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<b>14. ABSTRACT</b> This report is a summary of a symposium that was planned and held on December 5-6, 2005, in Houston, TX. The focus of this symposium was on surgery in extreme environments. During this two day event, invited experts from academia, government, and industry gathered to discuss what has already been accomplished in the area of surgery during spaceflight. This included activities underway within DoD, TATRC, NASA, the Russian Space Program, and other activities in which a surgical presence, although limited, was used in extreme environments. This symposium looked at the many challenges that are faced in providing advanced surgical care.					
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## **EXECUTIVE SUMMARY**

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This report summarizes the events that led up to and conduct of a discipline-specific symposium on surgery in extreme environments. Although the principle focus was on surgery in space, the participants and stakeholders, including government, industry, and academia, provided valuable insight and content for surgical applications in extreme environments.

On December 5<sup>th</sup> and 6<sup>th</sup>, 2005, representatives from government (the National Aeronautics and Space Administration [NASA], the Canadian Space Agency [CSA], the Defense Advanced Research Project Agency [DARPA], the Telemedicine and Advanced Technology Research Center [TATRC]), and the Russian Institute for Biomedical Problems [IBMP]); academia (University of Cincinnati, Baylor College of Medicine, University of Calgary, and McMaster University); and industry (MD Robotics) assembled at a site adjacent to the NASA Johnson Space Center (JSC) in Houston, TX. The assemblage of astronauts and researchers participated in a series of didactic lectures on surgery in extreme environments, including spaceflight, the battlefield, the jungle, and Mt. Everest. The presentation material provided and the literature search accomplished prior to the meeting established a strong foundation for establishing a definitive collection of materials to meet the one of the key objectives of this work.

The development of a monograph or text on surgery in extreme environments will be of great value to government, academia, and industry. In the coming months, a set of manuscripts will be prepared and submitted for publication. The journal *Aviation, Space and Environmental Medicine* (ASEM) has expressed interest in publishing this collection of manuscripts in early 2007 as a supplement to its monthly publication. Various individuals are currently preparing manuscripts for review and submission to this special issue.

The financial support provided by TATRC through a conference grant helped the investigators organize an outstanding symposium. This final report is submitted as the deliverable.

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## **BACKGROUND**

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The challenges faced in delivering surgical support in extreme environments are daunting regardless of the location – space, battlefield or other areas. The challenges that NASA faces in the delivery of healthcare in extreme environments are similar to those that the U.S. military faces. Each year, technological innovation improves the way medicine is practiced. Sometimes this technology makes its way into application and practice. This is evident to a degree in the military and less evident in support of human spaceflight. While surgical services are delivered on the battlefield, there has been a limited amount of work done on surgery in space. Although, there is some published information, none of it is assembled in a cohesive, single source or definitive text. In fact, there is very little in the form of peer-reviewed literature specifically on surgery in extreme environments. Such a definitive text would be a significant adjunct in the establishment of new requirements, leading to new technologies for application. This is important in meeting the President's announced space initiative of long duration space exploration of the moon and Mars. It also can be of value to the military's as they continue to evolve their medical support for the warfighter of the 21<sup>st</sup> Century.

Recently, the Bush Administration announced a set of new priorities related to the exploration of space, including human missions to the moon and Mars in the coming decades. Such visionary steps will require improved medical support and infrastructure to maintain and sustain a healthy, productive crew during the duration of such missions. Surgical care in the current environment on the Space Shuttle or International Space Station (ISS) is limited. It will have to be developed further to support exploration class missions.

The knowledge gain in this endeavor is relevant to not only NASA but to the U.S. Army Medical Research and Materiel Command (USAMRMC) as well. First, it is a unique opportunity to leverage existing activities to gain knowledge and capabilities, thereby, illustrating a strategic alliance. Second, those requirements, capabilities and aspirations in support of NASA's mission also have value to military medicine as it meets its requirements in the 21<sup>st</sup> Century. These include special operations, aerospace medicine, and critical care air transport.

The use of robotics, telemedicine, and information systems are key elements of addressing surgical needs in the foreseeable future. These elements will not only be of importance in modernization of medicine but also will enable more robust systems for addressing unmet needs and the challenges of extreme environments. There are synergistic approaches to surgery in space and other extreme environments that must be capitalized on and leveraged. These include smart systems, robotics, tele-manipulation systems, and biomedical informatics.

The Center for Surgical Innovation (CSI) at the University of Cincinnati (UC) through its relationships with government and its faculty's background, developed plans to conduct a discipline-specific symposium on surgery in extreme environments. This symposium was designed to bring together expertise from those individuals who have been involved in surgery in such environments.

## PROJECT DESCRIPTION

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Based on first-hand knowledge and discussions with current officials within NASA and those who have been associated with NASA's Space Medicine Program since the 1960s, it is clear that there is dearth of knowledge regarding the application of surgery in space. There have been funded research efforts in this area over the past 10 years and there have been rudimentary capabilities on various human-tended spacecraft. However, there is not a central collection of the knowledge or experience gained. There are several peer-reviewed journal articles that have been published in the literature, including work currently under consideration for publication by the PI (C. Doarn) and Co-I (Dr. Timothy J. Broderick) of this effort. Nevertheless, no complete report, monograph or anthology exists, that captures all the experience garnered over nearly 5 decades of human spaceflight. Much of the knowledge or experience base is retained by astronauts or other discipline expert. This knowledge base is slowly ebbing away and is shared by a small number of individuals who have had direct experience in this area.

It is important to gather this information from these experts. This information will be of value in establishing strategies for supporting our Nation's vision to explore space. A key tenet in this endeavor is the ability to support surgery in space and development of the appropriate tools and procedures in application, training, and education. The academic community in partnership with industry provides an excellent foundation for collaborating in this regard.

In order to appropriately address the opportunities and challenges as outlined above, the following specific aims were addressed.

*Specific Aim (1)* the collection of preliminary data through a questionnaire and interviews targeted at a select group of ~ 20 researchers or astronauts who have worked on surgery in this environment;

*Specific Aim (2)* the development of a comprehensive monograph of this data that will make the basis of a definitive text on the subject; and

*Specific Aim (3)* the development and conduct of a small, limited attendance conference of select individuals to review surgery in space. Such a conference will result in several outcomes, including establishment of guidelines and requirements for establishing a center of excellence at UC for training surgical skills for space and developing innovative tools and procedures. This will also provide a platform for leveraging Department of Defense (DoD), Telemedicine and Advanced Technology Research Center (TATRC), Defense Advance Research Project Agency (DARPA) and NASA expertise.

## METHODS

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An exhaustive literature review was conducted. This review included all library materials such as the limited peer-reviewed journals as well as any news print. A

comprehensive collection is highlighted in Appendix A. Interaction was also undertaken to determine what systems, attributes, and methodologies from DoD can be leveraged or enhanced through mutually beneficial collaboration.

A discipline-specific symposium on surgery in extreme environments was organized and hosted. This limited-attendance symposium assembled leading experts, innovators, and users of surgical interventional strategies in space exploration and the military. This symposium captured what has been learned to date and what strategies must be developed to support applications and training. Key stakeholders and thought leaders from government (NASA, Canadian Space Agency [CSA], DARPA, TATRC, and the Institute for Biomedical Problems [IBMP]), academia (University of Cincinnati, Baylor College of Medicine, University of Calgary, and McMaster University), and industry (MD Robotics). The agenda appears in Appendix B.

The principal outcome of the symposium was a collection of reports and manuscripts that will collated into a monograph or book. These are currently being written. A list of manuscript working titles and initial authors is outlined later in this report. These are subject to change as refinements are made. Each participant gave a 20-30 minute presentation on their work or their discipline as it related to the subject matter. This collection will serve as a valuable reference for current use as well as a substantive adjunct for developing strategic initiatives for future applications and direction of surgery in support of human space exploration and potentially the development of systems for expeditionary medicine for military applications. This will provide an association with the development of appropriate tools, devices, protocols and procedures which enable surgical intervention for future human exploration and development of space in low earth orbit and those missions that are outside the immediate boundaries of earth.

## **PREVIOUS WORK**

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Although there has never been a need to conduct surgical procedures on humans in space, there has been a commitment and an effort to have rudimentary tools available to support this capability should an event occur. These capabilities date to the early days of NASA's Apollo and Skylab missions as well as the Soviet space missions. During the past decade or so, there have been several experiments conducted on the Space Shuttle and Mir Space Station. In addition, there have been several activities performed on porcine models or simulators on NASA's KC-135. Recent work by the Co-I, Dr. Timothy Broderick, provided opportunities to evaluate various tools and techniques. In addition, research performed by Dr. Mark Campbell, et al, in the mid 1990s has shown tremendous value. This work is often recorded in internal reports to NASA and occasionally in the scientific literature. However, there is a tremendous amount that remains unavailable. Nevertheless, it is extremely important to gather all available information to develop better approaches, more comprehensive and realistic requirements to meet the challenges.

Additional work that is illustrative of the relationship between NASA and TARTC includes the NASA Extreme Environment Mission Operations (NEEMO) #7 and #9, where telesurgery efforts have been evaluated between distance sites. The PI and Co-I have also worked with NASA and TATRC on exploring unique communications

applications using High Altitude Platforms Mobile Robotic Telesurgery (HAPsMRT). Several years ago, the PI worked closely with DARPA, NASA and others organizations in exploring telemedicine applications at Base Camp on Mt. Everest (1998 and 1999).

