NASA/TM–2014-217384

Identification of Medical Training Methods for Exploration Missions

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January 2014

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Acronyms and Abbreviations

AAMC	Association of American Medical Colleges
ACLS	advanced cardiac life support
BLS	basic life support
BME	biomedical engineer
CMO	crew medical officer
CPR	cardiopulmonary resuscitation
EMCL	Exploration Medical Condition List
EVA	extravehicular activity
ExMC	Exploration Medical Capability
HRP	Human Research Program
IMM	Integrated Medical Model
ISS	International Space Station
JIT	just-in-time
LEO	low-Earth orbit
NASA	National Aeronautics and Space Administration
NEA	near-Earth asteroid
OSCE	objective-structured clinical examinations
SME	subject matter expert

1.0 INTRODUCTION

As the National Aeronautics and Space Administration (NASA) and its international partner agencies anticipate eventual exploration missions of longer duration, there is a need to plan for the medical capabilities necessary to maximize crew health and provide the best likelihood of mission success. Current space flights consist of 5- to 6-month excursions to the International Space Station (ISS) in low-Earth orbit (LEO), and a 12-month ISS mission is currently in planning stages. However, missions to a near-Earth asteroid (NEA), a return to the moon, or even a mission to Mars will demand unprecedented medical capabilities, particularly relating to the training of the crew medical officers (CMOs).

The Exploration Medical Capability (ExMC) element within NASA's Human Research Program (HRP) defines a series of "gaps" in its attempts to address the questions about medical preparation for space flight beyond LEO. These gaps are shortcomings in knowledge, training, or technology that require resolution before an exploration mission can be undertaken. The ExMC element maintains current information about measures to close these gaps while developing plans for further investigation and research. Data pertaining to the gaps and their present status are available to the general public on the NASA Human Research Wiki and the NASA Human Research Roadmap Web sites.[32, 34]

One such gap, Gap 3.01, identifies a lack of knowledge about "the optimal training methods for in-flight medical conditions identified on the Exploration Medical Condition List (EMCL), taking into account the crew medical officer's (CMOs) clinical background".[31] This broad statement encompasses several related issues with the current methods of training CMOs and the medical ground support staff, specifically flight surgeons and biomedical engineers (BMEs) located in mission control, in addition to questions pertaining to the ways in which training will need to be adapted for the medical contingencies unique to exploration missions. Current CMO training methods, and potential alternative training methods were identified to determine the optimal methods of medical training for an exploration medical crew and their ground support team, the historical context of medical operations.

1.1 Historical Context

Space flight presents a considerable risk to crew health, safety, and performance, the maintenance of which is essential for human exploration beyond LEO. The limitations of human physiology, disease, and injury have accounted for a significant number of mission objective losses in human space flight history.[45] The current health-care paradigm for LEO operations is designed to provide medical prevention strategies with the aim of reducing the occurrence or impact of hazards. Astronauts undergo extensive screening and medical examinations before they are selected to be astronauts. Screening standards have evolved over the many years of space flight experience and are designed to assess health-related risks for each astronaut candidate and minimize the potential for medical impact on future mission success. After astronauts are selected, crew physicians, known as flight surgeons, are responsible for the development of prevention and therapeutic strategies that are put into place for astronaut health maintenance.

In more than 50 years of human space flight history, about 400 men and women have flown in space.[45] Although medical incidents have occurred, the most common medical events are self-limited illnesses or exacerbations of chronic conditions requiring only an ambulatory level of care.[19,45] Minor injuries during space flight are common and encompass mainly abrasions, contusions, and strains.[40] More serious musculoskeletal injuries such as dislocations and sprains are exceedingly rare and, despite documented bone density loss, there is no history of a skeletal fracture occurring in space.[7] Other common ailments reported during space flight include exercise-induced overuse injuries, space motion sickness, sleep disturbances, and extravehicular activity (EVA)-associated injuries. Despite the low acuity of most medical events during space flight, events do occur with some frequency: about 75% of Space Shuttle astronauts used medication to treat a nonemergent problem.[45]

Although these data are both available and useful, there are several limitations to using a historical review of medical events to predict future medical challenges. Methods of data collection and the types of data collected have evolved over the history of human space flight, even within the U.S. program. Furthermore, the data that do exist are stored in multiple formats in many repositories located at a variety of institutions in different countries. Other challenges include the small number of subjects available for analysis and the possibility of underreporting among space program participants. In addition, no suitable control population is available for comparison to validate the data collected. Finally, exploration missions are fraught with unique challenges that surpass those faced by the LEO experiences of historical space flight.

When long-duration missions are planned, it is necessary to develop a way to better anticipate a multitude of medical events including both the common and minor problems with which experts in aerospace medicine are familiar, and a host of other, more serious, conditions.[6] To this end, the integrated medical model (IMM), a statistical prediction model, has been developed to project the likelihood of a wide range of medical contingencies. The IMM establishes the mathematical relationships between the likelihood of a medical event, potential risk mitigations, and subsequent clinical outcomes based on those mitigations, then uses a simulation technique to determine the probable outcomes.[16] With this model, ExMC maintains the EMCL, a dynamic document listing the medical conditions expected to occur in the course of several defined mission parameters.[33] Although this list identifies the conditions the CMOs should be capable of managing, preparing the crew and ground personnel for in-flight management requires the development of new training programs that specifically account for the risks and limitations of exploration missions.

1.2 Unique Risks of Exploration Missions

Plans for a long-duration interplanetary exploration mission must address many limitations not previously encountered in human space flight. The logistics of traveling such a great distance away from the Earth, and the environment faced by astronauts living and working in interplanetary space or on a distant planetary body impose novel challenges to the delivery of health care to exploration crewmembers.

Medical Risks

The technical requirements for an exploration mission, such as a mission to Mars, necessitate an expedition of as much as 2 to 3 years of extended space flight. No human has yet spent such a consecutive length of time in space. This extended stay in an austere environment increases the likelihood of occurrence of medical events, both minor and severe. These events include, but are not limited to, disease, trauma, decompression sickness, burns, toxic exposures, overheating or overcooling, life support failure, depressurization, and meteorite impacts.[6] The distance imposes additional challenges on an exploration mission. As the spacecraft travels away from the Earth, the time needed for a communication signal to travel from the Earth to the crew and back will be increasingly prolonged. With current technology, it could take as long as 45 minutes to complete a communication loop between mission control on the Earth and a crew on the Martian surface, depending on the orbital positions of both planets. Definitive care on the Earth could be as much as 4 to 6 months away.[24] The distance renders both rapid medical evacuation and timely resupply impossible, meaning that the crew must bring with them all the medical equipment, disposables, and even knowledge and skills that they would require for the duration of the mission. However, it will be difficult to anticipate all of the medical equipment the crew might need to carry for a 2- to 3-year mission, particularly because of the lack of any precedent for such an undertaking.

