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Surgery in Space: Where are we at now?

Laura Drudi^a, Chad G. Ball^b, Andrew W. Kirkpatrick^c, Joan Saary^d, and S. Marlene Grenon^e

^a Medical Student, McGill University. Montreal, Quebec.

^b Assistant Professor of Surgery. University of Calgary. Calgary, Alberta.

^c Assistant Professor of Surgery, University of Calgary Foothills Medical Centre, Department of Surgery and Critical Care Medicine. Calgary, Alberta.

^d Assistant Professor, Department of Medicine, Division of Occupational Medicine, University of Toronto, Toronto, Ontario

^e Assistant Professor of Surgery, University of California Francisco Veterans Affairs Medical Center, Division of Vascular and Endovascular Surgery. San Francisco, California.

Abstract

In the coming decades, as we continue our path of space exploration beyond Earth's orbit, we will be required to provide sound medical and surgical care for the safety of space travellers and space flight participants. A few investigations have taken place in the field of surgery in space. In this paper, the authors review the present literature in order to identify possible limitations that currently exist and that could impair our ability to provide surgical care during spaceflight, from the pre-operative to the post-operative period.

Introduction

Humanity is at the cusp of major changes in human spaceflight. The 30-year National Aeronautics and Space Administration (NASA) Space Shuttle program ended in July 2011, bringing important changes in the contextual framework of spaceflight. There have been simultaneous developments in the commercial spaceflight sector, including contractual works for private industries, the development of spaceports, and the growth of the space tourism enterprise. The possibility of adverse medical outcomes requiring medical and surgical intervention remains present and may increase as space access becomes more accessible to the general public. This may subsequently lead to a push for exploratory class missions if the private sector and appropriate markets are present.

Space surgery is a sub-discipline of space medicine with close associations to other space-related fields pioneered by Dr. Iaroshenko in 1967 with his work in rodents at the Russian Space Agency [1]. Thus far, no surgical procedure has ever been performed on a human during spaceflight. Despite that, surgery involving anaesthesia, interventions, and survival was successfully performed in rodents for the first time on the STS-90 Neurolab Shuttle

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Corresponding Author: S. Marlene Grenon, MDCM, MMSc, FRCSC Assistant Professor of Surgery Division of Vascular and Endovascular Surgery University of California, San Francisco Veterans Affairs Medical Center- Surgical Services 4150, Clement Street, Mail Box Code 112 San Francisco, CA 94121 marlene.grenon@ucsfmedctr.org Phone: 415-307-5275 Fax: 415-750-2181.

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mission demonstrating that minor surgical procedures may be feasible in humans [2]. Medical events that might possibly be managed with surgical interventions during spaceflight are postulated to include blunt and penetrating traumas (from impact with debris, during extra-vehicular activities, constructions and repairs, vehicle docking and refuelling, and servicing payloads), chemical contamination and burns (with electrical equipment repair, chemical and biological research, orthopaedic injuries in the setting of muscular and bone loss), minor injuries, dental complaints and other surgical pathologies that may present in spaceflight [3-5]. It is evident that a major surgical event in space will impact mission objectives and outcomes further necessitating a medical infrastructure to be established for successful definitive medical care.

The goals of this paper are three-fold: 1) to review the literature in order to re-evaluate the status of space surgery in the contextual framework of increasing private spaceflight opportunities, b) to identify areas where research is needed, and c) to provide a forum of discussion to facilitate international research efforts to advance the field of space surgery.

Materials and Methods

The PubMed database was searched for records from 1960 until October 2011 using the terms “surgery”, “surgical techniques”, “anaesthesia”, “wound healing”, “microgravity”, and “spaceflight”. Only papers written in English or in French have been considered, including original papers, reviews and commentaries. All references were crosschecked to identify other potentially relevant reports. The experimental findings were then classified according to Advanced Trauma Life Support (ATLS), diagnostics, restraints, anaesthesia, sterile field, surgical techniques, wound healing, and commercial spaceflight. These categories represent a classification framework to evaluate different aspects of surgical care. Finally, discussions with active microgravity investigators also supplemented the published articles. The data and information obtained from these sources were analysed to summarize the state of knowledge in space surgery and identify areas that would benefit from directed research efforts. In our brief literature review, 23 articles were identified to be relevant to the topic of interest.