## **SYMPOSIUM SUMMARY**

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The PI, Mr. Charles R. Doarn and the Co-I, Dr. Timothy J. Broderick, assembled a robust group of experts. These experts highlighted in Table 1 represented government, academia, and industry. Invitations to participate were limited and based on the individual's background and expertise in a variety of areas. They included astronauts, flight surgeons, and researchers involved in surgical activities in human spaceflight and ground-based research. Government representatives from DARPA (Dr. Richard Satava) and the U.S. Army's TATRC (Dr. Gerald Moses) participated. In addition, representatives from the international community participated, including Dr. Igor Goncharov from the IBMP in Moscow, Russia, and representatives from several Canadian organizations both academic and industrial. Figure 1 is a photograph of the attendees.



**Figure 1.** Symposium participants. (Front row l to r: Hal Doerr, Jeff Jones, Mark Campbell, Tim Fielding, Zavin Sargysan. Second row l to r: Ken Kamler, Gerry Moses, Nita Grimsley, Chuck Doarn, Trevor Chapman, Andy Kirkpatrick, Russell Kerschmann, Ellen Baker, Igor Goncharov. Third Row l to r: Rick Satava, Tom Husted, Tim Broderick, Dave Williams, and Scott Parazyński. Ken Mattox, Rich Linnehan, Brett Harnett, and Elyssa Westrich not shown.



**Table 1.** Participants in the Surgery in Extreme Environments Symposium (Detailed list appears in Appendix C).

<b>Name</b>	<b>Expertise</b>	<b>Organization</b>
Ellen Baker, M.D.	NASA Astronaut	NASA Johnson Space Center
Timothy Broderick, M.D.	Academic Surgeon / NASA – Funded Researcher	Center for Surgical Innovation – University of Cincinnati (UC)
Mark Campbell, M.D.	Private Practice Surgeon / Former NASA Flight Surgeon	Private Practice
Trevor Chapman	Academic Researcher – Robotics	Centre for Minimal Access Surgery
Charles Doarn, M.B.A.	Academic Research – Former NASA Program Manager – Aerospace Medicine / Telemedicine / NASA Advisor	Center for Surgical Innovation – UC
Hal Doerr, M.D.	Academic Anesthesiologist / NASA-Funded Researcher	Baylor College of Medicine
Timothy Fielding	Robotics Engineer - Medical Robotic Systems	MD Robotics Corp
Juanita Grimsley	Technical Support for TATRC Medical Applications Division	US Army's - TATRC
Igor Goncharov, M.D.	Russian Flight Surgeon – Medical Operations	Institute for Biomedical Problems
Brett Harnett	Technical Support	Center for Surgical Innovation - UC
Thomas Husted, M.D.	Surgery Resident	University of Cincinnati
Jeffrey Jones, M.D.	NASA Flight Surgeon – Extreme environment explorer	NASA Johnson Space Center
Kenneth Kamler, M.D.	Surgeon – Extreme Environment Explorer	Private Practice
Russell L. Kerschmann, M.D.	Life Sciences – Environmental quality (dust, particulate matter)	NASA Ames Research Center
Andrew Kirkpatrick, M.D.	Canadian Trauma Surgeon	Foothills Medical Centre
Richard Linnehan, D.V.M.	NASA Astronaut	NASA Johnson Space Center
Kenneth Mattox, M.D.	Trauma Surgeon – NASA Advisor	Baylor College of Medicine
Gerry Moses, Ph.D.	U.S. Army's TATRC Medical Applications – Program Manager	TATRC
Scott Parazynski, M.D.	NASA Astronaut	NASA Johnson Space Center
Richard Satava, M.D.	Surgeon	DARPA - University of Washington
Elyssa Westrich	Administrative Support	University of Cincinnati
Dave Williams, M.D.	Canadian Astronaut – Assigned to NASA	NASA Johnson Space Center

The symposium was held at a hotel [Hilton Clear Lake] adjacent to NASA JSC, Houston, TX, on December 4-6, 2005. The agenda (See Appendix B) was designed to focus on the challenges and opportunities for surgical care in spaceflight, what kind of work or experience that has already been done, key disciplines that will shape future systems and future medical capabilities currently under development by DARPA. Presentations given by each participant provided a foundation for discussion and interaction.

The meeting was chaired by the PI - Mr. Doarn. Dr. Broderick and Canadian Astronaut Dr. Dave Williams served as Co-Is and as co-chairs of the meeting.

Presentation material for each presentation appears in Appendix E. The following are highlights of each presentation. These highlights were gleaned from the transcription of each speaker. Speakers were audio-taped.

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**Introduction**

*Charles Doarn, MBA, Timothy Broderick, MD and Dave Williams, MD*

Mr. Doarn and Drs. Broderick and Williams welcomed everyone to the symposium and set the stage for the meeting by outlining the purpose and intent of the workshop. Mr. Doarn provided a summary statement from Richard S. Williams, MD, MS, NASA’s Chief Medical Officer. Dr. Richard Williams’ comments were one of encouraged interest in the outcomes and how this was important work for NASA. Mr. Doarn indicated there was interest expressed in the symposium’s goal from NASA, DoD, the National Library of Medicine (NLM), and the Journal of Aviation, Space and Environmental Medicine, the official journal of the Aerospace Medical Association.

Dr. Dave Williams stressed this event was not about making policy but gathering the necessary information into a single source and its importance to NASA.

Mr. Doarn highlighted that providing surgical intervention in extreme environments has many challenges. Some of these have been addressed through NASA experience as well as the experience garnered on the battlefield. These challenges include those items list in Table 2.

**Table 2.** Challenges for Surgery in Space

Anatomical changes	Monitoring devices
Anesthesia	Peri-Operative System
Common terms	Power
Culture	Resource management
Data collection, storage, retrieval and management	Resupply
Death	Shelf live of pharmaceutical and medical supplies
Environmental	Simulation
Fluids and fluid management	Smart systems
Historical	Standard-of-care
Imaging	Training
Language	Trash management
Micro/Macro	Types of surgical procedures

Mr. Doarn highlighted a variety of activities that have focused on surgery in space. These include the activities listed in Table 3.

**Table 3. Historical Perspective of Surgery in Space**

Limited surgical capabilities on Skylab
Limited surgical capabilities on STS
Limited surgical capabilities on ISS
Proceedings of SSF Medical Experts Seminar – NASA Conference Report 10069 – April 1991
Strategic Considerations for Support of Humans in Space and Moon/Mars Exploration Missions – NAC Aerospace Medicine Advisory Committee report – 1992
Dr. Samuel Pool / Dr. Norman McSwain Working Group
Subject matter experts (Dr. Bruce Houtchens, Dr. Mark Campbell)
Ground-based research

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**NASA’s Exploration Architecture: Space Medicine Challenges and Constraints -**  
*Jeffrey Jones, MD*

Dr. Jones is a NASA flight surgeon who has worked both Shuttle and Station missions. He has spent significant time in Russia, supporting the various programs and is working with NASA JSC to establish the necessary medical systems for lunar and Mars exploration. He is also the Exploration Medical Operations lead, chair of the Exploration Crew Health Integration Team and System Manager for the Crew Exploration Vehicle (CEV) Crew Health Interfaces Team.



Dr. Jones provided an in-depth review of NASA’s mission and the challenges in meeting President Bush’s exploration initiative. He presented the concepts of living off the land and how the ISS and moon serve as stepping stones for Mars exploration. The moon would serve as a laboratory for training and preparation for human exploration of Mars. He discussed many of the constraints on design architecture for the Space Shuttle replacement and future transportation systems. In addition, he highlighted the roadmaps being developed for achieving the various milestones of reaching the moon a second time and eventually Mars that are safe, accelerated, affordable and sustainable.

One of NASA’s primary missions is to focus its efforts on developing the Crew Exploration Vehicle (CEV). The CEV will serve as a ferry to move people to and from the ISS as well as the crew transport to the moon. This would serve in a limited capacity as the return vehicle in the case of a medical or other emergency. Dr. Jones’ presentation contained the broad scope of various designs and capabilities that would support the exploration initiatives.

*“The cause of exploration and discovery is not an option we choose; it is a desire written in the human heart.”*  
– George W. Bush

The size in volume and mass often drive medical capabilities more than requirements. This has been the case in all human spaceflight activities. Dr. Jones presented some



concepts and strategies for medical kits that would be deployed in support of getting ill or injured crew back to the Earth using the CEV. Such systems will be limited due to constraints. He indicated that such a system would be similar in capability to the systems used in ISS and on the Shuttle. They would be supported by telemedicine.

System design constraints were discussed for the lunar surface activities, including transportation systems and habitats. Dr. Jones presented plans for medical systems that incorporated limited medical capabilities as well as systems for environmental monitoring and exercise countermeasures.

Dr. Satava commented on radiation exposure and the possibility of a radiation vaccination. He also indicated that leveraging partnerships with government entities like DARPA would be of added value.

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## Medical Operations for Exploration

*Jeffrey Jones, MD*

The delivery of medical care in support of human exploration of the moon and Mars is based on over 40 years of experience in human spaceflight operations. The experience base from the American and Soviet/Russian programs has provided knowledge to help shape the strategies for the coming decades.

Dr. Jones highlighted the concept of operations ISS and return to Earth, CEV to moon and return, and CEV to Mars and return. In each of these missions, the strategy is be able to support contingencies that could happen. Many medical scenarios are not planned for



because they are selected out of the astronaut population and there is a strong focus on prevention. In fact a key tenet of exploration medicine is 'prevention'! NASA's cadre of astronauts current and future must go through an intense selection process. Just as in the military, planning and training, can ameliorate many situations, thus minimizing poor outcomes.

The capabilities in each includes a telemedicine capability similar to what is now done during ISS and Shuttle missions to support private medical conferences and private family conferences.