Environmental Concerns

Crewmembers of a distant exploration mission will face a level and duration of radiation exposure never before encountered in the history of space flight. Multiple authors identify radiation as a principal risk to crew health on an exploration mission.[4,18,19] During the 6-month journey between planets, nothing can protect the crew but their own spacecraft.[18] There remains no reliable way to forecast large radiation events; current technology enables less than 30 minutes of warning before a solar particle event.[18] Using a mission to Mars as an example, and assuming a 180-day surface stay and 65 EVAs (among the lower estimates encountered in the literature), the crew would face a 0.2% to 0.3% risk of a very large solar particle event delivering up to 1 Gray of radiation to blood-forming organs.[19] Though these percentages are small, they may constitute a risk of radiation-induced illness. Furthermore, the late effects of radiation exposure, likely to result from galactic cosmic radiation, occur months to years after exposure and manifest as an increased incidence of certain tumors, skin cancer, hematologic cancers, cataracts, tissue damage or mutations, and other symptoms.[19] Given a multi-year expedition, it is possible that astronauts may begin to show these late effects during the mission, with a potential operational impact.

Radiation is not the only long-term exposure with which the crew must contend. It is not clear how the crew will adapt to functioning in reduced gravity as would be encountered on an interplanetary mission. Even more uncertain is how the crew will tolerate the forces of liftoff from a planetary surface after a prolonged period of living and working in reduced gravity.[38] The deconditioning of the crew coupled with the increased demand of multiple, frequent EVAs may precipitate a variety of musculoskeletal injuries. There is a historical rate of injury (generally musculoskeletal) of 0.26 injuries per EVA or 0.05 injuries per hour spent outside the vehicle.[7] This becomes relevant for any exploration mission, as the frequency and total number of EVAs is anticipated to exceed current operations.

Behavioral Concerns

The long-term effects of reduced gravity may have a substantial impact on crew physiology and predispose crewmembers to physical injury, and the long-term effects of the mission itself may have a substantial impact on crew psychology and, in turn, the outcome of the expedition. Behavioral health is a perceivable threat to crew health and mission success, as it has resulted in substantial mission impact in analogous environments.[4] The Russian space program uses the term “space asthenia” to describe depressive and dissociative symptoms that occur in cosmonauts. The pressure of the mission, its associated workload and compressed timeline, the lack of privacy, confined living and working area, reduced sensory stimulation, loss of traditional social support, prolonged isolation, and the unique challenges arising from the interactions of a multicultural crew are all factors that can influence behavioral health.[18,38] These stressors will be more severe and of longer duration on a prolonged expedition, worsened by the inability to communicate with physicians, friends, and family in real time. It has been recommended that any CMO assigned to an exploration mission should be comfortable with the early recognition of psychological symptoms and the provision of an accurate description of a crewmember's psychological condition to the ground-support teams.

With consideration of all possible events, the CMOs of an exploration mission must possess all resources necessary for medical autonomy in prevention, diagnosis, and treatment.[24] These resources may be any combination of a medically trained crewmember, medical equipment, diagnostic and treatment aids, and decision-making tools. [38] Epidemiological data from analog environments have suggested that a crew with seven members will face one medical event with mission impact every 6 months, and that a major surgical case is likely to occur about every 9 years of cumulative space flight experience.[34] As NASA and its international partners plan for human interplanetary space exploration missions, the question of how to provide optimum medical care during a long-duration space flight becomes increasingly relevant.

1.3 Context of Current Medical Operations

Current ISS operations employ CMOs with the support of ground-based flight surgeons for the on-orbit assessment and treatment of medical contingencies. CMOs are astronauts chosen to serve as the in-flight medical care officers for the entire crew; they receive basic medical training on the use of essential on-orbit medical equipment and on the recognition of a variety of common medical conditions. ISS CMO training consists of about 40 hours of premission instruction with an additional (though optional) clinical observation component. During a 6-month mission, two CMOs on the ISS serve the medical needs of a six-person crew. Resources available to the on-orbit CMOs include just-in-time (JIT) training components such as written cue cards and computer-based tutorials, the ability to consult with flight surgeons and BMEs in mission control, and the potential for emergency medical evacuation to a terrestrial medical facility for definitive treatment in a worst-case scenario.

The CMO training flow for ISS expeditions generally includes lecture and practical lessons on medical diagnostics, medical therapeutics, and cardiopulmonary resuscitation (CPR) and advanced cardiac life support (ACLS) training adapted from American Heart Association standards. All astronauts, whether or not they are assigned as the CMO, must participate in ACLS training. A small portion of CMO training involves simulated "megacodes" that the entire crew is required to attend. These two 2-hour, instructor-led sessions focus on simulating medical emergencies such as electrocution, smoke inhalation, cardiac arrhythmia, and choking. Presently, the "megacode" crew instructors are registered nurses who remain in the room with the crew during the simulation and provide feedback in the form of prompts when needed. Although the crew flight surgeon is not required to attend, when present, the flight surgeon is in the room with participants and provides continual feedback during the first megacode simulation, then moves to a proxy console to simulate air-to-ground communication during all iterations of the second simulation. A low-fidelity Laerdal torso is used for simulation purposes. There is no pass-fail standard; rather, a subjective assessment of the crewmember's performance with informal feedback determines whether the simulation was successful. The latest refresher or megacode scenarios can occur up to 5 months before launch. Crewmembers are required to demonstrate their skills in simulation scenarios, but fortunately an acute cardiac arrest situation requiring actual use of these skills has never occurred in space flight. As a result, no outcome data exist with which to evaluate the success of crew training. The situation is similar for the management of numerous other potential medical problems.