Results/Discussion

Advanced Trauma Life Support (ATLS)

ATLS is a common algorithmic approach to trauma management promulgated by the American College of Surgeons to be used by physicians for the management of injured patients, with the goal to apply a simple and standardized protocol to trauma patients. Although dogmatic, ATLS has become the foundation for treating injuries with the greatest risk to life (including, but not limited to airway obstruction, haemorrhage, hemothorax and pneumothorax) [6]. It has only been in the last two decades that studies have addressed the need and the ability to provide special emergency care techniques to stabilize spaceflight crewmembers (patients and surgeons), restraints for fluids and equipment along with the feasibility of trauma care and minor surgical procedures [4]. Currently, the International Space Station (ISS) has an Advanced Life Support Pack able to deliver Advanced Cardiac Life Support (ACLS) and Advanced Trauma Life Support (ATLS); however, current definitive medical management requires medical evacuation from the ISS with a delay of at least 6-24 hours if not longer.

Adverse medical outcomes may occur during spaceflight requiring airway management for inhalation burns or injuries, foreign body aspiration and cardiac arrest. To date, airway management has never been necessary in human spaceflight; however, as mission durations are extended and the endeavours for human exploration continue, the risk of emergency

increases necessitating the need to properly deliver emergent medical care. It has been demonstrated that airway management is possible during spaceflight emphasizing the need for restraints, allowing the operator's hands to hold the intubation tube and guide it towards the airway [7]. Other studies have shown that a variety of patient stabilization procedures can be achieved in spaceflight and are no more difficult to perform than in the normogravity environment, including percutaneous dilatational tracheostomy, artificial ventilation, intravenous infusion using standing tubing and pressure bag system, chest tube insertion and draining, and foley insertion [5, 8]. Taken together, these studies demonstrate that many concepts in ATLS can be achieved successfully in a microgravity environment provided that the appropriate restraint system and equipment is available.

Diagnostic Evaluation

The physiological alterations that occur in the spaceflight environment will impact disease presentation, diagnostic evaluation, treatment and management. The most valuable diagnostic tool for trauma patients in spaceflight is ultrasonography using the extended Focused Assessment with Sonography for Trauma (eFAST) to evaluate the need for emergent surgical intervention [9-12]. Ultrasonography on Earth is dependent on gravity to locate free fluid in locations in the thorax and abdomen that can be easily detected, suggesting that pathological presentations may be altered in spaceflight. Despite this, studies have demonstrated that ultrasound evaluation of several conditions can be performed successfully in microgravity, including pneumothorax [13, 14] and sinus fluid levels [15]. Ultrasound-guided percutaneous aspiration of intra-peritoneal fluid using appropriate restraints was successfully performed in swine in microgravity [16]. Therefore, we can conclude that both diagnostic evaluation and a set of ultrasound-dependent interventional techniques could be performed in microgravity. Further investigations are required to evaluate potential other specific ultrasound-based techniques in the environment of spaceflight. As ultrasound is a technology with some user-dependent aspects, some current initiatives relate to guiding less experienced users from earth using skilled subject experts to remotely mentor the on-board astronauts [17, 18]. Such techniques have much to potentially offer remote patients on earth, and are good examples of the value of “space spinoffs” [19, 20].

Restraints

A cardinal finding of the integrated space surgery research results is that seemingly any terrestrial procedure can be performed in weightlessness, if the correct equipment is provided, and operator, subject, and tools are adequately restrained [5, 21, 22]. The uses of restraints are crucial for instruments, patients and personnel in order to provide effective medical and surgical care. Instrument restraints have been demonstrated to be feasible in microgravity using magnetic pads and Velcro for fixation of supplies, flypaper area for suture ends, and Styrofoam blocks for sharp items, and pockets for biologic trash [5, 22]. Surgical restraint systems should provide organization of all supplies, sterility, operator accessibility, and ability to dispose of sharp items and bio-hazardous materials safely, as well as provide ergonomic capability [2, 22]. Finally, operating personnel must be securely restrained with the ability to maintain manual dexterity, which can be achieved through restraints to a waist-level table, horizontal foot bar and floor-level pellets [5, 23]. From these, it appears that an appropriate restraint system can be achieved in microgravity and a combination of those will likely be required to provide restraints for the patient, the surgeon and the surgical equipment.