For CEV missions to ISS and Lunar Sortie, the plan is to bring ill or injured astronauts back to Earth for definitive care. Components, including the ISS ambulatory care and advanced life support packs, will be integrated into operational scenarios to address basic first aid (comfort medicine) and advanced life support. System design and capabilities must be based on anticipated events and activities such as extravehicular activities (EVA) and contingencies such as contamination in the cabin environment.

Medical management of EVAs is extremely important because of the nature of mission tasks on the surface of the moon and Mars. Medical management issues include a variety of items, including decompression sickness, injury from a fall, radiation protection, and dust toxicity.

The medical systems for CEV to ISS and Lunar Sortie missions will be similar to those on prior space vehicles, Shuttle and ISS. Surgical care is not planned. However for longer duration missions, to support a Lunar Outpost or for a Mars transit, landing and exploration, the design and capability of a medical system must change. Dr. Jones indicated that while surgical procedures in Mars transit is not in the concept of operations; it must be part of the strategy for Martian surface medical operations. The systems and capabilities on Mars will require more autonomous operations and technologies to support extended illnesses, acute medical emergencies, and chronic diseases.



Dr. Jones also highlighted many of the analog activities that have already occurred. These include the efforts at Devon Island, where telemedicine was evaluated; the NASA HMP-Haughton-Mars Project, Antarctica outposts; the NASA Extreme Environment Mission Operations (NEEMO) missions; the research efforts on the KC-135 and DC-9, a parabolic laboratory; and the ISS. In each of these activities, Dr. Jones stressed the need to learn, test, train, and engage.

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### **Surgical Needs and Strategies for Exploration**

*Dave Williams, MD*

Dr. Williams is CSA astronaut (STS-90, STS-118). He is an emergency medicine trained physician, and former director of NASA JSC's Space Life Sciences Directorate, Dr. Williams knows first hand the needs and capabilities for surgical intervention in space. His comments were focused on surgical needs and strategies of exploration. Dr. Williams served as symposium co-chair.

The strategies for medical care in spaceflight have evolved over time based on the experiences in the five decades since Gagarin made his first flight. These strategies include: (1) primary prevention – rigorous medical selection, (2) secondary prevention – training, (3) lunar healthcare, (4) telehealth, and (5) crew return. The strategies of surgical care include these attributes. Mitigating risks has been a key tenet of space medicine. This is due on principle to limited resources available to mitigate risk as well as risk aversion. Medical selection, prevention, and appropriate systems help in this regard.



This is due on principle to limited resources available to mitigate risk as well as risk aversion. Medical selection, prevention, and appropriate systems help in this regard.

The development of the necessary systems to support medical and surgical care on the lunar surface will provide the foundation as a technology accelerator. Lunar capability concerns include (1) optimization of safety, habitability, and biomechanics; (2) clinical infrastructure, limited resources and shelf life; (3) CMO/crew clinical skills; (4) signal delay – increases with distance between the Earth and the lunar orbit/surface; and (5) stabilization and transportation back to Earth for definitive care.

Dr. Williams presented several potential clinical scenarios. These include (1) trauma caused by burns, low-velocity accidental (LVA) injuries, and crush injuries; (2) toxicology events from fire, toxic spills or dust from the lunar surface; (3) decompression sickness (DCS); (4) radiation exposure from solar flares – this could be a major problem; and (5) although the system must be prepared for almost anything, there can and will always be unforeseen events.

The concept of the chain of clinical care in the space environment, including transportation to clinical care was also discussed.

Two additional areas which Dr. Williams focused on was CMO training and novel technologies. CMO training must include several aspects such as (1) remote medical training, (2) resuscitation and critical care, (3) time efficient training, (4) retention of judgment, skills and knowledge, and (5) tele-mentoring.

The systems that are being designed and that will be implemented for a lunar mission or exploration mission will include (1) minimal mass, volume and power, (2) enhanced capabilities for diagnosis and therapeutics, (3) the ability to be reliable and user serviceable, (4) be reusable, and (5) use very little consumables.

*What have we learned so far?*

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### **Surgical Capabilities for Human Spaceflight – A Russian Perspective**

*Igor Goncharov, MD*

Dr. Goncharov has been involved in human spaceflight in the Soviet/Russian Space Program for many decades. Dr. Goncharov works with the Institute for Biomedical Problem in support of the Russia Space Program. As a flight surgeon, trainer, and physician, he has seen first hand which systems have worked well both in the delivery of healthcare as well as in training and preparation for spaceflight missions.

The focus of Dr. Goncharov's presentation was on emergency medical care for a crewmember in the 'Sokol' space suit. This included experimentation and training on the ground both in the laboratory and in the centrifuge at Star City. Additional information was presented on the airway management and intubation on a mannequin in various simulation systems, including the Soyuz-TMA model and the 'Orlan' space suit.

Dr. Goncharov also discussed various on board diagnostic systems, including telemedicine systems. He highlighted several of the Russian medical kits and how they have been used in the Russian program.

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### **Pathobiological Effects of Lunar Surface Mineral Particulates**

*Russell L. Kerschmann, MD*

Dr. Kerschmann serves as the chief of the Division of Life Sciences at the NASA Ames Research Center.

Dr. Kerschmann presented some unique environmental challenges in spaceflight. A critical issue for surface exploration of the moon and Mars is the presence of dust particulates that can become entrained in the air within the space craft. Dr. Kerschmann discussed pulmonary particulate handling function and in situ pathophysiologic responses in reduced gravity.

He compared the plethora of experience from ground-based activities, including mining, asbestos exposure, and construction. The moon is covered in dust. The Apollo experience illustrated that moon dust adhered to the space suits and was brought into the space craft (see inset photo). Given the extent of mission activities on the surface, particulate matter will find its way into the habitats. This raises concerns of long duration exposure and diseases like silicosis and pneumoconiosis. Furthermore, the presence of dust, either from the moon surface or Martian surface will be of concern if surgical intervention needs to be conducted in these environments.



Dr. Kerschmann's comments reflected a concern over the health and safety of astronauts in this kind of environment. NASA has focused a lot of effort on radiation but limited effort on particulate toxicity. He stressed the striking similarities between these two, including the impact of disease in the long term and the need for vigilance on protection.

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## **Extreme Environments 'Medicine at the Top of the World'**

*Kenneth Kamler, MD*



One of the key goals of this symposium was to bring together individuals from a diverse background to share their knowledge and experiences. Dr. Kenneth Kamler, a hand surgeon, has spent many years as an explorer. Having been on numerous missions to the extremes of the jungle and Mt. Everest, he has used his medical knowledge in numerous events, including routine medical care and disaster response.

Dr. Kamler discussed his trip to the jungle. During this trip with the Explorer's Club, the expedition provided medical support to a young patient. In a remote village, a young boy required treatment of an injury to his hand. Using limited supplies, Dr. Kamler was able to suture the injury and bandage it. This procedure was performed in the jungle, using a flash light for brighter light. The use of limited resources in an austere environment is similar to other experiences that Dr. Kamler commented on.

Dr. Kamler highlighted the opportunity that he had in participating in the NEEMO.

Dr. Kamler discussed at great length his experiences on several expeditions to Mt. Everest. Each time he served as a physician for the expedition team that he was on. The environment of Everest Base Camp (EBC) as well as the Camps I – IV illustrates the extreme challenges of providing medical care. At EBC there is a significant medical presence, which includes medical supplies and during several expeditions, telemedicine – in the form of video-conferencing (VTC). There has even been a helicopter evacuation from EBC.

Two significant events from Dr. Kamler's time at Everest were presented. The first was his medical response to survivors of the ill-fated 1996 climbing expedition highlighted in Jon Krakauer's book, entitled 'Into Thin Air', and the NASA/Yale research expedition to EBC in 1999.

In 1996, several experienced climbers lost their lives near the summit of Everest. One individual, Beck Weathers was several frost bitten and in ill health. Dr. Kamler was the physician to administered medical care to Mr. Weathers, saving his life. Dr. Kamler reviewed in a riveting presentation the challenges and outcomes of administering health care at Camp II, which is 21,300 feet. Medical supplies needed to be brought up from lower camps. Earlier he had set up a sort of weigh station at Camp III, where Dr. Kamler



provided warm tea, oxygen, and steroid injections as necessary. He commented on the difficulty of administering the injection through clothing and the risk of exposure. There was also communication between the various teams, which provided some relief but also reinforced the inability to respond to those in need.

The medical kit – as sort of fishing tackle box of supplies - brought up from base camp provided Dr. Kamler some necessary tools to respond to his patient’s needs. He presented the various steps on how he responded to treating frost bite at this altitude – keeping the water temperature just right.

During this compelling story, it is clear that the experiences on Everest are similar to those in the jungle and in space. The environments are clearly different, but the limited resources, capabilities, and rescue are all daunting challenges.

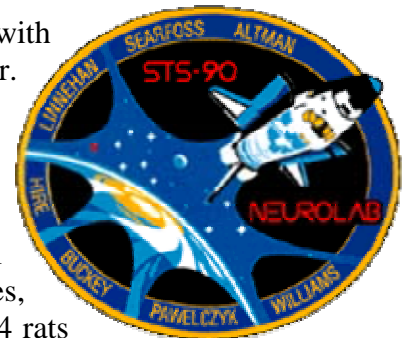
Dr. Kamler also touched on the Yale / NASA mission in 1999 to EBC. Researchers from the NASA Commercial Space Center Medical Informatics and Technology Applications at Yale University College of Medicine provided a telemedicine system and wireless sensing capability for vital signs and climber position during treks between Base Camp and Camp I.