During mission preparation for ISS crews, instructors generate a training report for each astronaut after the conclusion of a training activity. These reports consist of a checklist reflecting the instructor's confidence that the individual acquired the intended knowledge or skills. The reports also provide a forum for instructors to offer feedback to the crewmember. If desired, a crewmember can provide feedback on a given course or request tutelage in a specific area of training, though time is a limiting factor, particularly as launch dates approach. The postflight medical debrief consists of a 2-hour session in which the community of space medicine training instructors, remote guiders, and BMEs pose a list of previously released questions to the crew in a face-to-face format.

2.0 APPROACH TO GAP 3.01

Multiple challenges exist in the training of a CMO for a long-duration mission beyond LEO. The obstacles include inadequate information identifying space-specific treatment conditions, skills degradation during the course of a prolonged mission, and inadequate training methods and tools for preflight and in-flight application. Ultimately, the goal of this gap is to determine the best methods for training exploration-class CMOs. To provide for the highest success of an exploration mission and the health of the crew during the flight, mission planners need to generate the best possible medical training for the CMO, the best possible preparation for ground support, and the best medical technology and equipment. A thorough investigation of the needs of exploration medical training was undertaken in an effort to make progress toward this ambitious aim.

Multiple literature reviews were conducted on currently available literature about the topics of medical education and training using databases including Medline, PubMed, Web of Science, Scopus, and Google Scholar. This literature review facilitated an effort to define more specifically the areas of training needing investigation for gap closure. Within each area, a comprehensive list of questions about training was extrapolated with the intention of subdividing the current gap into smaller and more precise topics that experts in corresponding areas of training might readily address. These topics are defined in Table 1.

Table 1. Classification of Areas to be Investigated to Identify Optimal Methods of Medical Training for Exploration Missions

Topic of Investigation	Examples of Associated Questions
Validation	How are medical education and medical training validated? How can we apply the standards established in the validation of medical education teaching to validate training methods for exploration missions?
Metrics/Quantification	What metric do we use to assess the effectiveness of our training programs, strategies, and techniques? How do outside groups certify their medical personnel?
Telemedicine	Are there gold standards for training users of telemedicine in a terrestrial environment?
Just-In-Time Training	Are there gold standards for just-in-time training programs in a terrestrial environment?
Dental	What are the gold standards for dental-focused training in a terrestrial environment? How can we adapt the current terrestrial gold standards to the limitations of our training environment?
Medical Knowledge	What are the gold standards for medical knowledge training in a terrestrial environment? How can we adapt the current terrestrial gold standards to the limitations of our training environment?
Medical Skills / Procedures	What are the gold standards for training in medical skills/procedures in a terrestrial environment? How can we adapt the current terrestrial gold standards to the limitations of our training environment?
Hardware Use	What are the gold standards for training on use of hardware in a terrestrial environment? How can we adapt the current terrestrial gold standards to the limitations of our training environment?
Behavioral Health	What are the gold standards for training in the area of behavioral health screening, diagnosis, treatment, and counseling techniques in a terrestrial environment? How can we adapt the current terrestrial gold standards to the limitations of our training environment?
Prevention of Knowledge and Skill Degradation	How do we quantify the degradation of skill and knowledge with increasing time since last training? What strategies do outside groups use to assess need for currency training and maintain training currency?

Next, subject matter experts (SMEs) were identified in each of the above areas. A list of SMEs was created including experts from within NASA as well as outside of the organization. Outside experts were identified by (a) reviewing lists of previous participants in past training working groups, (b) perusing the literature reviewed for authors whose names occurred more than once on papers focusing on medical education, and (c) searching the SciVal® Experts commercial networking database.[42] This exercise resulted in a list of contacts organized by area of expertise.

The SMEs identified through this activity have been called on in various endeavors to address this gap. First, in 2012, ExMC hosted a Telemedicine Workshop at Johnson Space Center. The goal of the workshop was to create an operational concept for an exploration mission.[5] The results of that workshop are described in detail in Barsten et al.[5]; pertinent findings will be referenced here. In addition, an information-gathering survey was compiled by ExMC and e-mailed to a selection of SMEs to gauge their opinions on topics relating to CMO training. The remainder of this document outlines the information currently known with regard to each area of this gap, lists the lessons learned through initial investigations into the questions above, and provides an overview of the questions that remain unanswered.

3.0 IDENTIFYING OPTIMAL TRAINING FOR CREW MEDICAL OFFICERS

The current CMO training flow serves as a template for building a more comprehensive medical curriculum specifically targeted to the needs of a CMO serving on an extended-duration mission. However, before the work was done for this gap, the optimal training methods for medical care in exploration missions were unknown, nor was it known how to sufficiently retain medical skills over the duration of such a mission.[45] Currently, NASA standards require the inclusion of a physician crewmember on any lunar or planetary mission outside of LEO and lasting longer than 210 days.[53] Given the time and cost constraints of exploration mission planning and training, this standard identifies a need for the inclusion of a CMO with a medical background and clinical experience. Therefore, the authors will presume herein that an exploration mission will include a physician-level CMO.

In an effort to identify best methods for crew medical training, an information-gathering survey was sent to 46 SMEs. These included NASA flight surgeons, crew medical instructors, and those with military, austere environment, and behavioral health backgrounds. Twenty-seven individuals responded (15 crew trainers and flight surgeons, 6 behavioral health experts, 1 austere environment expert, and 5 military experts). Although this survey was purely observational, the three major consensus points regarding crew medical training were as follows. First, 93% of respondents thought a NASA-developed examination for CMOs would be beneficial to validate their preparedness to perform autonomous medical care during an exploration mission. Next, 100% of respondents felt that scenario-based simulation exercises are an efficient means to rehearse contingency scenarios and work out complex actions at low expense. Additionally, they recommended that NASA invest training time for crewmembers and CMOs in scenario-based exercises simulating exploration mission contingencies. Finally, 61% of respondents felt that, if a medical curriculum to include comprehensive CMO training was developed for exploration missions, they would recommend that the range of hours devoted to the curriculum training be 80 to 120 hours.

The case for increasing training hours was further supported by free-text comments by the SMEs, arguing for increased training hours from the current 40-hour curriculum to a range of 80 to 120 hours for exploration missions. (It is worth noting that this range of hours was identified as “most ideal” based on the answer choices provided; the survey provided the options of 40 hours, 80 hours, 120 hours, or “other.”)