Anaesthesia

Minimal research has been done in the applications of anaesthesia to crewmembers during spaceflight. Little is known about pharmacokinetics and pharmacodynamics of drugs in

microgravity, which is essential in the delivery of critical care. Research has demonstrated excellent results from general anaesthesia in rodents on-board STS-90 [24]. However, inhalation anaesthetics that are used on Earth remain a challenge for crew members in spaceflight as an anaesthetic gas leak could contaminate the closed loop environment on the ISS [25]. Spinal anaesthesia also poses a problem in spaceflight as the anaesthetic may be distributed differently secondary to the cephalad fluid shift that occurs in microgravity thus limiting the uses of such anaesthetic delivery [5]. A more promising technique for anaesthetic delivery is intravenous anaesthesia [23]. Local and regional block on the other hand may remain the safest method to deliver anaesthesia, but would also bring the challenge of appropriate training of the Crew Medical Officer or other physician-astronaut delivering the technique. It is clear that extensive aerospace medical research is needed in the field of anaesthesiology if surgical procedures are to be done during spaceflight.

Sterile Field

Establishing a sterile field is possible in the simulated microgravity environment in parabolic flight, comprising gloving, skin preparation, scrubbing, gowning and draping [26]. Surgical workstations were created to address the need to conduct minor surgical procedures in spaceflight. Different surgical chambers were developed to protect the sterile surgical field and the cabin environment, consisting of an expandable surgical chamber [27], “surgical overhead canopy” (SOC) [28] with laminar flow [23], as well as a surgical isolation containment system [29]. These surgical workstations are useful to provide effective surgical care for the patient and protect spaceflight crewmembers and the cabin environment from the surgical field. It is noteworthy, that minimally invasive surgical procedures take advantage of the patient's body itself, to provide “natural SOC” within which to operate [30-32].

Surgical Techniques

Many aspects of human physiology are altered in the microgravity environment, including the behaviour of fluids and organs. Organs also behave differently in the microgravity environment, as bowel floats in the operating field, as well as the kidney when released from Gerota's fascia [33]. Arterial and venous bleeding in microgravity appears to form domes around the bleeding tissue secondary to the increased surface tension [34]. The bleeding can typically be controlled with sponging and cauterization [5, 23].

Taken together, a unique system for delivery of medical care in space must be capable of handling medical events given the extreme operational medical setting. A variety of studies have demonstrated the feasibility of conducting extensive surgical procedures in the simulated microgravity environment and in spaceflight, including open peritoneal drainage [8], leg dissection [24], ureteral stenting [35], thoracotomy [24], thoracoscopy [36], laparotomy [24], laparoscopy [30, 31], craniotomy [24], and microsurgery [37]. The evaluation of surgical skills in these settings demonstrates equivocal results. Studies have shown that manual suturing in microgravity is similar but slower than normogravity [38], peak forces seem to be increased [39-41], decreased with number of tasks performed [42], or may remain unchanged [42]. Finally, subjective evaluation suggests that surgical procedural performance decreases when the operator is not acclimated to the microgravity environment [24], which may further lead to task erosion and subsequent tissue injury [43].

Wound Healing

Preliminary reports for wound healing in animals do not offer any definite conclusions. Incisions made in rodents in spaceflight on STS-90 appeared to heal well after surgery with no evidence of dehiscence or infection after 48 hours [24]. Other observational studies showed no healing on rodent incisions in simulated weightlessness [44]. Finally, a variety of

in-vitro studies demonstrate ambiguous results with abnormal cellular migration, collagen formation, increased inflammation and decreased cellular organization [45, 46].

A Word on Commercial Spaceflight

If the retirement of the Shuttle program stimulates the growth of a commercial spaceflight industry, the general public may potentially have easier access to space. In anticipation of such an event, the Federal Aviation Administration (FAA) has taken the lead in the regulation of commercial human spaceflight through its Office of Commercial Space Transportation. Currently, the FAA requires all crewmembers of a commercial space vehicle to carry a FAA first-class airman medical certificate and demonstrate the ability to withstand the stresses of spaceflight. Despite this, it is ultimately the responsibility of commercial space vehicle operators and the designated flight surgeons to ensure that there are appropriate medical screening programs for non-crew occupants. To date, most of the research in space medicine and surgery has been focused on understanding the effects of microgravity on normal human physiology; however, with the emergent commercial space sector, this will pave a new area of research for space medicine. A paradigm shift is now beginning to emerge in aerospace medicine focusing on the effects of microgravity and the hostile environment of space on existing medical pathologies. Physicians and researchers will thus need to tailor future studies in space medicine and surgery to a new patient population that will gain easy accessibility to the space environment.