### ***Flight Experience***

#### **Surgery in Space Flight Experience on the Shuttle - Panel Discussion**

*Dave Williams, MD, Scott Parazynski, MD, and Richard Linnehan, DVM*

Drs. Williams, Parazynski and Linnehan are all astronauts with extensive space flight experience. Dr. Williams (STS-90), Dr. Parazynski (STS-66, STS-86, STS-95, and STS-100) and Dr. Linnehan (STS-78 and STS-90) each have a strong background in surgical care, having performed a number of activities during the Neurolab mission (STS-90) and on other flights. During this 16-day mission in April 1998, surgical procedures, including thoracotomies, laparotomies, craniotomies, laminectomies, and exposure of lower extremity muscles on 24 rats



and 18 mice. These procedures were conducted in the General Purpose Workstation (GPW) on board the Space Shuttle Columbia. General intramuscular and intraperitoneal



anesthesia was used on all animals for the surgeries. This research is highlighted in full detail is published in *Aviation, Space and Environmental Medicine* (Vol 16, No. 6, June 2005) ‘Animal surgery during spaceflight on the Neurolab shuttle mission by Mark Campbell, Dave Williams, Jay Buckley, and Andrew Kirkpatrick.

This presentation by Drs. Williams, Parazynski and Linnehan was focused on their experiences during this mission and similar events. Dr. Williams presented the

challenges of the GPW, which is where the aforementioned surgeries were conducted during the Neurolab mission. Dr. Williams commented regarding an image (see inset), “This is inside the general purpose workstation that we used for STS-90 and in the center the operative table we used. Remember the largest animal we operated on was an adult rat, so the size is roughly 12 inches by 30 inches or so. You can get a feel for the surgical kits that we had. This is one of them over on the left-hand side. You have instruments in individual compartments and you have Velcro on the instrument itself, velcro on the compartment to hold the instrument in place, and sutures that are velcroed to the back and essentially with this whole kit everything has been laid out in a fairly intuitive manner, so you can just grab and go when it is needed. We have alcohol swabs up here, packing tissue, Sharp’s container in the back, bactericide for wiping down and cleaning the general purpose workstation. All of the anesthesia was prepared ahead of time and pre-labeled in individual syringes.”

Dr. Williams indicated that there were challenges in delivering the prepackaged anesthesia due to the rat’s tail being different than expected due to spaceflight. He also commented, “In reality, as we were performing the procedure, this is how it looked. We have Jay Buckley at the front of the general purpose work station. I am at the side of the general purpose workstation and we are performing the neonatal surgical procedure. We have two constant infusion pumps in the back, which we were using for perfusion fixation. We had a little needle to put into the heart, cannulated the heart, and then perfused and fixated the animal. We have the anesthetics over here and right up in there are the fixative vials, because once we remove the tissue from the animals, we would then immerse them, fixating the tissues as well. A couple of interesting things though were strange. We had huge challenges ahead of the mission, trying to get what we thought was an incorporated restraint for the operators to use to actually perform the surgical procedures. In the end, we ended up with foot loops on the ground, so you slide your whole feet into these foot loops. We had your elbows which were resting against the sleeves of the general purpose workstation (see inset photo) and we also adapted this little belt system to hold your waist in place. I actually put some foam up on the side of the general purpose workstation and pushed with my forehead, so I was pushing back against the belt and pushing with my forehead to keep from immobilized while performing the procedures. My personal feeling on this is, we need to learn some lessons on how we can immobilize people more effectively, and the operators who are performing the surgery cannot be moving around.”



Dr. Williams’ comments on surgeon or operator restraint sparked discussion from Drs. Parazynski and Linnehan as well as other participants both from space flight activities as well as other KC-135 work. The type and amount of restraint is dependent upon the procedure that is being performed, such as fine versus gross movements. Dr.

Williams commented on his comfort level regarding his position at the workstation and his neck muscles.

Someone commented, “I want to say one thing, though, regardless of how you stabilize, you stabilize the subject, you stabilize yourself, if you are not stable in one axis, then you can’t define the other. You need some kind of stable to work on it, you can stabilize yourself against the subject and rotate in that frame or you stabilize yourself and then work on the subject. You have to be at some point, somehow stable. You can’t float. I thought that it would be easy and in the end, it was hard if you weren’t totally stable.” This observation has been made by numerous astronauts and researchers on the KC-135 as well.

Dr. Williams discussed how advanced cardiac life support (ACLS) has been evaluated on a porcine model on the KC-135 (a controlled environment), including running code resuscitation, IV access, defibrillation, chest tube insertion, and cricothyrotomies.

Dr. Williams presented nine different slides during his presentation that discussed key issues for surgery in space.

#### Slide 1: Surgical Procedures

As indicated above, the ability to perform ACLS is a critically important. Simulation using animal models (porcine) has been done on the KC-135 and in Building 9. Surgical procedures were conducted on the adult rat and the neonatal rat during space flight. These were discussed above. The neonatal rat procedures represent the first survival surgery during space flight. This included exposure and injection of the soleus and extensor digitorum longus; perfusion fixation, craniotomy, laminectomy, and leg dissection. These experiments also permitted the evaluation of IV insertion using the autonomic protocol and plebotomy.

#### Slide 2: KC-135 ACLS Training

Work on the KC-135 involved the flight of a porcine model. This flight provided additional understanding on the processes for IV access – cutdowns, the use of a defibrillator, multiple resuscitation scenarios, chest tube insertion, and performing cricothyroidotomy. These events were designed and rehearsed prior to evaluation during limited microgravity portions on the airplane.

The lessons learned from this set of experiments indicated that (1) resuscitations could be successful performed in this kind of environment; (2) that drug and IV fluid administration could be successful accomplished; (3) that chest tube insertion was successful performed; (4) a cricothyroidotomy was successful done; and (5) management of instrument would be done successfully.



Dr. Williams pointed out the lessons learned indicated that it is possible to train surgical procedure in 20 second increments on the KC-135. He also stressed that the KC-135 is not spaceflight.

### Slide 3: IV Procedures

Although there has been experience of IV and associated systems in both flight and on the KC-135 using inanimate object, the experience during the Neurolab mission on live animals demonstrated that there were no issues with phlebotomy and that pre-positioning was important. Access was not an issue and there were limited consumables.

### Slide 4: Microgravity Surgical Lessons Learned

Dr. Williams discussed many of the outcomes of the surgical procedures performed during the Neurolab mission. He indicated the following: (1) there were no significant changes in fine motor coordination; (2) hemostasis was not an issue; (3) reversible anesthesia was successful, as was temperature control and wound healing, which was normal 3 days post-op; (4) wound cement (Nexaband) was used and shown to be successful; (5) instrument used for surgical procedures could be successfully managed; (6) there were no safety issues; and (7) operator restraint/mobility aids are important considerations.

### Slide 5: Implications for Human Surgery

The need for surgical intervention during long duration spaceflight increases due to the duration of the mission, distance from the earth and the type of tasks that will be performed by crew members onboard. The following outpatient procedures will most like be the kinds that the crew healthcare systems on Mars missions will be required to address:

- Repair of lacerations; wound cement, layered closure
- Incision and drainage of abscess
- Needle aspiration of abscess
- Incision and drainage of thrombosed external hemorrhoid
- Repair of Extensor Tendon
- Extremity splinting
- Needle decompression of pneumothorax
- Foley catheter insertion
- Nasal cautery and packing

The ability for IV access and volume infusion for volume resuscitation an ability to safely perform a cricothyroidotomy is important.

## Slide 6: Anesthetic Implications

Surgical care of course cannot be accomplished without the ability to provide anesthesia. Dr. Williams indicated that the need to do peripheral nerve blocks for the digits, hand, foot, face, ear, mouth (dental), and rib for a pneumothorax is important. A need to perform a Bier block for regional anesthesia is important as well.

Dr. Williams summarized by highlighting issues that must be addressed to adequately support surgery in space. These included (1) a diagnostic capability; (2) pre-operative care; (3) an ability to deliver and monitor anesthesia; (4) operative care; (5) post-operative care; and (6) the ability to train and skill retention.

Clearly the limited efforts performed on Neurolab provided a wealth of knowledge on what could be done and what will be used as the foundation for creating the necessary systems for surgery in space.

### ***Ground-based Experience***

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#### **Surgical Experience on the KC-35**

*Mark Campbell, MD*

Dr. Mark Campbell is a general surgeon in Plano, TX. He spent several years as a consultant on surgery to NASA and Wyle Laboratories (formerly Krug Life Sciences) at the NASA JSC. In addition, he spent some time as a NASA flight surgeon working in Russia. During the 1990's Dr. Campbell spent a lot of time conducting surgical research on NASA's KC-135 parabolic laboratory.

Dr. Campbell began his presentation with a summary of current constraints and capabilities in the U.S. Space Shuttle Program and the ISS Program. The constraints include power, volume, mass, compatibility, reliability and the ability to maintain and repair. He highlighted the Shuttle Orbiter Medical System (SOMS) kits and the integrated medical system originally designed for the Space Station Freedom program. Known as the Health Maintenance Facility (HMF), this system was designed with many features (defibrillator, ventilator, digital x-ray, IV pump, suction fluid separator, etc.) to maintain crew health for periods up to 45 days. Additionally, it weighed in at approximately 2,400 pounds. As the ISS program became reality in the mid 1990s, the HMF system was trimmed down in size and scope.



Several factors have and continue to drive the requirements for medical care in human spaceflight. These include but are not limited to the mission profile (duration),



proximity to the Earth – for return to definitive care, crew selection and risk aversion. Strategically, NASA has incorporated the philosophy of stabilize and transport. This philosophy changes dramatically for exploration missions of Mars. Dr. Campbell discussed the use of telemedicine and the communications delay, specifically how the long delay impacts the ability to work with the ground in real-time. He stressed that this factor alone impacts the possibility of telesurgery or robotic surgery through

communications links with between the spacecraft and ground controllers. However, he did indicate that advanced medical technologies such as those under development with DARPA will be of value to NASA on the long duration missions to Mars.