The SMEs also identified concerns about the retention time for skills taught in the current CMO curriculum, the best training methods for exploration CMOs, and how to best prepare CMOs for missions with communication delay and no evacuation options. These questions warranted investigation of both the evolution of the current CMO curriculum and simulation data in current medical education literature. These issues will be addressed in the following paragraphs.

3.1 Developing a Prelaunch Medical Curriculum

Multiple restrictions must be accommodated when a baseline prelaunch medical curriculum is being designed for exploration missions. They include not only the confines of time available for premission training and for tasks during flight, but also limits on the mass and volume of medical equipment available for the mission. Furthermore, inherent risks that are unanticipated at this time are possible with extended-duration space flight and flights beyond LEO, and any curriculum must be fluid enough to accommodate training for new risks that may be discovered in the course of mission planning.[39] Finally, a JIT-training curriculum will play an integral role in conveying new information during missions while also providing for maintenance of knowledge through periodic refresher modules.

Successful preparation for an exploration mission requires defining a list of procedures and skills necessary for each condition on the EMCL and prioritizing procedures or skills to emphasize the training necessary to diagnose and treat the conditions that are most likely to threaten lives and missions. A goal for future workshops would be to agree on an ideal level of CMO familiarity or comfort with each condition. Assigning priorities to the conditions on the EMCL allowed mission planners to determine the skills for which to train CMOs, not only during premission preparation, but also through modules designed to maintain knowledge and skill during the mission. Additionally, this system of ranking the expected abilities of the CMOs allowed identification of the medical training most suited to JIT training. CMOs do not necessarily need intensive training in more routine or minor ambulatory procedures, or may not need to be as familiar, before the start of a mission, with the medical conditions that are least likely to occur. By contrast, some procedures and skills necessary for a successful intervention in a more critical situation, such as cardiac arrest algorithms, require training to a goal of autonomous performance.

3.2 Ground-Based Medical Training for Crew Medical Officer and Non-Crew Medical Officer Crewmembers

The surveyed SMEs agreed that CMOs should receive dedicated training that exposes them to live patient experiences; incorporating didactic sessions and hands-on training to practice skills.It has been recommended that CMOs become self-sufficient and specifically *not* require real-time assessment and assistance from ground-based flight surgeons for common conditions and emergent medical stabilization, and autonomy should be encouraged if not required. Training that specifically incorporates the crew flight surgeon for guidance and assistance was recommended, and all experts specifically agreed on the necessity of scenario-based exercises that force CMOs to practice their medical skills and consultation, when appropriate, with the ground. Although hospital or clinical observational training was considered a useful adjunct, according to survey results actual hands-on skills utilization scenarios, such as moulage or simulation training techniques, are considered to be more helpful in ensuring both the acquisition and retention of medical skills.

Basic life-saving scenarios would need to be drilled repeatedly to ensure CMO confidence. Much of this training is already provided in the current CMO prelaunch training flow. In light of the specific challenges of an exploration mission, the SMEs agreed that even non-CMO crewmembers should receive this basic level of training so that each is independently capable of providing emergency life-saving care in accordance with basic life support (BLS) or ACLS standards. This was echoed at the 2012 ExMC Telemedicine Workshop, where participants stated that all crewmembers, even the non-CMOs, “should be familiar with performing expected medical procedures and should know the location of supplies and equipment.”[5] The risk for CMO incapacitation is worth concern: for example, the HRP Requirements Document lists exploration mission parameters including three to six crewmembers for various missions to the lunar surface, Mars, or a NEA.[35] In the case of a three-person crew, if one crewmember is injured or becomes ill, there is a 33% chance that that crewmember will be the medically trained CMO. Should the CMO be compromised, non-CMO crewmembers would need some degree of medical training and autonomy. With the added resources of telemedical consultation, emergency procedures, JIT training, and guidance from the CMO (if only partially incapacitated), training should be intended for non-CMO crewmembers to handle only the most emergent stabilization scenarios.

3.2.1 Prelaunch medical hardware training

Premission ground training would need to focus on familiarization with onboard medical equipment, particularly hardware and pharmaceutical capabilities, so that the CMO is familiar enough with these items to be comfortable with rapidly finding and using assets in the case of an emergency. Current CMO training includes instruction on the medical hardware available on the ISS. However, preparation for exploration missions will drive the creation of new technological advances. The goal of these technologies is to streamline the inputs required from the CMO in an effort to reduce time spent by the CMO away from the patient and minimize opportunities for error. Furthermore, such technological advances may reduce the CMO training burden by being more intuitive or automated. Although new equipment will necessitate new training curricula, such curricula may be more straightforward or user-friendly than previous methods or practices.

3.2.2 Dental training

Dental conditions are among the predicted medical events for exploration missions. ExMC Gap 4.11 specifically addressed the limitations of current dental care capabilities and the identification of capabilities that would need to be explored for missions outside of LEO. NASA held a dental working group in March 2012, with participants including Johnson Space Center personnel and NASA contractors, private dental practitioners, and an Army Special Forces dentist. Together, the members of the group identified and prioritized specific dental skills deemed necessary for exploration missions. Those skills already identified as necessary based on current EMCL projections received priority, but experts in the field of dentistry assisted with the identification of other areas of concern. To determine how best to teach these skills to CMOs, the group reviewed terrestrial training standards, emphasizing analogous environments such as remote military operations. A separate technical paper further summarized the results of this working group; in general, the group identified multiple ways of training CMO in dental skills needed for exploration missions.[29] These suggestions included dedicated hands-on training time, with patient experience in a high-volume setting. These methods are similar to those used to train military Special Forces medics before deployment to austere environments.

3.2.3 Behavioral health training

The mental and emotional health of the crew is essential to the success of a long-duration mission.[4] From historical experience in isolated and extreme environments, such as various military settings and Antarctic stations, it is evident that, despite prescreening of crewmembers, the isolation, prolonged separation from friends and family and other mission stressors may result in behavioral health issues.[12] The CMO must be able to diagnose and treat those behavioral health problems most likely to occur and most critical to the well-being of the crew. The best way to train the CMO to recognize or address behavioral health factors remains uncertain, but a starting point for designing a training approach lies in analyzing the strategies used to prepare personnel for analogous remote and high-stress environments. Although behavioral concerns will likely be managed by telemedical consultation with the ground support teams, it is likely that CMOs would want to be, at a minimum, familiar enough to recognize behavior or emotional signs and symptoms that would raise concerns over the psychological health of a crewmember, and be comfortable in describing and expressing such concerns to the ground team.