Conclusions

Our review of the literature demonstrates that several surgical procedures have been investigated with demonstrated feasibility. At the present time, diagnostic capability, limited to ultrasonography has been developed. The capabilities of providing basic and advanced life support have been established in analogue environments for weightlessness as well as spaceflight. Local and intravenous anaesthetic agents appear to be the preferred methods for major operations during spaceflight because of the potential risks associated with inhalational anaesthetics and spinal anaesthetics. With proper equipment (sterile drapes, sutures, instruments, operating table) and restraints (for the patient, the surgeon and the equipment), surgical procedures can be performed in microgravity. Some critical aspects that have remained poorly investigated and may further represent challenges for successful provision of surgical care. These include aspects related to pharmacodynamics, pharmacokinetics and bioavailability of drugs particularly in the setting of fluid shifts that are known to occur in microgravity, wound healing, and the effects of immunosuppression and radiation on risks for postoperative infection. Furthermore, ongoing discussions and research will be required to establish appropriate training and the skills-set needed for the future space surgeon.

As further development in space medicine and space surgery become an essential component of space exploration in order to ensure the health and safety for all those who travel beyond Earth's gravity, several important milestones have been reached in space surgery. We conclude that the baseline concepts of space surgery are established with proven feasibility of performing surgery in microgravity. Despite this, there are large gaps in our knowledge including wound healing, anaesthesia issues, uses of artificial gravity and the surgical training required in the microgravity environment. We call upon other medical and surgical investigators to place a special interest on these issues in upcoming years to improve the safety of space travel and exploration.

Biography

Ms. LAURA DRUDI

Laura Drudi completed a diplôme d'études collégiales (D.E.C.) in health science at Dawson College, and obtained a diploma in space sciences from the International Space University (ISU) in 2011. She is currently pursuing a Medical Degree at McGill University (candidate 2013). She has also received many awards for leadership and research activities in clinical medicine and aerospace medicine.

DR. CHAD BALL

Dr. Ball is an Assistant Professor of Surgery at the University of Calgary. He has completed training in general surgery, trauma and critical care, as well as hepato-pancreato-biliary surgery in prestigious institutions. He is a Fellow of the Royal College of Surgeons of Canada and is Board-Certified in both general surgery and critical care from the American College of Surgeons. He has brought numerous contributions to the field of trauma, critical care and surgery, and has extensive experience in the field of aerospace medicine and surgery. He is the recipient of several awards for research and clinical care.

DR. JOAN SAARY

Dr. Saary is a Fellow of the Royal College of Physicians and Surgeons of Canada with a specialty license in Occupational Medicine. She received national level funding from CIHR (Canadian Institutes of Health Research) to complete a PhD in the Clinician-Investigator program at the University of Toronto, and has been recognized by the Royal Society of Canada for her work. Her areas of interest are provision of quality occupational health service programs and the development and assessment thereof, as well as health services research in general, including the incorporation of stakeholder perspectives and health promotion programming. Her clinical expertise is occupational medicine with a special interest in occupational diseases. From a research perspective, she has experience with both human and animal studies, with both quantitative and qualitative methods, and with evidence-based methods such as systematic reviews requiring quality ratings.

She also has a longstanding interest in aerospace and diving medicine, and has research experience and international training in the field from institutions such as Johnson Space Center, and the International Space University (ISU). She completed Flight Surgeon and Diving Medical Officer training with DRDC (Defense Research and Development Canada, formerly DCIEM – The Defense and Civil Institute of Environmental Medicine) where she is now involved in aircrew selection for the Canadian Forces. She is Civil Aviation Medical Examiner, having previously worked with Air Canada, and she is currently a consultant to the Canadian Space Agency where she is the CSA representative to the ISS (International Space Station) Medical Standards working group, supporting the Multilateral Medical Operations Panel.

She serves on the Board of Directors of the Canadian Foundation for ISU where she has an additional role on the selection committee. She has published in the field, participates in various national and international conferences, and is a reviewer for the journal *Aviation, Space, and Environmental Medicine*.