Dr. Campbell provided a detailed summary of surgical research conducted on the KC-135. This research was conducted during the 1990s and provided an outstanding opportunity to evaluate a variety of surgical issues in simulated microgravity. He pointed out that although simulated microgravity is a great evaluation step it is NOT like space flight. There are many questions that have been looked at and evaluated. Patient restraint and instrument restraint are key in supporting surgical procedures during flight. The inset photos illustrate various restraint designs that have been considered.

This is apparent as the multitude of researchers who perform CPR on the KC-135. Dr. Campbell demonstrates this concept on a porcine model. All medical instrumentation must be attached to something, at table, the wall, a surgeon vest. Otherwise, things will float away. Dr. Campbell illustrated the various concepts, including a vest and instrument tray. Each of these demonstrated good characteristics. He stressed that the kits must be organized into procedure kits as well as individual, single use items.



Another area that Dr. Campbell highlighted was an isolation chamber. This is important for isolating materials, including blood streams (arterial bleeder) and droplets (venous) that can leave the surgical field in a hurry. He illustrated this concept with several experiments on the KC-135. The surface tension of the blood causes it to stay at the bleeding site. It pools up and unless agitated will remain in the same place. Over a series of experiments, the isolation chamber was eliminated it was felt that it was not needed. However, Dr. Campbell commented that it took about 50% longer to

perform the tasks because you must maintain awareness of instrument restraint and nothing gets loose and floats away.

Dr. Campbell discussed laparoscopic surgery. He indicated that surgeons were well restrained. He discussed the changes in anatomy positioning and forced bleeding – incisions made in the abdominal cavity. The blood pooled because of the surface tension forces and remained adhered to the abdominal wall. Additional tasks including thoracoscopy were challenging. Chest tubes were shown to have poor drainage.

Imaging is important in diagnosis. During these parabolic flights, ultrasound evaluations on porcine models were conducted. Dr. Campbell highlighted several issues. (1) “First of all, by ultrasound, you can see the air in the chest cavity. The lung floats centrally and the pneumothorax is centered around it. If you put fluid in the chest cavity, it doesn’t lobulate posteriorly, but again, seeps out and disperses within the chest cavity which made chest tube drainage of the hemothorax definitely more difficult. (2) If you put fluid in the abdominal cavity, it also doesn’t tend to lobulate posteriorly, but it stays wherever it is created. In other words, let’s say you have a catheter anterior to the liver and you inject it with fluid in zero g, it stays right where it is created. It stays anteriorly. It doesn’t go to the posterior portals. It does, once you hit that 1.8 g window, it will hit back and all the fluid goes posterior and settles there. (3) We found that ultrasound is very useful in pneumothorax detection and you can use ultrasound to detect pneumothorax. We found this was quite reliable, not only in our animal model at ground, in our animal model at 0 g. (4) We also did humans on the ground in a trauma situation and we found in all three cases that ultrasound was very reliable for detection of pneumothorax, which is very important, because in space flight we don’t have X-ray. You can’t auscultate the chest very well, so this is a very useful thing we have now.”

Dr. Campbell also commented. “We also found ultrasound very useful in performing a variety of percutaneous techniques. Dr. Andy Kirkpatrick was able to put a needle in the abdominal cavity to drain fluid out from the abdominal cavity or from the bladder. This is all in zero g that we did this in. We also found that ultrasound is very easily trainable and we also did tele-event train actually in parabolic flight, using people that were just minimally trained on ultrasound techniques, so it is a very feasible thing to use telemetrically.”

Dr. Campbell summarized the parabolic flight experiences. (1) Restraint can be accomplished by simple methods for a patient and the crew medical officer. (2) Instrument restraint is important and needs to be integrated into the system. (3) Bleeding can be controlled. (4) Advanced Trauma Life Support (ATLS) procedures can be performed. (5) Complex surgical procedures can be performed – The length of time is longer than ground-based work. (6) Fluids behave differently in microgravity than in one 1 g.

Dr. Campbell concluded his remarks by reviewing some previous work. This included a NASA Surgical Training Working Group, assembled in 2003. Although a formal report was not produced, this group poised several pertinent questions. The questions and the conclusion the group developed are included below.

- (1) What surgical diseases do we need to be able to treat?
  - a. There needs to be enough surgical capability to perform major open procedures (exploratory laparoscopy and appendectomy). This is specific to a Mars mission.
  - b. Some surgical diseases cannot be treated (vascular surgery is not trainable)
- (2) What surgical procedures do we need to be able to perform?
  - a. Laparoscopy may not be available
  - b. Many procedures can be performed with imaging and percutaneous techniques
- (3) What surgical skills do we need to teach the Expedition Medical Officer?
  - a. Need surgically-trained CMO (level of second year resident in selected areas)
- (4) How do we train the Expedition Medical Officer?
  - a. Trained in multiple disciplines
  - b. Need an M.D. who has already finished a board certified residency
  - c. Can train with a two year program (six months of surgical training)

Dr. Campbell concluded by stating, “So my convictions were that we need a surgically-trained crew medical officer, about the level of a second-year resident. He would be trained in multiple other disciplines besides surgery. So we probably would need an M.D., someone already finished with a board certified residency in a number of specialties. It could be Internal Medicine. It could be anything. You could take this person and you could train them with a two-year program with six months of surgical training.”

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### **Surgical Training for Spaceflight in Analog Environments**

*Timothy Broderick, MD*

Dr. Timothy Broderick is on the faculty of the University of Cincinnati. He has been a NASA and TATRC-funded researcher, focusing his effort on surgery in extreme environments. Dr. Broderick served as a co-chair on the symposium. Dr. Broderick’s comments summarized the challenges of surgical training in analog environments, including virtual reality simulation on NASA’s KC-135 and during recent NEEMO missions.

The need for surgical care must be full integrated into to the mission profile. Short duration missions, those characterized by close proximity to the Earth, will not require an extensive surgical capability. This capability will most likely be capable of supporting trauma from events such as crush injuries. So mission profiles that are short in duration will be characterized by stabilizing and transporting to the ground for definitive care. Long duration missions, human-tended missions to Mars, must include more autonomous medical care capabilities, including a surgical capability.



Each of these scenarios has similar challenges to those of earth-based activities, including the military, underwater research and other extreme environments. These include: (a) surgeon/non surgeon; (b) limited mass, volume, and power; (c) limited telecommunications; (d) adverse, unpredictable weather; (e) transportation; (f) gravity, (g) pressure; (h) temperature; and (i) water.

Dr. Broderick highlighted that as surgical systems become more complex the skill set of the person doing the surgery changes. "... surgeons who might be good at open surgery are not necessarily good at minimally invasive robotic surgery and telesurgical care." Therefore, less invasive surgery requires more skills and more technology requires more support. Using a video clip of an unrestrained surgeon the KC-135, Dr. Broderick illustrated the necessity for training and additional research both on the ground and in space. Although the experience gained to date is of great importance, it is not sufficient. He stressed that "we need to decide what is necessary and target our approach, our care, and our technology for surgical needs."



In 2003, Dr. Broderick conducted the 'Computer-based Virtual Reality Surgical Simulation in Microgravity' on the KC-135. This research effort was in response to the 2002 NASA Research Announcement (NRA). The purpose of this research was to compare 20 participants, including surgeons, non surgeon MDs, astronauts, medical students, and non medical (but technical) personnel on the use of two different kinds of inanimate simulators. One was a computer-based virtual reality simulator. The other was an inanimate box. The objective was for each of the 20 participants to conduct 4 basic surgical skills (cutting, suturing, clipping and grasping).

Participants were trained prior to the actual flight days for several hours over 5 days. During the each of five flights, each participant had approximately 25 seconds of to do as



many of the tasks as possible on each of the two simulators. Completing all four tasks on both simulators created about 66 million data points. Dr. Broderick illustrated the data in graph format, highlighting that performance degraded in microgravity by each participant on all tasks. Another area of importance measured was the use of force. On the inanimate trainer a strain gauge was used to measure force applied during task accomplishment. The data showed that

astronaut participants used less force application than the other participants. This is probably secondary to their experience in the microgravity environment. Other data from this experiment was also presented.

Dr. Broderick also highlighted additional KC-135 activities, including the evaluation of the Hand-Assisted Laparoscopic Surgery (HALS) device and the Emergency Care Simulator (ECS).

The remainder of Dr. Broderick's discussion was on the NEEMO 7 mission. The overall objective was to evaluate telesurgery and a robotic surgery in the underwater laboratory, Aquarius. During NEEMO 7, the science objectives were (1) to evaluate telementoring and robotic assistance, enabling astronauts to perform emergency diagnostic and surgical tasks in an extreme environment; (2) assess the limits of current technology in telecommunications and robotics; and (3) begin to develop portable, robust surgical robotics platforms for use in extreme environments. The NEEMO 7 project brought together collaborators from the U.S. Navy, Air Force, Army, NASA, CSA, and National Oceanographic and Atmospheric Administration (NOAA).



During the NEEMO 7 mission, the Automated Endoscopic System for Optimal Positioning (AESOP) (originally Computer Motion, Inc) surgical arm was deployed in the Aquarius Habitat. It was operated from Hamilton, Ontario, Canada. This research showed that the robotic system could be controlled from a distant site. The remote commands for controlling the robot were troublesome because of packet loss and jitter. Voice commands were unsuccessful because voice was not recognized by the computer due to change in voice at pressure.

The experiences of telementoring during the NEEMO 7 mission demonstrated that latency can be overcome by technology and technique. In addition, it was shown that (1) non physicians can provide expert medical care in extreme environment using enabling technologies; (2) telementoring facilitates expert surgical care at a distance; (3) surgical robots must be modified to operate with humans in confined, extreme environments; and (4) this kind of project is a great 'technology accelerator'.