3.3 Telemedicine Training

Although CMOs are likely to need a degree of autonomy that does not require reliance upon ground-based medical expertise for routine or common medical issues, crewmembers should understand when guidance from the ground is both available and advantageous. With the communications delay of an exploration mission, CMOs must be capable of providing emergency point-of-care, such as BLS and ACLS skills, as well as basic medical stabilization techniques. However, ground-based flight surgeons can still be called upon for medical guidance, particularly in diagnostic or nonemergent treatment scenarios. Even with a significant communications delay, ground expertise can be used for image interpretation, synthesis of medical data points (such as laboratory values, vital sign trending, etc.), and higher-order medical decision-making, much as hospital-based consultants offer primary medical providers in an inpatient medical scenario. Coordination of hospitalists and consultants, even with delayed consultant input into clinical decision-making, has been demonstrated to be highly effective in inpatient medical scenarios; similarly, the augmentation of CMO decision-making by ground-based medical support teams could provide a level of medical knowledge that crewmembers will not have time to achieve before the mission.[47] Although the Telemedicine Working Group stated that greater than 90% of medical conditions encountered in long-duration missions would be primary care, in the survey circulated among the training experts most agreed that emergency training should be the premission training priority, with critical actions taking precedence for ground-based training.[15] In contrast, other techniques (including telemedicine, on-board protocols, and JIT training) could be used to supplement medical training in the case of a particular medical contingency, particularly for a nonemergent condition.

As with all other medical training, the use of telemedical capabilities could be practiced to ensure crew comfort before an emergency scenario during a mission. It is recommended that CMOs become familiar with the presentation of necessary medical data to ground-based support teams. Preferably, crews would train on delayed communication techniques with the support team with whom they will actually be interfacing during the mission. This would ensure understanding and allow for the most valuable feedback from the ground support team members. Incorporation of delayed communications scenarios for diagnostic- or treatment-related clinical decision-making should be considered as premission training simulations are developed.

3.4 Just-In-Time Training

The JIT training will be a priority for exploration missions. At the present, CMOs on ISS missions are able to access computer-based tutorials at point-of-care to acquire knowledge and procedural skills necessary to perform medical tasks. There is an ongoing need to develop a complete library of resources accessible to the CMOs without ground intervention. Ideally, JIT utilization will correspond with telemedical consultation with the ground-support team: as the CMO recognizes a medical contingency, the ground team is notified and provides guidance in the form of both telemedical assistance in decision-making and provision of new JIT programs that could be uploaded to advise further medical practices and treatments. For CMOs to most effectively use these resources, they will require training programs during premission preparation to familiarize themselves with the JIT-training database. The degree of training and the time required will be dependent upon the final configuration of the JIT-training database.

3.5 Simulation-Based Training

Simulation is an intuitive way to train for critical performance. Simulations are increasingly proving to be a means of improving crew resource management, leadership and teamwork, checklist accuracy, communication, mission-specific training, and performance of critical tasks.[10] Medical schools, aviation, and other aspects of military operations regularly integrate simulation as part of standard training curricula for its ability to offer deliberate practice, targeted assessment, feedback, and reflection of lessons learned.[30] Medical simulation has been proven in several systematic reviews and meta-analyses to be a significantly more effective training tool when compared to lectures and small group discussions, especially when training for higher order outcomes such as skill performance.[8,9] It has also been shown to increase participant satisfaction, knowledge acquisition, efficiency, accuracy, procedure success, quality of procedural performance, and transfer of skills.[8,44] In addition to the training benefits, simulation may indirectly improve patient safety by increased retention of skills and improved risk management.[17]

Additionally, simulation is becoming increasingly necessary due to technological advances in medicine that can only be practiced via simulation, such as ultrasound and other image-guided procedures necessary for critical or emergent interventions. The educational features afforded by high-fidelity simulation (simulation using particularly realistic materials and equipment) are numerous, including educational feedback, repetitive practice, curriculum integration, multiple learning strategies, clinical variation, controlled environment, and defined outcomes.[22] Of the few patient outcome studies published, simulation-based mastery of inguinal hernia repairs has been proven to decrease operating time, increase surgical performance and decrease patient complications.[49] One study identified simulation-based medical education as a means of constant skill improvement, not just skill maintenance.[28] The potential for simulation to similarly impact CMO skills is therefore promising.

4.0 VALIDATION OF MEDICAL TRAINING

The autonomy required of an exploration-class crew suggests that crewmembers would need to demonstrate the ability to perform medical skills without external assistance. Such evaluations could be used to indicate CMO mastery of the lessons provided during the training flow, and whether further refresher courses might be needed before the mission. Although the training flow for an exploration mission would be understandably full, identification of medical areas in which the CMO is not as confident could prompt trainers to dedicate refresher time to better assist the crewmember in preparation for the mission. This could also prompt the use of increased on-board training in these areas during the mission to maintain or even improve CMO skills.

According to the survey results, the SMEs agreed with the need to validate medical knowledge of health care providers on exploration missions, stating that exploration medical capabilities will require skill sets for all crewmembers that must be integrated and competency-tested. Several types of medical assessments can be used for the purpose of evaluation, including work-based assessments such as written examinations, mini-clinical evaluation exercises, direct observation of procedural skills, case-based discussions, objective-structured clinical examinations (OSCEs), and simulation-based exams. Each of these methods will be discussed in the following paragraphs.