She maintains involvement in collaborative interdisciplinary work that incorporates the commonalities between occupational medicine, aerospace medicine, and engineering, as well as innovative new technologies such as telemedicine and simulation, in order to enable the provisions of exemplary medical care and programming.

DR. ANDREW W. KIRKPATRICK

Dr. Kirkpatrick is cross appointed as a Professor of Surgery and Critical Care Medicine at the University of Calgary and Foothills Medical Centre, in Calgary, Alberta.

Dr. Kirkpatrick began his career as an undergraduate in microbiology and physics at the University of Toronto. He went on to receive a Medical Degree at the University of Ottawa, and his fellowships in Surgery and Critical Care at the University of Toronto. Elective studies during his internship and residency took him to near and distant regions of the world including Sierra Leone, Ghana, the Republic of South Africa, Washington, District of Columbia, New Orleans, Louisiana, Detroit, Michigan, and the NASA/Johnson Space Center in Texas.

National service has included postings to the Canadian Airborne Regiment, the 1st Canadian Field Hospital in the 1991 Persian Gulf Conflict, and with the Canadian Hospitals in Kandahar and Kabul, as well as a military Flight surgeon. Dr. Kirkpatrick then earned a Master's of Health Science degree in Health Care and Epidemiology from the University of British Columbia.

Dr. Kirkpatrick received several awards for both research and military service including a Young Investigator Award by the Aerospace Medical Association, a Canadian Forces Gulf Service Medal, and a Canadian Decoration (CD).

Dr. Kirkpatrick has authored and co-authored over 200, journal articles book chapters and abstracts in the trauma and critical care fields. His main interests are in focused emergency sonography, hypothermia, aerospace medicine, the abdominal compartment syndrome, and pneumothoraces. He has served as a member of various committees including the serving as the President of the Trauma Association of Canada, a member of the Canadian Association of General Surgeons Committee on Critical Care and Trauma, and is a co-editor of the section of Critical Care and Trauma for the Canadian Journal of Surgery.

DR. JOAN SAARY

Dr. Saary is an Occupational Medicine specialist, and Assistant Professor of Medicine at the University of Toronto. She also has a longstanding interest in aerospace and diving medicine, and has research experience and international training in the field. She completed Flight Surgeon and Diving Medical Officer training with DRDC (Defense Research and Development Canada, formerly DCIEM – The Defense and Civil Institute of Environmental Medicine) where she is now involved in aircrew selection for the Canadian Forces. She serves on the Board of Directors of the Canadian Foundation for ISU where she has an additional role on the selection committee. She has published in the field, participates in various national and international conferences, and is a reviewer for the journal Aviation, Space, and Environmental Medicine.

She maintains involvement in collaborative interdisciplinary work that incorporates the commonalities between occupational medicine, aerospace medicine, and engineering, as well as innovative new technologies such as telemedicine and simulation, in order to enable the provisions of exemplary medical care and programming.

DR. MARLENE GRENON

Dr. Marlene Grenon was born in Quebec, Canada. She obtained a diploma in space sciences from the International Space University (ISU) in 1998. She graduated from McGill Medical School in 2000 and obtained a Masters' degree from the Scholars in Clinical Science Program of Harvard Medical School along with a post-doctoral fellowship in cardiovascular space medicine and endocrinology from Brigham and Women's Hospital and the

Massachusetts Institute of Technology (MIT) in 2004. She then completed training in cardiac surgery at McGill University in 2007, vascular surgery at the University of British Columbia in 2009 and endovascular surgery at the Arizona Heart Institute in 2010. She is a fellow from the Royal College of Physicians and Surgeons of Canada (RCPSC) and maintains a Certificate of Specialist in both cardiac and vascular surgery from RCPSC.

Dr. Grenon is presently an Assistant Professor in the Department of Surgery at UCSF, a Staff surgeon at the VAMC San Francisco and an Adjunct Faculty at the International Space University. She is a member of many professional organizations and has been an invited lecturer at several regional, national and international meetings and conferences. She is the recipient of several awards for research and was one of the finalists in the 2009 Canadian Astronaut selection.

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Highlights

1. There are changes in space travel with a shift towards commercial spaceflight
2. Surgical capability may become essential to ensure the health of crewmembers
3. Surgical care in microgravity is feasible, but areas need to be further explored
4. Discussions and research efforts should continue in the field of space surgery