Dr. Broderick concluded by stating "Similar to flight, surgical simulators allow effective training, safe development of surgical capabilities. Microgravity MIS surgery is associated with more force, more time, and more errors. There is a need to develop surgical performance countermeasures, especially restraints. The same enabling technology that will be used for surgery in space has other space applications, so we need to make sure we are talking to non-medical operations personnel. Also, we need to talk to people outside of NASA to get some of these enabling technologies brought into NASA. Exploration medical care systems, technology and team development will require time and money to ensure success. If we don't put some money in the short-term, at least a small amount, we are not going to have the care systems ready when we need to go."

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## Department of Defense Initiatives

*Gerry Moses, PhD*

Dr. Moses is the Director of the Clinical Applications Division at the U.S. Army's Telemedicine and Advanced Technology Research Center (TATRC).

Dr. Moses began by indicating that America's men and women in uniform face similar challenges to what NASA faces in providing healthcare in extreme environments. He discussed his division's research focus, including advanced surgical technologies, clinical medicine, and DARPA biomedical projects. The premise of his talk was to discuss the portfolio of TATRC activities in surgical robotics, telesurgery, and surgical simulation. TATRC manages about 500 different projects. These projects are organized along common areas, each with a portfolio manager. Often the portfolio managers are on assignment to TATRC through academic relationships. These relationships have provided expertise not available within the government. He mentioned, Drs. Mehran Anvari and Timothy Broderick as two experts in telesurgery that TATRC looks to. Several other individuals were highlighted as well. Many are internal to TATRC – through Intergovernmental Personnel Agreements (IPA) and many are external, which is accomplished through grants.

Dr. Moses stressed the importance of collaborative, interactive, and cooperative ventures. One such area that he focused on was robotic surgery; stressing growth in opportunities beyond the currently available platform (da Vinci). This growth includes portability, mobility, autonomous systems, haptics, and so on. Such emerging technologies will be of value on the battlefield, space and other areas in the coming years.

One particular TATRC-funded project that Dr. Moses highlighted was Penelope, a robotic scrub technician or nurse. This system interacts with a surgeon. It responds to voice commands to deliver surgical instruments to the surgeon at the surgical field. This system recently worked well with a surgical robotic system. Human clinical trials are on the calendar.

Dr. Moses spent the remainder of his presentation focusing on TATRC's telesurgery portfolio. He mentioned the first nephrectomy performed over the Internet with the da Vinci robotic system between Cincinnati and Sunnyvale, CA. This effort demonstrated the unique ability of academia (University of Cincinnati, Johns Hopkins), industry (Haivision, Intuitive Surgical) and government (TATRC, WRAMC) to collaborate in a mutually beneficial ways. Other TATRC initiatives presented included the University of Cincinnati's High Altitude Platforms for Mobile Robotic Telesurgery (HAPsMRT) project and NEEMO 9. In each of these activities, telesurgery is a significant research objective.



Dr. Moses concluded his remarks with a presentation and discussion of simulation activities, including the Trauma Non-Technical Skills (TNTS) at the University of California at San Francisco, Affordable Haptics, Context Aware Surgical Assistance of Virtual Mentoring (CASA) at the Johns Hopkins University, and the DARPA Trauma Pod.

The wide range and scope of activities and the wealth of knowledge highlight many similarities in the challenges and opportunities that NASA and the military face. The emerging technologies presented will serve as key attributes in moving medicine and surgery forward.

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## Future Surgical Systems

*Richard Satava, MD*

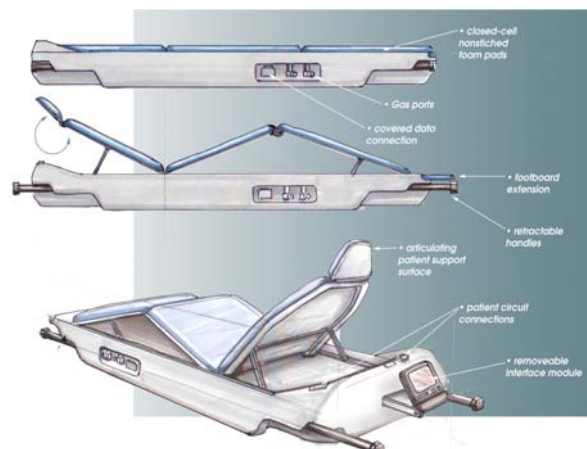
Dr. Richard Satava has served many roles over the past two decades. In each, he has moved surgery to new heights. These include new surgical tools as well as advanced medical technologies. Dr. Satava is affiliated with the University of Washington and DARPA.



Dr. Satava's comments were on the future of surgery in 2020 and beyond. His comments were tempered with the knowledge and awareness of the various far-reaching DARPA programs, which he has been at the forefront since the early 1990s.

The experiences of the Everest Extreme Expedition (E<sup>3</sup>), conducted through a NASA activity at Yale University in 1999 were presented by Dr. Satava. He highlighted the need to monitor climbers in an extreme environment and how telemedicine was used in real-time to diagnose medical issues.

Dr. Satava presented several technologies that are currently under development. These included the 'TriCorder', High Intensity Focused Ultrasound (HIFU), Plasma Discharge Sterilization, the Life Support for Trauma and Transport (LSTAT) and the Nightingale Unmanned Airborne Vehicle (UAV). The LSTAT, equipped with variety of advanced life support components, can be integrated with the UAV for extraction from the battlefield.



Commenting that ‘The future is here....it’s the Information Age’, Dr. Satava presented the concept of the virtual soldier. Using whole body scans, a Holomer, and virtual autopsy is possible. The possibilities of this technology are tremendous.

The concepts of education using simulation were presented with discussion on various surgical simulators, passive recording devices like ‘Blue Dragon, a MEMS-based system that tracks hand motion, operating room ceilings embedded with LEDs for light and perhaps a ceiling embedded with thousands of camera to record events in the operating room. These kinds of technologies lead to ‘Paradigm Change’ in surgical education and training. Curriculum will change to incorporate surgical simulation and robotic surgery. Nascent technologies in ‘intelligent tutors’, ‘complex procedures’, and ‘digital libraries’ will enable the rehearsal of surgery before the actual surgery is performed on the patient, and provide objective methods to validate readiness – rather than subjective.

Dr. Satava provided an in-depth discussion on robotic surgery. This included several video clips of robotic systems such as Massachusetts Institute of Technology (MIT) robot, DARPT Trauma Pod, and Penelope. He compared and contrasted surgical robots with those used in industry today. Highlighting automatic tool changers and parts dispensers, he conveyed that the operating room of the future would look much different than today.



Switching gears, Dr. Satava presented ‘Disruptive Visions’, including the ‘Bio Intelligence Age’. He presented several leading edge concepts including, micro-robots, the femtosecond laser, a surgical console for cellular surgery, new surgical tools, intelligent prosthesis, tissue engineering, and suspended animation. Each of these concepts has a potential for surgery in space and extreme environments. These technologies will change the future of medicine. The rate of discovery is accelerating exponentially, thus raising profound fundamental issues in addition to the opportunities. Moral and ethical issues naturally follow. These may take decades to be resolved.

The remainder of Dr. Satava’s talk was about futuristic ideas at the cellular level, replacing organs, regeneration of human tissue, and ultimately the interface of human and machine. His final comment was ‘Do Robots Dream’.

## *Unique Challenges*

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### **Anesthesia**

*Hal Doerr, MD*

Dr. Hal Doerr is an anesthesiologist at the Baylor College of Medicine. In addition, he is funded researcher through the National Space Biomedical Research Institute (NSBRI) and NASA JSC.

Dr. Doerr's comments were focused on anesthesia, space medicine, and medical training through simulation. He began his talk was 'Post Space Flight Rapid Sequence Induction.' He discussed the concerns with providing general anesthesia immediately post flight. This concern arose over the Russian's Bion Satellite Primate Experiments in 1995 and 1996. Twenty two monkeys were flown in pairs on 11 flights of 14 days each in low earth orbit. The first 10 pairs received anesthesia on post flight days 2 and 3 with no significant issues. The 11<sup>th</sup> pair received Ketamine and Isoflurane (the same as the other 10 pairs) on post flight day 1, resulting in one death and the other significant complications. This event, the first ever, illustrated the need for a greater understanding of the following questions: (1) Can anesthesia be given safely to astronauts in the immediate post flight period?; (2) Does exposure to micro gravity alter the physiologic effects of anesthetics?; and (3) How long after flight is it safe to administer anesthesia?

Dr. Doerr indicated that NASA had created a working group in space medicine to review these questions and concerns. This group included medical experts within NASA and academia. He also formed the Medical Operations Support Team (MOST). He discussed the need for simulation to train nominal and off-nominal medical events.

Key issues in space physiology that Dr. Doerr expressed concern about, included (a) Neuro-vestibular [vestibular and space motion sickness]; (b) Neuro-vascular [dehydration, decreased red cell mass, autonomic, baroreceptors, and 3<sup>rd</sup> spacing]; (c) Neuro-muscular [atrophy, rhabdomyolysis, and capacitance vessels]; (d) Skeletal [bone loss]; Renal [increased Ca<sup>+</sup> loads]; and (e) Gastrointestinal [nausea and vomiting]. A greater understanding of pharmacodynamics is also of interest. This includes automaticity, catecholamine depletion, volume of distribution, drug delivery, drug half-lives, and radiation effects. Each of these can and will be affected by space flight both in duration and distance from the earth.