4.1 Written Examinations

Although generally the most easily implemented option, written examinations are often considered to be the least representative of actual clinical capabilities. According to the Association of American Medical Colleges (AAMCs) Task Force on Clinical Skills Education of Medical Students, written examinations are not sufficient to accurately assess the clinical skills of any practitioner; instead, maximal clinical performance learning (and assessment) occurs only when practitioners "engage in the material they are expected to assimilate."[3] Furthermore, extrapolation of knowledge gaps from incorrect answers on a written exam is often more difficult than assessment of coordinated skills.[3] The AAMC does recommend evaluation, stating that effective clinical training requires "education through both teaching and the assessment of clinical skills"; and recommendations from this association tend to favor nonwritten evaluation methods.[3]

4.2 Mini-Clinical Evaluation Exercises

This is a work-based assessment tool that requires medical students or trainees to engage in workplace-based patient encounters while being observed by senior physician. The parameters evaluated include history taking, physical examination, professionalism, clinical acumen, and organizational skills. The main advantage is that it permits a review of current performance and enables the senior faculty member to provide structured and specific feedback. This can be done by several faculty members and patients, and can be used to evaluate a number of skills. These examinations are feasible, low cost, and there is evidence for reliability.[14,36] Major disadvantages include lack of generalizability to other clinical scenarios and difficulty in providing set parameters for evaluation of clinical competence; further, this evaluation could only be conducted in a prelaunch, ground-based scenario.[14]

4.3 Direct Observation of Clinical Activity

This assessment tool focuses on evaluating procedural skills in a workplace setting. The skills assessed include venipuncture; endotracheal intubation; nasogastric tube insertion; intravenous, intramuscular and subcutaneous medication administration; peripheral venous cannulation; and arterial blood sampling. The benefit is dependent on the number of encounters, the type of procedure, and the quality of the feedback received. These encounters are also difficult to reproduce and compare among different students. In addition. significant observer bias may occur. As with the mini-clinical evaluation exercises, this form of evaluation is only applicable to prelaunch, ground-based scenarios.

4.4 Case-Based Discussion

This assessment tool involves discussing a clinical case with senior physicians. It involves an oral presentation of a clinical encounter with the complete history, clinical examination findings, investigations, treatments, and follow-up. This type of performance assessment focuses on evaluating clinical reasoning.[36] Trainees are expected to engage in multiple encounters with multiple examiners during the training period.[36] There are several studies supporting the validity of case-based discussions, including recent studies that demonstrated that case-based discussions correlate with oral and written examinations.[36] Unlike the first two evaluation methods, case-based discussions could be performed as onboard continued training, even with a communication delay.

4.5 Objective Structured Clinical Examinations

An attempt to reduce the variability of performance evaluations relies on the use of standardized clinical scenarios. The design of these assessments focuses on similar attributes, behaviors, and competencies rated by experts during on-the-job evaluations. The OSCEs require trainees to interact with real or simulated patients to demonstrate a specific skill. The parameters evaluated include history taking, physical assessment, clinical reasoning, or patient education. The patients and the scenarios are standardized with a pre-established checklist of skills that examinees must demonstrate, allowing an objective comparison of trainees over a range of specialties and skills.[14,43] The rater is typically an expert in the field of training, such as a fully credentialed attending physician, who supervises the trainee regularly over an extended period of time. The factors that influence the accuracy of the ratings include the amount of time spent with the subject, the idiosyncrasies of the evaluator, the number of behaviors assessed, the number of evaluators assessing each subject, and the definition of the rating scale. The reliability and validity of an OSCE depends on the appropriateness and sample size of the competences assessed as well as the structure and specific predetermined checklists that ensure consistency in scoring.[20] The disadvantages of OSCEs are that they take place in an artificial setting, can be time-consuming and expensive if specialized equipment is required, and crewmembers would need to be specifically trained to this format of examination. Even so, most medical educators much prefer this evaluation method over written examinations for the assessment of skills and professional competencies, particularly when the OSCE format is augmented by high-fidelity simulation as discussed below.[25]

4.6 Simulation as a Validation Tool

Simulation is increasingly being used as a means to judge the adequacy of training, and is likely to introduce new paradigms for certification and credentialing.[11] A number of medical entities rely on simulated experiences for licensure and board certification. For example, the second step of the United States Medical Licensing Exam, traditionally taken during the fourth and last year of medical school, includes a simulation component used for specifically focusing on clinical skills on standardized patients. Since 2010, the American College of Surgeons and the American Board of Surgery require residents to pass a "Fundamentals of Laparoscopic Surgery" simulation before being able to take their first written board examination. There is also consideration for this to become a requirement for maintenance of certification for attending surgeons.[11]

More pertinent to CMO training, simulation has been shown to be useful in advanced trauma life support evaluation. In a study of 10 military medical teams comprised of physicians, nurses and medics on a 28-day trauma hospital rotation, a human patient simulator was used as a pre- and post-test evaluative tool. On 28-day retest, the military team's performance significantly improved in four out of five scored exercises and six out of eight timed tasks, and approached the performance level of expert trauma physicians and nurses used as the validation gold standard.[21]

4.7 Development of Crew Medical Officer-Specific Performance Data Acquisition Methods

A NASA-specific medical training examination could be built into already existing simulation exercises, consolidating the two processes of training and validation. The details of the evaluations could be borrowed and adapted from the established entities mentioned above in consultation with flight surgeons. Evaluations could assess the knowledge retained by CMOs undergoing training for exploration missions as well as validate the teaching and training methods by presenting off-nominal scenarios, high-fidelity simulation, and crewmember challenges that require synthesis of materials and knowledge learned in the training flow. In an ideal scenario, these evaluations would identify areas in which training for an exploration mission could be enhanced, such as small-group dynamics, item clarification, more hands-on training, and quality assurance with inter-trainer reliability. Designing assessments of the medical training algorithms already in place can provide valuable data about the effectiveness and validity of exploration mission training methods. Analysis of these data may lead to improvements in current training and facilitate adaptation of that training to the goals of extended-duration missions. Additionally, quantifying the knowledge, capabilities, and medical judgment of subjects with differing clinical specialties can provide data that may prove useful in reaching a determination of the best clinical background for an exploration-class CMO.

5.0 RETENTION OF SKILLS

Once a CMO completes a training flow for an exploration mission, it becomes important to maintain the medical knowledge and procedural skills acquired for the remainder of the prelaunch period and the duration of the mission. Refresher training will be necessary during prelaunch mission preparations and in flight. In both situations, time restrictions will be a significant limiting factor. For example, extensive studies investigate how best to maintain proficiency in ACLS. Authors identify the rarity of events requiring implementation of ACLS in many clinical settings and infrequent or inadequate training programs as two key factors contributing to lapses in the abilities of ACLS providers. As medical events in any mission are likely to be rare and unique, currency training to mitigate knowledge and skills decay will need to be individualized based on the strengths, weaknesses, and varying interests of each crewmember. Adaptation of the training elements to the mission timeline will help reduce the impact on time constraints. For instance, it may be most helpful to review the diagnosis and management of musculoskeletal injury just before or during portions of the mission involving many EVAs when such problems are more likely to occur. Another consideration is the possibility of incorporating an element of currency training into other crew tasks. For example, while performing an equipment inventory, the CMO could simultaneously engage in a JIT-training activity on the use of a specific piece of medical technology. How to accomplish this objective best will depend on the mission timeline and objectives.

