line) and one 500ml bag of saline • Sharps Container • Patient and rescuer restraints • Operational Bioinstrumentation System to provide the ability to downlink Electrocardiogram • Contaminant Cleanup Kit • Medical Accessory Kit (storage location for all crewmember personal medications)
ISS	Advanced Life Support Pack	• Injectable medications • Intravenous fluid and administration equipment • Airway management equipment. • Blood pressure cuff • Stethoscope • Pulse oximeter
	Ambulatory Medical Pack	• Oral medications • Topical medications • Bandages for most in-flight problems • Portable Clinical Blood Analyzer • Dental hardware • Minor surgical supplies
	Crew Medical Restraint System	The CMRS provides restraint, with spinal stabilization, for an ill or injured crewmember, while also providing restraint for the CMOs attending to the patient
	Crew Contamination Protection Kit	Multipurpose cleanup kit. Its primary purpose is to protect crewmembers from contamination from toxic and non-toxic particulates within the ISS environment.
	Medical Equipment Computer	Laptop with a customized Medical Operation Software load. • Displays physiological data from exercise devices • Collects and stores medical data • Maintains medical records • Tool to assess crew health • Provides up link/down link capability

	Defibrillator	Provides for defibrillation, ECG and heart rate monitoring and analysis, and transcutaneous (external) pacing.
	Respiratory Support Pack	Ventilates an unconscious crewmember automatically, provides oxygen to a conscious crewmember.
	Blood Pressure/ Electrocardiograph	Provides the capability for automated, auscultative, noninvasive systolic and diastolic blood pressure measurements and the capability to monitor and display heart rates/ECG waveforms on a continual basis during the performance of exercise countermeasures on orbit.
	Countermeasures System	• Treadmill with Vibration Isolation System • Resistive Exercise Device • Cycle Ergometer with Vibration Isolation System

Table 2 - Medical Hardware Limitations for Constellation Vehicles

Vehicle/Mission	Size (inches)	Mass (lbs)	Role
CEV to ISS	10x7x6	10	Treatment of minor ailments on route to ISS and return to earth
LSAM Medical Contingency	32x12x16	30	Portable medical gear to be able to respond to surface illness and injuries as required. Must interface with CEV
Lunar Base Contingency	16x16x8.5	16	Portable medical gear to be able to respond to surface illness and injuries as required. Must interface with LSAM and CEV

Table 3 – Levels of prevention

Prevention	**Definition ***	**Rationale**	**Methods**
Primary	Those measures *"provided to individuals to prevent the onset of a targeted condition*"	Eliminate the hazard e.g. by selecting in crew members without disease, and who have no symptoms of disease	This is achieved by estimating the incidence and prevalence of pathology in the astronaut cohort. The astronaut cohort is small, and therefore risk data must be derived from observations, likelihoods, and severity of illness or injury in similar cohorts such as the military.
Secondary	Those measures *"that identify and treat asymptomatic persons who have already developed risk factors or preclinical disease but in whom the condition is not clinically apparent"*	Protect against a hazard that could not be controlled by primary prevention alone such as the effects of reduced gravity on bone or chronic low dose radiation on increased cancer likelihood.	During space travel there are root-causes to environmental and operational hazards which are not adequately controlled by mission design or other primary prevention strategies. These root-causes need to be mitigated using secondary prevention such as load bearing exercise to reduce bone loss in reduced gravity environments.
Tertiary	Those measures *"which the care for established disease, with attempts made to restore to highest function, minimize the negative effects of disease, and prevent disease-related complications"*	Tertiary prevention is invoked in most medical systems when primary and secondary prevention has failed. It is the least cost effective means of providing medical care in an extreme environment.	Illness or injury may be due to an uncontrolled hazard harming the crew (fire), an ineffective countermeasure (decompression sickness), or previously undetected disease causing an acute illness requiring treatment. The ability to provide tertiary capabilities can be categorized as Advanced Life Support care, Transitional care and Ambulatory care.

* Adapted from U.S. Preventative Services Task Forces' Guide to Clinical Preventive Services

Table 4 – Levels of Care for Mission duration and destination

Levels of Care	Mission	Suggested Capability	Rationale
I	LEO < 8 days (STS and CEV)	BLS + first-aid capability	All serious illness and injury will be evacuated to an Earth based DCMF.
II	LEO < 30 days SST to Hubble	Level I + Clinical diagnosis, Ambulatory Care, Private audio (+/- Video) Telemedicine	Relatively short mission duration eliminates need to evaluate for long-term changes during the mission
III	LEO > 30 days ISS (or Lunar sortie)	Level II + Limited ACLS, ATLS, Minor surgical care, return vehicle with dedicated capability.	Immediate return to Earth capability shall be available for more serious illness/injuries.
IV	Lunar Outpost > 30 days	Level III + imaging and sustainable ACLS	Advanced Life Support capability, but not the critical care needed after such an event since the evacuation vehicle(s) shall support Advanced Life Support equipment for return to Earth.
V	Mars Expedition >210 days	Level IV + without immediate return to earth capability. Autonomous ALS, Basic surgical care and palliative care.	Trial of therapy for patients requiring Advanced Life Support. The training and caliber of the primary caregiver shall be a physician. Palliative care shall be manifested since failure of therapy may result may result permanent impairment or death.

BLS – Basic Life Support

ALS – Advanced Life Support

ACLS – Advanced Cardiac Life Support

ATLS – Advanced Trauma Life Support

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