Dr. Doerr used an 'off nominal landing' simulation to illustrate the issues faced with anesthesia in spaceflight. In this scenario, a crewmember is severely injured, receiving head injuries, on impact of the Soyuz landing. At this point, given that the spacecraft has

landed in Kazakhstan, the medical personnel attending the landing (Russian and American) have three options. The first is ‘stand and fight’, which means do the best that can be done with limited supplies available. The second is ‘scoop and run’, which means return injured crewmember to Ramstein/Landstuhl, Germany – a 9 hour rotor and fixed wing transport. Treatment of this injury in the field using an anesthesia protocol will include preop, induction, maintenance, and emergence. He presented the previous post flight RSI anesthesia protocols – standard and head trauma, and the current protocols.

He closed his remarks by indicating anesthetic considerations, including neuromuscular blocks, inhaled anesthetics, benzodiazepine, hypnotics, beta blockers, direct versus indirect agonists, pressors, fluids, and code drugs. In addition, he discussed methods of administration, including total intravenous anesthesia.

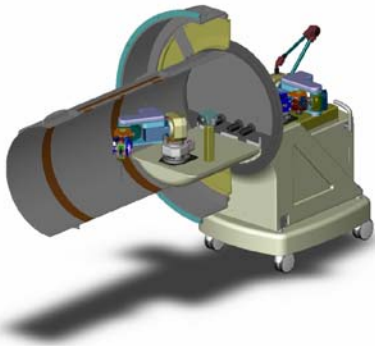
Clearly surgery in space requires anesthesia. This will include a greater understanding of the physiological consequences at post flight as well as in flight. The environment in which anesthesia may be delivered will also require a greater understanding.

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## **Robotics**

*Timothy Fielding*

Mr. Timothy Fielding is affiliated with MacDonald, Dettwiler (MD) Robotics, a subsidiary of MacDonald, Dettwiler Associates (MDA), Ltd. MDA is involved in the manufacture and supply of robotic arms for the U.S. Space Shuttle and ISS.



Mr. Fielding’s presentation was focused on “Microsurgical Robotics: Space Heritage in the OR”. Using their wealth of knowledge on robotic systems in existing space and terrestrial systems, MDA is developing surgical robotic systems. They have established 5 key performance capabilities for microsurgical robotics. They are (1) accuracy, resolution, and responsiveness suitable for microsurgical motions; (2) provision of meaningful haptic feedback to the surgeon; (3) an ability to be integrated with external image and sensed data; (4) a capability to perform preplanned, automatic tasks such as stereotaxy; and (5) environmental compatibility.

MDA has worked with world leaders in neurosurgery to develop the ‘NeuroArm’. This system, which has been built, is schedule for testing in late 2006 at the University of Calgary. This system has many unique features, including image-guided and force feedback to the surgeon.

Mr. Fielding presented a proposed commercial product architecture, which included a hand controller and a core base system with a variety of arms for multiple surgical disciplines as well as simulators for training. Such surgical platforms would be high precision and have high responsiveness. Enabling technologies will include enhanced haptics and advanced imaging guidance. He stressed that technology will provide surgical

tools that do not have to fit into the human hand – “...the range of tool possibilities is limited only by the imagination.”

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## **Tele-presence – From the OR to Orbit**

*Trevor Chapman*

Mr. Trevor Chapman is associated with Dr. Anvari and the Centre for Minimal Access Surgery at the McMaster University in Hamilton, Ontario, Canada.

Mr. Chapman’s comments were focused on four areas: (1) telementoring; (2) tele-robotic surgical services; (3) extreme environments; and (4) space exploration.

Tele-mentoring is a natural extension of an expert to distant site. This has been a key activity of Dr. Anvari’s group at CMAS. Using the Zeus robotic surgical platform and Canadian Bell communications (IP and VPN service), his team has mentored and conducted tele-robotic surgery between St. Joseph’s Hospital in Hamilton, Ontario and North Bay General Hospital. Dr. Anvari has used this set up to perform over 22 surgical procedures, all laparoscopic, successfully. Mr. Chapman indicated that this work clearly demonstrates that a surgeon can be remotely located from the patient safely with less than 500 msec of latency.



Mr. Chapman discussed surgical efforts in extreme environments. He highlighted many of the issues that confront the conduct of surgery in such an environment. These include confined space, limited telecommunications, adverse and unpredictable weather, transportation to and from, limited power supply, and location (battlefield, natural disaster, etc.). He indicated that robotics must become smaller, more robust, mobile and rapidly deployable, and adaptable to both laparoscopic and open/micro surgery.

Regarding surgery in space, Mr. Chapman’s remarks were focused on the following areas: (1) build upon the lessons derived from the clinical deployments of tele-mentoring, tele-robotics; (2) surgical procedures in orbit will have to employ semi-autonomous robotics and pre validation; (3) image guidance using computed tomography/MRI will be required to drive the autonomous routines; (4) bandwidth and network jitter will need to be assessed; and (5) tele-mentoring will also have a large impact on surgery – non invasive procedures. Mr. Chapman highlighted the biggest hurdle to overcome is latency.

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## **Issue of Trauma Surgery in Space Flight**

*Andy Kirkpatrick, MD*

Dr. Andrew Kirkpatrick is a trauma and emergency room physician in Canada. He is board certified general surgeon and critical care medicine specialist. He has worked with NASA and Wyle Laboratories over the past several years in several projects.



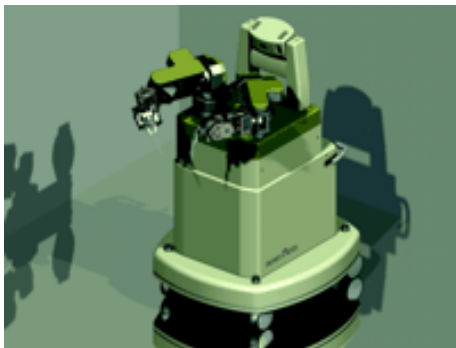
The ability to address trauma caused by a variety of activities during space flight is of vital importance to crew survivability. Currently, medical care in space is limited by several well known factors, including weight, power, volume, crew training, duration of the mission, and proximity and return to the earth. Return to definitive care has been a key factor in the compliment of what is available on board. Low earth orbit missions can be evacuated to terrestrial care in hours, whereas, missions to return from Mars to the earth can be measure in months or years.

Dr. Kirkpatrick commented that analogue studies aboard U.S. Navy submarines provide a general understanding of the kinds of injuries that might be seen during flight. Space flight missions that are characterized by increased EVA's and construction, both of which are inherently risky. Other areas of potential injury, especially blunt trauma, are the movement of large voluminous objects that are weightless. To further exacerbate these conditions are the body's physiological changes due to weightlessness.



The ability to respond to illness or injury is paramount for crew health and safety. Dr. Kirkpatrick discussed the ability to perform tasks such as endotracheal intubation, and percutaneous tracheostomy, using KC-135 experiments as a tool for training. He highlighted the use of ultrasound for detecting pneumothorax, and he discussed internal bleeding in this environment.

Citing the work done by Dr. Campbell et al., Dr. Kirkpatrick discussed minimally invasive surgery (MIS), the environment of the space cabin, visualization within the abdomen – specifically that in reduce gravity or 0 g, the abdominal cavity assumes a rounder configuration, limitations of MIS in trauma surgery, hemorrhage control gaseless laparoscopy, and the challenges in intra-abdominal pressure and its effect on organ systems.



Dr. Kirkpatrick presented data on fibrin bandages and foam, requirements for laparotomy for the Space Station Freedom program (circa 1990), access to major vasculature, and central access using SMART (Doppler) and the use of portable ultrasound with fully automated vascular target identification. He discussed thermal control and hemodynamic support for shock during space flight. New technologies such as interventional angiography adjuncts to physical hemostasis, recombinant factor VIIa, and suspended automation.

Dr. Kirkpatrick closed his comments with a short discussion about the University of Calgary / MD Robotics neuroArm surgical robot. This robotic system incorporates concepts in autonomous image-guided therapies.

Clearly trauma injuries will occur during space flight operations, especially as construction continues (EVA's, etc) and the length of stay increases. Return to definitive care rapidly and limited communications will require sufficient systems, training and supplies to support the kind of trauma that can be predicted.

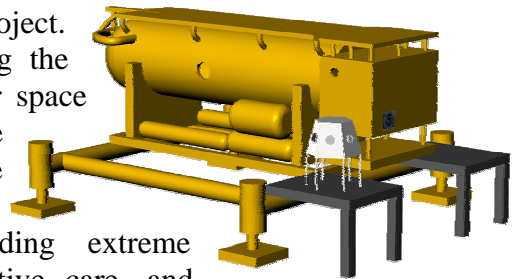
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## **Mission Preparedness - Training and Simulation**

*William Todd*

Mr. William Todd is a lead in simulation and crew training at the NASA JSC. In addition, he is responsible for the coordination of the NEEMO Program.

Mr. Todd's comments were about the NEEMO project. He provided an overview of the project, including the NEEMO Charter and how it is an ideal analog for space flight. The NEEMO missions are conducted in the Aquarius Habitat off the coast of Key Largo, FL. The habitat, located in approximately 70 feet of water, has many similarities to space flight, including extreme environments, telemetry, delayed return to definitive care, and isolation. The facility is owned and operated by the National Oceanic and Atmospheric Administration (NOAA). The NEEMO missions have focused on a variety of space related activities.



Crew preparation for ISS missions is similar to NEEMO preparation. The approach to mission planning is the same, including baseline data collection, training, and crew contact. The mission profile permits NEEMO crews to evaluate technologies for space operations. Mr. Todd highlighted many of the activities conducted during recent NEEMO missions, including answering (1) life sciences 'critical path roadmap to Mars queries', telemedicine, telerobotics, telesurgery, and tele-robotic surgery; (2) hardware and procedure testing including wireless location tracking, exercise countermeasures and medication tracking; and (3) crew health monitoring, including diagnostic ultrasound, bone density measurements, in situ hearing loss testing, physiological Monitoring and environment monitoring.