Numerous studies have identified lack of sufficient training and limited practice as the main factors that lead to the decay of medical skills over time.[11] The efficacy of training without continued refresher or retraining courses has been called into question, as first responders often face criticism for lack of basic lifesaving skills despite supposedly “adequate” training.[15,37] Even with regular renewal courses, such as BLS and ACLS requirements for retraining every 2 years, emergency response scenarios often demonstrate poor skill application and retention by the responders.[15,26,37] Most studies encourage the use of skills-based refresher scenarios, such as simulation, to improve retention of skills.[2] Here, both simulation and JIT refresher scenarios will be discussed as viable options for CMO refresher training.

5.1 Retention of Skills by Simulation Training

A number of studies have evaluated the effect of simulation training on retention of medical skills. As a baseline, it has been shown in a systematic review from 2012 of 11 previous studies that a statistically significant decay in ACLS skills occurs between 6 months to 1 year after initial training, which is well before the recommended 2-year renewal of certification.[48] Skills were shown to decay faster than knowledge, and there appeared to be increased decay of skills for nonphysicians compared to physicians.[48] Of the articles reviewed that showed statistically significant long-term skill retention, the average number of simulator hours for ACLS skills was 3.8, with an average retention time of 10 months (for experienced providers) and a minimum retention time of 6 months (for novice providers).

When simulation is introduced as an educational intervention for internal medicine residents, ACLS skills are retained up to 12 to 18 months after the initial simulation training compared to residents who received simulation 6 months before retest, with no statistical difference in performance.[13] Simulation groups also scored significantly higher than nonsimulator trained residents (N = 47 code simulations; $P < 0.001$).[13] The residents involved received a total of 6 hours of high-fidelity simulation time to achieve the reported results. Another study dealt with teaching life-threatening condition management to third-year medical students, and demonstrated that AED, CPR, and airway management skills did not decline after 18 months from the time of training.[1] These studies demonstrate that a heavily simulation-based curriculum can greatly improve skill retention.

Clinical experience, even when simulated, appears to contribute to skill retention. A randomized study of 86 third-year medical students, categorized as novice providers, found no difference between high-fidelity simulation and traditional training for ACLS skill retention at 1 year.[27] The high-fidelity simulation group received a total of 3 hours simulator time, plus 1 hour of face-to-face time with an ACLS instructor and a home eACLS self-study module. The traditional training group underwent 16 hours of lecture and hands-on training with a low-fidelity mannequin. Of note, all participants in this study showed a small decline in skill retention in true resuscitation scenarios during the study period; therefore, these authors also suggested that a refresher course before the 1-year mark is needed for full retention.[27]

These studies do not appear to demonstrate much correlation between simulation hours and skill level or with retention time. However, given that the same number of simulation hours results in as low as 6 months of ACLS skill retention for medical students and 10 to 11 months of skill retention for residents and attending physicians, it does appear that clinical experience contributes to longer retention times and better simulation performance.[48] In the spectrum of training levels, medical students of all levels (first year through fourth year) are all described in the literature as "novice providers". Regarding the training of non-CMO crewmembers, nonphysician crewmembers would most likely fall in the novice provider spectrum of training. Based on a career background that is not medically focused, non-CMO crewmembers would be expected to possess minimal retention times, about 6 months of skill retention for ACLS skills. Thus, for non-CMO crewmembers to be capable of managing the basic responses to life-threatening scenarios, on-board training and/or simulation would need to be refreshed at least every 6 months.

Systematic reviews of simulation trials support the observation that feedback received in simulations slows the decay of acquired procedural (non-ACLS) skills as well.[22] Skills such as auscultation and physical exam showed a wider spectrum of retention times with simulation compared to ACLS skills. Various other metrics are found in the literature, including scores based on a performance checklist of critical actions, number of iterations to achieve mastery level, etc. These markers of performance are likely more useful guidelines than time spent in training.

Although simulation of critical procedures and actions can be more time-consuming during initial development and training, it has been shown to reduce overall procedure time with continued use. As training time is very limited before an exploration mission, and multiple other disciplines will be vying for prelaunch crew training time, use of simulation could make skill learning more efficient after only a few iterations of the training flow.[23] With the use of simulation training, successful skill acquisition and retention could require less overall time compared with current training flows.

5.2 Retention of Skills with Just-In-Time and On-Board Training

Although simulation has been demonstrated to be an excellent means of retaining skills, the preparation of high-fidelity simulation may be prohibitively complex for use in normal on-orbit activities. JIT and on-board training are currently used on ISS as "refresher" courses on ultrasound and basic medical procedures. JIT has been proposed as an alternate or additional method of skill retention for exploration missions.

Computerized ACLS-simulator modules have been compared to JIT-training methods, as they both review materials in an interactive software program context. One study regarding computerized training followed 45 resident and attending anesthesiologists that were given a computerized ALCS module to use as a refresher 10 to 11 months after their initial ACLS training. Of the group, 84% who used a simulator module (for a minimum of 1 hour of self-study) had passing scores on re-test, whereas only 53% of the group who used the textbook for self-study had passing scores 1 year after initial training.[41] In another study, 126 medical and nursing students were divided into computer-assisted learning, expert-assisted learning, and peer-assisted learning groups. Of the three groups, the peer-assisted learning group scored statistically lower than the expert-assisted learning group and computer-assisted group, suggesting that the expertise level of the trainer is a critical factor in influencing the effectiveness of training.[46] This suggests that crewmembers would do best with refreshers using either JIT or instruction from an on-board physician-astronaut, but not through peer review and feedback sessions with fellow crewmembers.