Mr. Todd summarized the NEEMO projects #1-#8. He discussed NEEMO 9, which had not yet occurred when this symposium was held. He indicated that the NEEMO missions offer offers a highly effective spaceflight analog for crew preparation for ISS missions. It offers an unequalled opportunity as an exploration enabling analog in answering many open questions that must be answered in fulfillment of NASA's exploration initiatives. He also indicated that this project effectively fulfills NASA's goals of inter-agency cooperation and Educational Outreach.

NEEMO has involved a number of organizations within NASA and outside. These organizations have included the Canadian Space Agency, the Center for Minimal Access Surgery at McMaster University, the U.S. Army’s TATRC, the U.S. Navy Experimental Dive Unit, Rice University, the University of Cincinnati, Dartmouth University, the University of Texas Medical Branch, and the University of North Carolina at Wilmington.

This venue provides a unique platform for conducting research in the delivery of healthcare in extreme environments, including surgery. The NEEMO 7 and future missions (NEEMO 9 and 12) have a focus on robotic surgical tools that will enable a more comprehensive understanding of how surgery might be performed during space flight.

## **PROJECT DELIVERABLES**

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The main purpose of this TATRC-funded activity was to conduct the symposium on surgery in extreme environments. The resulting deliverables include this final report and a list of the manuscripts that are in preparation. These manuscripts will provide much more detail on the various challenges that are faced in conducting surgery in extreme environments. The Journal of Aviation, Space and Environmental Medicine (ASEM) has indicated that a Special Issue, entitled ‘Surgery in Extreme Environments - Space and Beyond: Where we have been and Where we are going’, published in 2007 will be of great interest to its readers. Table 2 highlights the working title and preliminary authors.

<b>Manuscript Title</b>	<b>Authors</b>
Surgery in Extreme Environments: A Symposium Summary	Doarn, Williams, Broderick
Space Medicine: A Historical Perspective	Williams, Jones, Barratt, Doarn
Space Medicine for Exploration	Jones, Barratt
Surgery in Space: Initial Experience	Husted, Williams, Parazynski, Campbell, Broderick
Surgery in Extreme Environments	Kamler, Merrell, Broderick, Doarn
Trauma in Space	Kirkpatrick, Mattox, Broderick
Anesthesia Delivery in Spaceflight: Challenges and Opportunity	Doerr, Buckley, Williams
Exploration Enabling Advanced Medical Technologies for Future Surgical Systems	Satava, Moses, Broderick
Surgery In Space: The Vision	Doarn, Broderick, Williams

## **SUMMARY**

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Surgery in space will become an increasingly important requirement as spacecraft are built and crews are trained for exploration missions to moon and Mars. The collective knowledge gained from the U.S. and U.S.S.R/Russian space programs, as well as ground-based research will provide the foundation for the medical care delivery systems. These systems will be tempered by design, resources, and risk. Such systems must provide a standard-of-care that is similar to that on earth. This has long been the philosophy for

Space Medicine. The challenges are daunting but discovery, innovative technologies, and training will be enablers.

Those who left the warmth of their hearths in antiquity, through the age of discovery, and into the 21<sup>st</sup> century did so with determination, skill and a hunger for knowledge of what's out there. They took with them the necessary tools for survival. Space voyagers will take the necessary tools for survival and the skills to undress seen and unforeseen events. Surgical capability will be a necessity on a multi-year expedition to Mars. The experience gained from space missions, KC-135 – parabolic flight experiment, NEEMO missions, the military and other analogues have done will be of great value in help us move forward in creating the necessary systems for performing surgery in extreme environments.

This report represents a summary of the Surgery in Space Symposium held in Houston, TX, December 4-6, 2005. This meeting was sponsored in part by a grant from TATRC, a grant from the UC College of Medicine, and support form MD Robotics.

## APPENDICES

**APPENDIX A**  
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**APPENDIX B**  
**Agenda**  
**Surgical Science in Support of Human Space Exploration**  
**Hilton Clear Lake - JSC**  
**5-6 December 2005**

**Monday, December 5, 2005**

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- 7:30 Continental Breakfast / Registration
- 8:00 Welcome  
Introductions and Meeting Agenda  
Surgery in Extreme Environments – Setting the Stage  
Charles Doarn, MBA  
Executive Director, Center for Surgical Innovation  
Timothy Broderick, MD  
Medical Director  
University of Cincinnati Center for Surgical Innovation  
Dave Williams, MD  
CSA Astronaut  
Johnson Space Center

**Exploration – Meeting the Challenge**

- 8:30 Historical Perspectives on Exploration – Medical Needs  
Richard S. Williams, MD  
NASA Chief Medical Officer
- 9:00 NASA's Exploration Architecture: Space Medicine Challenges and Constraints  
Jeffrey Jones, MD  
NASA Flight Surgeon
- 9:30 Medical Operations for Exploration  
Jeffrey Jones, MD  
NASA Flight Surgeon
- 10:00 Break
- 10:15 Surgical Needs and Strategies for Exploration  
Dave Williams, MD  
CSA Astronaut

**What have we learned so far**

- 10:30 Present Surgical Capabilities for Human Space Flight – A Russian Perspective  
Igor Goncharov, MD  
Institute for Biomedical Problem
- 11:00 Unique Environmental Challenges in Spaceflight  
Russell L. Kerschmann, MD  
NASA Ames Research Center
- 11:20 Analog Environments  
Desmond Lugg, MD - Invited  
NASA Headquarters

11:45 Lunch Buffet  
Extreme Environments 'Medicine at the Top of the World'  
Kenneth Kamler, MD  
Everest Expedition(s) Surgeon

**Flight Experience**

1:00 Surgery in Space Flight Experience on the Shuttle  
Dave Williams, MD  
Scott Parazynski, MD  
Richard Linnehan, DVM

3:00 Break

**Ground-based Experience**

3:10 Surgical Experience on the KC-35  
Mark Campbell, MD

3:35 Surgical Training for Spaceflight in Analog Environments  
Timothy Broderick, MD

4:00 DoD Initiatives  
Gerry Moses, PhD  
Director, Clinical Applications  
US Army, Telemedicine and Advanced Technology Research Center (TATRC)

4:20 Future Surgical Systems  
Richard Satava, MD  
University of Washington  
DARPA

**Unique Challenges**

4:40 Anesthesia  
Hal Doerr, MD

5:00 Robotics  
Timothy Fielding  
MD Robotics

5:20 Summary and Adjourn

6:45 Group Dinner – Kemah

**Tuesday, December 6, 2005**

- 7:00 Continental Breakfast
- 7:30 Summary of Day 1 Discussion  
Dave Williams, MD  
Timothy Broderick, MD
- 8:15 Tele-presences  
Mehran Anvari, MD / Trevor Chapman  
Center for Minimal Access Surgery
- 8:35 Issue of Trauma Surgery in Space Flight  
Andy Kirkpatrick, MD
- 9:00 Mission Preparedness - Training and Simulation  
William Todd  
NASA Johnson Space Center
- 9:20 Needs Assessment – What are the realities  
Meeting the President’s Vision  
NASA Personnel
- 10:00 Break
- 10:15 Break out Groups - Discussions  
Group A – Surgical Systems  
Group B – Training and Education  
Group C – Applications / Operations
- 11:30 Group Presentations
- 12:15 Next Steps/Closing Remarks  
Charles Doarn, MBA  
Timothy Broderick, MD
- 12:30 Adjourn

## APPENDIX C Participants List

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**APPENDIX C**  
**ACRONYM / SYMBOL DEFINITION**

ACLS	Advanced Cardiac Live Support
AESOP	Automated Endoscopic System for Optimal Positioning
ARC	Ames Research Center
ASEM	Aviation, Space and Environmental Medicine
ATLS	Advanced Trauma Life Support
BMIST	Battlefield Medical Information System-Tactical
CEV	Crew Exploration Vehicle
CME	Crew Medical Officer
CPR	Cardio Pulmonary Resuscitation
CSA	Canadian Space Agency
CSI	Center for Surgical Innovation
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
DCS	Decompression Sickness
E <sup>3</sup>	Everest Extreme Expedition
EBC	Everest Base Camp
ECS	Emergency Care Simulator
EVA	Extra Vehicular Activities
JSC	Johnson Space Center
GPW	General Purpose Workstation
HAPsMRT	High Altitude Platforms Mobile Robotic Telesurgery
HALS	Hand-Assisted Laparoscopic Surgery
HIFU	High Intensity Focused Ultrasound
HMF	Health Maintenance Facility
IBMP	Institute for Biomedical Problems
ISS	International Space Station
LSTAT	Life Support for Trauma and Transport
LVA	Low-Velocity Accidental
MDA	MacDonald, Dettwiler Associates
MIS	Minimally Invasive Surgery
NASA	National Aeronautics and Space Administration
NEEMO	NASA Extreme Environments Mission Operations

NLM	National Library of Medicine
NOAA	National Oceanographic and Atmospheric Administration
NRA	NRA
NSBRI	National Space Biomedical Research Center
NURC	National Undersea Research Center
SOMS	Shuttle Orbiter Medical System
SRI	Stanford Research Institute
STS	Space Transportation System
TATRC	Telemedicine and Advanced Technology Research Center
TNTS	Trauma Non-Technical Skills
UAV	Unmanned Airborne Vehicle
UC	University of Cincinnati
USAMRMC	U.S. Army Medical Research and Materiel Command
VTC	Video-teleconferencing
WRAMC	Walter Reed Army Medical Center