To best use JIT training, it is first necessary to develop training modules that address all aspects of medical skills training, then to train crewmembers to access and review the training modules effectively. Familiarization with the training database will reduce the time on orbit that must be dedicated to skills refreshers. Finally, as mentioned above, consultation with ground support teams in the case of a medical contingency will allow ground-based flight surgeons to recommend JIT courses that directly address the concerns at hand, allowing the CMO or other crewmembers to focus on pertinent knowledge needed at that time. In this way, regular refresher courses can be supplemented by point-of-care training to best attend to an injured or ill crewmember. Again, ground teams will need to be similarly trained on the JIT database to ensure rapid and effective retrieval of such courses to best guide the crew through a medical contingency response in real time.

6.0 CONCLUSIONS

Based on the topics discussed above, a number of recommendations can be made regarding ideal medical training for exploration-class crewmembers. First, the design of the exploration-mission parameters will influence the resources available during the mission, including medical supplies, medical hardware, and JIT-training resources. In turn, such parameters will guide priorities of medical training. Future work could include reaching a consensus about the degree of familiarity and response expected of an exploration-class CMO specifically for behavioral or other specific health concerns.

Based on the materials presented above, there seems to be a consensus that training based largely upon simulation is the best method for CMO training. While some materials may be presented in didactic lecture style, it is recommended that the majority of medical training be in the form of hands-on simulation. CMOs should be specifically trained to use adjunctive capabilities, including telemedical consultation with ground support teams and use of JIT on-board software to best address a given medical contingency. Simulation could be designed with incorporation of these elements for a high-fidelity training program.

Regarding time dedicated to the training flow, the expert consensus is to increase premission training time to 80 to 120 hours of dedicated medical training for exploration-class CMOs to ensure a high degree of familiarity and comfort with all medical hardware, procedures, high-likelihood medical conditions, and mission-specific risks. The use of these 80 to120 hours will be dependent, again, upon the clinical background of the CMO, mission parameters, and on-board capabilities. Within this training flow, it is recommended that there be dedicated time for evaluation and refresher courses in areas in which CMO familiarity could be improved. At the same time, a strong argument has been made that non-CMO crewmembers should undergo, at a minimum, familiarization with on-board medical hardware, resources, and emergency procedures, for the possibility of CMO incapacitation and the need for medical autonomy. One approach to this training would be to use the nonexperienced CMO training flow already in place for ISS missions, with tailoring to mission-specific hardware and procedures for the exploration mission at hand.

Skills retention requires use and repetition. Incorporating simulation sessions into the training flow would provide the necessary skill utilization that has been demonstrated to improve retention times for practitioners of all levels. Nonexperienced crewmembers, such as the non-CMO astronauts, would need to undergo simulation refreshers every 6 months to ensure emergency skills retention. Experienced crewmembers are likely to be able to go longer periods of time without the need for review, but it is recommended that they still undergo simulation refreshers at least every 9 to 10 months for critical or emergent procedures.

Multiple evaluation techniques presented above could be tailored to evaluate CMO performance after progression through the training flow. Techniques that rely upon expert evaluation, observed performance, and trainer feedback are considered to be the most reliable means for data acquisition in current medical training schemes. The materials reviewed indicate that direct observation of clinical activity, OSCEs, and simulation are likely to be the most reliable and successful means of evaluation. Simulation in particular would be recommended, as it would serve both as an evaluation and an opportunity to practice the skills learned, improving knowledge retention. Prelaunch evaluation could help guide the need for refreshers or remediation before a mission; on-board evaluations could guide the scheduling of refresher courses for both CMOs and non-CMO crewmembers. Again, the use of simulation would provide a tool for both evaluation and refresher training.

Should a CMO be previously medically trained with a clinical background, it is recommended that efforts be made to ensure that such a valuable knowledge resource is maintained. Dedicated clinical time could be protected for physician-astronauts to ensure that their medical capabilities do not lapse over the course of their premission training flow. This protected time will serve to decrease the training time needed to refresh the out-of-practice medical provider and would undoubtedly prove beneficial.

The medical providers on a long-duration space flight must be prepared to manage diverse clinical quandaries. Many variables may affect crew health during an exploration mission, and there is no way to accurately predict or prepare for every eventuality. Medical conditions that could be encountered during an exploration mission span a wide spectrum, with diagnostic and treatment requirements ranging from relatively standard treatment of common EMCL conditions with delayed definitive care, to advanced trauma life support and point-of-injury stabilization, to improvisation and high-level medical technique. As vocalized by the majority of surveyed training experts, preparing for exploration missions may lead to modifications to the current crew medical training model to address these uncertainties, particularly a need for including more simulation, formalizing the training validation process, and increasing the number of training hours. With these concerns addressed, medical providers can be best prepared for the challenges they will face during an exploration mission.

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REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE January 2014	3. REPORT TYPE AND DATES COVERED NASA Technical Memorandum

4. TITLE AND SUBTITLE Identification of Medical Training Methods for Exploration Missions	5. FUNDING NUMBERS
6. AUTHOR(S) Rebecca S. Blue; Laura M. Bridge; Natacha G. Chough; James Cushman; Muska Khpal; Sharmi Watkins	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Lyndon B. Johnson Space Center Houston, Texas 77058	8. PERFORMING ORGANIZATION REPORT NUMBERS S-1148
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001	10. SPONSORING/MONITORING AGENCY REPORT NUMBER TM-2014-217384

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT Available from the NASA Center for AeroSpace Information (CASI) 7121 Standard Hanover, MD 21076-1320 Category: 52	12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

As NASA and its international partner agencies anticipate eventual exploration missions of longer duration, there is a need to plan for the medical capabilities necessary to maximize crew health and provide the best likelihood of mission success. Missions to a near-Earth asteroid, a return to the moon, or even a mission to Mars will demand unprecedented medical capabilities, particularly relating to the training of the crew medical officers. The Exploration Medical Capability element within NASA's Human Research Program defines a series of "gaps" in its attempts to address the questions about medical preparation for space flight beyond low Earth orbit. These gaps are shortcomings in knowledge, training, or technology that require resolution before an exploration mission can be undertaken. The Exploration Medical Capability element maintains current information about measures to close these gaps while developing plans for further investigation and research. Current crew medical officer training methods, and potential alternative training methods were identified to determine the optimal methods of medical training for an exploration medical crew and their ground support team, the historical context of medical operations.

14. SUBJECT TERMS long duration space flight; aerospace medicine, telemedicine; astronaut training; astronaut performance	15. NUMBER OF PAGES 32	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited