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Review article

Surgical Aspects of Space Medicine

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Abstract

Although the perception of surgery in space may appear obscure, it is vital to initiate planning early if new frontiers in space travel are to be accomplished. Conditions necessitating surgery in space are rare, but they are challenging in their management. Telemedicine can allow consultation and instruction at the time of surgical intervention. This may permit optimal guidance for conduction of simple surgical maneuvers by non-medical crew members.

Robots could be used for more complex interventions in the absence of a trained crew member. Earth-to-space telesurgery is yet to be attained. However, National Aeronautics and Space Administration [NASA] has successfully did several basic procedures at an underwater facility, simulated the space environment.

The communication delay between craft and earth is the main potential issue affecting telesurgery. For example a communication delay of radio signals between 4 and 22 minutes is expected between earth and Mars. Thus, available telesurgical capabilities are not suitable for a Mars mission. In addition, to facilitate endogenous repair of injured structures, the use of absorbable nanoparticulate scaffolds could offer temporary structure support, while eluting drugs stimulate endogenous mesenchymal stem cells to differentiate into osteoblasts. Otherwise, direct delivery of extrinsic mesenchymal stem cells to injured sites via nanoparticulate delivery system provide a reasonable alternative. The use of 3D printing allows fabrication of complex surgical tools from a computer-aided design template from a digital database of nearly each instrument. In addition, 3D-printed surgical tools may be disposable, meaning no requirement for space-occupying sterilization appliances.

Keywords: Space; Telesurgery; Telemedicine; National Aeronautics and Space Administration; Robotic surgery.

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INTRODUCTION

Space medicine could be defined as: "The practice of all aspects of preventative medicine including screening, health care delivery, and maintaining human performance in the risky environment of space and preserving the long-term health of space travelers"[1]. Spaceflight describes trips carried out above Karman line [at more than 100 km above the sea level]. Spaceflights are divided into three categories: 1] suborbital, 2] low Earth orbit [LEO], and iii] exploration tasks [e.g. missions to the Mars][2].

Pathophysiological effects of spaceflight

1. Fluid shift and cardiovascular compensation

Early effects: Spaceflight is considered a near weightlessness environment [microgravity]. Micro-gravity is due to free-fall movement of the vehicle as it orbits the Earth. It exerts a profound effect on human body. These effects are harmless and help adaptation to the space environment. The immediate effect is sensory disturbances of the vestibular structures. Overall, 60% - 80% of cosmonauts suffer "space adaptation syndrome" in the first three days. Symptoms include nausea, pallor and vomiting, which could be disabling. Alleviating strategies include avoiding provocative head maneuvers and postponing critical actions during the first days in space. In addition, prophylactic treatment was considered for short duration commercial trips[3].

The most evident primary physiological alteration is the redistribution of body fluids from the lower to upper body. It is due to removal of the load of gravity exerted by the Earth. This expressed clinically as 'puffy face' [facial edema and decreased leg volume producing the characteristic 'chicken legs' appearance. In addition to fluid shift, volume of plasma decreased by 10–15%. The intravascular fluids shifted into extracellular space due to increased capillary permeability [4].

2. Musculoskeletal system

Exposure to prolonged microgravity had a profound effect on the musculoskeletal system. Demineralization of bone occurs. There is an increased excretion of calcium, with higher fracture risk and predisposition to renal stone formation. Bone loss is about 1-1.6% per month in the spine, femur neck, trochanter and pelvis. Exercise is the main countermeasure against bone loss. It seems to stimulate osteogenesis especially resistive exercise. In medical therapy such as bisphosphonates and diet are considered[5, 6]. In the absence of loading forces of gravity, the legs become redundant due to skeletal muscle atrophy [7]. In addition, the volume of lower limb muscle decreased and muscle mass continued to be lost in absence of exercise [8].

3. Neuro-vestibular system

Positioning in space is associated with acute changes occur in the neurological system. The impairments of neurovestibular system become more prominent with prolonged mission period. In addition, there is reduction in visual acuity [28% and 60.0% of 300 astronauts reported reduction in far and near vision respectively. Other ophthalmic abnormalities include edema of optic disc, globe flattening, choroidal folds and cotton wool spots [9]. This collection of clinical complaints is termed Spaceflight Associated Neuro-ocular Syndrome [SANS], previously known as visual impairment and intracranial pressure syndrome [VIIP] [10].

4. Multisystem considerations

Nearly every system of the human body is affected by spaceflight. For example, spaceflight disturbs immune system regulation [e.g., increased granulocytes & B cells, reduced lymphocytes & natural killer [NK] cells[11]. Hemopoiesis is also affected with reduced red cell mass "space anemia'. Alterations of light and dark cycles, illumination and team workload is associated with significant sleep disturbance [12]. The respiratory system revealed changes in both static and dynamic lung volumes. In addition, renal stones have been reported [13]. Hypercalcuria and other factors [e.g., decreased urinary output and alterations in urine concentration, with increased urinary phosphate and sodium] sharing in the formation of renal stones [14].

Possible pathologies related to spaceflight

1. Trauma

Due to its disabling and mission-compromising effects, trauma is of uppermost distress in spaceflights [15]. It may disable any member, regardless of optimal physical health. Trauma may be in the form of airway obstruction, hemopneumothorax, bone fractures, head injuries and hemorrhages[16,17].

2. Non-traumatic surgical emergencies

On the earth, common emergencies include appendicitis and cholecystitis [18, 19]. No case of confirmed appendicitis has been reported in space travelers. However, suspected appendicitis was reported in Russian astronauts, one patient needs emergent repatriation to Earth [20]. Alerted immunity and physiology during spaceflight could increase vulnerability to appendicitis and/or cholecystitis [21].

3. Head injuries

There have been no reported head injuries encountered in spaceflights. However, it has been postulated that, there was proportional increase in intracranial tension with fluid shifts brought by microgravity. Thus, the severity of traumatic or pathological intracranial hemorrhage may be increased in space [22].

4. Radiation-induced pathology

Chromosomal and DNA destruction could by occurred by high-energy particles. High-energy particles could produce high-grade cancers and amplified metastatic potential. The National Aeronautics and Space Administration [NASA] expects a risk of death related to spaceflight-induced cancers to be 3.0% [23].

5. Infections

Infection risk in spaceflights is increased. It is due to dysregulation of the immune system, increased virulence of microbes, microbial antibiotic-resistance and diminished clearance of aerosols in microgravity. Vaccination and rigorous screening are mandatory for candidates for NASA-sponsored missions [24].

6. Occupational health hazards

Many harmful substances were encountered in spaceflight. Exposure to hydrazine [a rocket fuel] and water iodine contents are examples of such substances. In addition, biohazards were considered a significant threat when the Apollo astronauts landed on the moon and back on Earth once they had returned [25].

7. Decompression sickness

In spaceflights, many factors can increase the risk of decompression sickness [DCS]. These include individual susceptibility and physical activity. Before spacewalks astronauts breathe 100% oxygen to off-load the body's nitrogen stores and decrease the risk of DCS; this is enhanced with In-Suit Light Exercise [ISLE] [26].

8. Re-entry, landing and post-flight considerations

The medical distresses of re-entry relate to risk of: i] depressurization of the spacecraft, ii] crashes iii] fire, iv] trauma related to normal landing [e.g. loose articles and impact forces] and v] post-landing survival. Immediately post-landing astronauts may compliant of a general weakness, orthostatic intolerance and neurosensory troubles, including pitch sensitivity [which could affect an individual's capabilities to walk]. Once able, astronauts experience a prolonged period of physical re-conditioning to recover both musculoskeletal and cardiovascular systems [27].

Diagnostic Tools in Spaceflight

In spaceflight, ultrasonography [US] has proved to be the most appreciated diagnostic tool. The extended focused assessment with sonography for trauma [eFAST] has been proven on orbit to assess the need for emergent surgical intervention [28]. US has been found to outline several conditions, including pneumothoraxes and sinus fluid levels [29]. The development of three-dimensional US improved the analysis of injuries in acute abdomens [30]. US contrast media used to quantify and follow any hemorrhage in real time [31]. In addition, use of integrated computer programs aid to predict the progression of injury [32].

Miniaturized computerized tomography [CT] or magnetic resonance imaging [MRI] scanners can be adapted for spaceflight. However, this will need special operators or automated tools for direct analysis. Otherwise and unlikely, images could be transmitted back to consultants for analysis. Thus, both diagnosis and intervention could be carried out in microgravity with the use of US-dependent maneuvers. A noninvasive way to perform surgery is by focused ultrasound. This can be used to ablate or emulsify soft tissue tumors in abdomen, brain, or heart. It provides a way to manage benign prostatic hyperplasia and bone cancer [33].

Anesthesia in space

In the space, microgravity, power and equipment express sole challenges for conduct of anesthesia. The closed setting of a spacecraft leads to a problematic inhaled techniques. Vapors could contaminate the cabin, affecting other team members, while oxygen leak in the cabin environment would increase the risk of fire. In addition, the numerous changes in physiology that accompany position in microgravity affecting the cardiovascular system are likely to disturb response to anesthetic drugs and vasoactive medications. These alterations were proposed to play a role in sudden death and the "less-than-optimal" physiological circumstances of primates anaesthetized soon after arrival to Earth. On the other side, general anesthesia has been successfully conducted using intravenous agents in a diversity of animal models on orbit [34]. Many of the distinct skills and maneuvers of general anesthesia have been achieved either on orbit or during simulation. Ketamine has been postulated by some researchers as the ideal intravenous agent for sedation, induction and maintenance of anesthesia. It is associated with cardiovascular stability when compared with other intravenous anesthetic drugs and has less effects on airway reflexes and respiratory depression [35]. Other researchers advocate regional anesthetic techniques as a preferred technique to deliver anesthesia in the spaceflights. This is because the patient is left conscious with a decreased dependence upon additional physiological aids and general anesthesia equipments. However, regional anesthesia is not suitable for a number of surgical interventions and need significant skill and training in order to be used effectively. Furthermore, microgravity opposes the spread of local anesthetics agents in central neuraxial blockade [36].

Surgery in spaceflight

Background:

Surgery has been performed in simulated parabolic flights. Microgravity needs a secure system of restraint for the physician and the patient. In addition, careful measurements must be considered to prevent the contamination of the wound, which is more probable due to high number of weightless, non-sterile particles floats in the cabin. The contamination due to blood was adequately prevented by sponges and suction, with the exception of arterial bleeding. In peritonitis not responding to medical treatment, a variety of maneuvers have been established in parabolic flight animal studies [e.g., laparoscopic surgery and percutaneous aspiration of intra-peritoneal fluid with sonographic guidance] [32].

In anticipation of International Space Station operations requiring stabilization of crew members before evacuation to Earth, advanced trauma life support [ATLS] techniques through parabolic flights were shown to be reasonable. Furthermore, the ability to carry out complex surgery was reported in animal models during the STS-90 Neurolab Shuttle mission [34]. The degree of training and experience of the crew medical officer on board will greatly affect the surgical and anesthetic capabilities of the crew. A compromise may be to offer specific and focused surgical training to the designated crew officer, who can work in a common surgical emergency event in collaboration with terrestrial telemedical support [37].

Advanced life support and minimal invasive surgery

The risk of a serious medical emergency has been estimated at approximately 0.06 per person-year of flight, or one event per 68 person months. Thus, one emergency event should be expected for a crew of six on a 900-day mission to Mars[38]. Cardio-pulmonary resuscitation is an emergency intervention used to maintain blood circulation and oxygenation in the event of acute loss of cardiac output. If CPR is needed during spaceflight, there are various techniques that have been modified to microgravity. Alternatively, a mechanical device could be used when CPR operator affected by the effects of deconditioning. However, even if effective resuscitation was attained, the complex supportive critical care is essential after a cardiac arrest is unlikely to be available or sustainable over any extended period in the space environment [39, 40].

Spacecraft emergencies

In addition to normal medical conditions, spacecraft emergency conditions should also be considered. The top three emergencies are: i] loss of pressurization, ii] fire, and iii] toxic leak [e.g. ammonia] all of which have reported during actual spaceflight missions. Leak in the habitat, vehicle or spacesuit [either small or large] is responsible for loss of pressure, each with differing possible etiologies and emergency consequences [41]. The medical decompression consequences depend on the speed and amount of pressure loss. Hazards include barotrauma, arterial gas embolism, acute hypoxia, decompression sickness and ebullism [vaporization of water in the soft tissues and low pressure areas of the circulation]. Astronauts are trained for such scenarios, with availability of emergency oxygen systems to guard against hypoxia or filtering respirators for smoke or toxic fumes. Ultimately they may require evacuating the spacecraft if the problem cannot be isolated, stabilized and resolved. These efforts are locally controlled on the spacecraft but with additional support from ground stations. For interplanetary tasks, abort decisions and real-time ground technical support would be severely limited when compared to technical support for low Earth orbit [LEO] tasks [2].

NASA conducted numerous parabolic flights to test operative and resuscitative techniques in a microgravity habitat. These tests were conducted to see what procedures could be done, how the equipment behaved, and if the procedures could be done with minimal equipment. The crew medical officer [CMO] for each journey may be a non-physician. CPR was found to be more difficult in lower-gravity environments, but can be accomplished. It was reinforced that restraint of both the subject and the rescuer was critical in most situations. The “handstand” procedure of placing one’s feet on the wall opposite to the victim’s chest and placing the CMOs hands over his head and on the chest was found to be effective. Also, the Heimlich method of standing behind the victim and performing CPR was validated as providing adequate CPR [42]. Ventilation support with artificial ventilators was performed, and the parameters were unchanged from the terrestrial environment. Similarly, respiratory mechanics on ventilatory support was not clinically different [34].

ALS [Advanced Life Support] procedures of venous cut downs, cricothyroidotomies, peritoneal lavages, and chest tube insertions were also evaluated. These proved to be more difficult than in normal gravity. Fluid infusions and drainage systems required modifications to the techniques. Intravenous fluids had to have all the free air removed and required fluid pumps to infuse the fluids. Pressurizing the fluids with external pressure bags did work well. Drainage lines had to be as short as possible and large in diameter to prevent surface tension and capillary action from inhibiting flow. Percutaneous peritoneal lavage was more dangerous. The GI tract is more dilated due to decreased peristalsis in low-gravity environments. This resulted in additional pressure of the bowel on the abdominal wall and increased the risk of perforation [43].

A modification of the technique would be required to increase the air in the abdominal cavity to decrease this likelihood. Another complicating factor was that the increased fluid tension and lack of capillary fluid pull lead to decreased lavage fluid drainage. An advantage to this procedure is that it required less training than their open lavage counterpart. Open peritoneal lavage techniques were accomplished, but required more training and the use of surgical canopies. Chest tube insertion was also performed on the surgical evaluation parabolic flights. The equipment employed incorporated a Heimlich valve and a Sorenson drainage system. This proved to provide adequate drainage and eliminated the risk of contamination from the vehicle environment. Another advantage was that the blood from a hemothorax in this type of system could be used to autotransfuse a trauma victim [44].

A percutaneous Seldinger dilatation method proved easy to train, required only a minimal amount of equipment, and did not require a dedicated surgical field. Suture ties around the chest tube site to secure the tube had to perform several functions and were critical in the procedure. Studies have shown that suturing in microgravity is similar but slower than normogravity. They had to retain the tube in position and control fluid and blood leakage. Chest tube drainage generally did not require suction, because the intrathoracic pressure provided the push to the drainage system. The advantage of a chest tube placed in microgravity was that the hemothorax fluid was equally distributed along the chest wall in an adherent sheet rather than pooling in a dependent location. Some loculation did occur though by surface tension, but overall was not as critical as in a one-G environment. The procedure only encompassed about 1 h of ground-based instruction and could possibly be done by computer-based training [CBT]. Telemedicine guidance of peritoneal lavage and chest tube insertion could also be done by a remotely located surgeon [45].

Other surgical procedures have been performed in the simulated microgravity environment. Leg dissection, thoracotomy, laparotomy, and craniotomy were simulated. Specifically craniectomy, C-section, and laminectomy were conducted on the STS-90 Neurolab flight [34]. Other procedures included ureteral stenting, thoracoscopy, and microsurgery [46].

There are numerous publications that have raised the question on the use of MIS in critically ill subjects [47]. This raises questions if an injured astronaut can tolerate the increased intra-abdominal pressures required for MIS. Astronauts have reduced red cell counts and plasma volumes and decreased cardiac output which put the crewmembers at risk for injury and may be compounded with the stresses of laparoscopy [48].

In any minimally invasive surgical procedure, the CMO would need to have the training, ability, and experience specific to endoscopic procedures in order to perform them. Highly trained surgeons with considerable proficiency would be needed to carry out these procedures. In addition, significant deskilling occurs when a surgeon does not continually practice these procedures. It would require a simulated surgical environment to accompany the mission to remain proficient in these skills. Several studies have been undertaken to reduce the required training and skill-level retention to accomplish minimally invasive surgical procedures [43].

Broderick et al. [49] investigated simulating hand-assisted laparoscopy in parabolic flights. Use of Mini-laparoscopes has also been proposed for peritoneal drainage with tele-monitoring.

New methods and equipment have been developed making space surgery a more viable and easier option. Miniaturization of laparoscopic equipment has made the possibility of these procedures even more viable. Large amounts of supporting equipment are no longer required for most procedures. A portable computer had substituted for large bulky video monitors, and fiber optics can provide adequate lighting and visualization of the field. Stereoscopic three-dimensional displays are coming on line that can be incorporated into virtual reality headgear. Abdominal wall lift devices are in development that may eliminate the need for CO_2 or N_2 insufflation [50]. This would allow the abdominal wall to be retracted anteriorly improving the visual field and allow the mesenteric attachments to hold the bowel in place. The change in the abdominal wall shape is different with lift devices than with insufflation. The viscera have a higher propensity to float and obscure the visual fi led in the intra-abdominal compartment [15].

Controlling hemorrhage is made easier by fibrin glue injectors, laser scalpels, and advanced stapling devices. Tissue sealants and fibrin glues have been compounded into foam and easily applied. These have been found to be more effective than surgical packing currently in use[51].

A device now is in development that can detect vascular flow prior to cutting and suturing. This uses pulsatile light absorption characteristics of hemoglobin to noninvasively characterize hidden blood vessels. By using a multichannel LED/sensor pair that employs NIR and red light, blood vessels can be detected and vessel size determined. This would help avoid unintended cuts to the vasculature caused by poor visibility in a minimally invasive maneuver. Such a device prevents the obscuration of the visual field by streams of blood caused by inadvertent vessel injury [52].

Accessing disease pathology via an intraluminal route is a revolution in medicine. This has been demonstrated in trauma, vascular surgery, and cardiology care. Access to the central circulation also enhances hemodynamic support and measurements and can enhance guided interventional angiographic therapies. It also can provide an extremely efficient method to administer specific pharmacologic treatments. Via central venous access, inotropes and vasopressors can be administered safely. Vasopressors may be required in the treatment of space-adapted physiology. Heparin-bonded extra-corporeal circuits are used in multisystem trauma for both rapid rewarming and also facilitating hemodynamic support [53].

Doppler guided needles are currently available and smart ultrasound-guided “bibs” that use automated algorithms for vascular identification are being developed [54].

Surgical Field Testing

One of the major impedances to surgical care in microgravity [low Earth orbit] or zero gravity [away from planetary gravitational forces] is the atmospheric contamination of the vehicles’ atmosphere with blood or other body fluids. The closed-loop systems could easily be overwhelmed with surgical debris and blood. The spacecraft also presents a hazard to the surgical site. The clean vehicle at launch accumulates dross that increases the risk of wound area contamination. Particles tend to be larger and contain dust, food particles, and sloughed skin elements. In a limited space environment, the surgical zone may be in close proximity to the galley or exercise facilities. In addition, there can be numerous scattered areas or waste disposal. This may aid in surgical trash disposal, but it would also be a possible cause of contamination for the procedure. Long-duration spaceflight has shown to produce immune-suppression and altered immune responses [55].

Impaired healing of wounds has also been seen. A system for contaminant containment for the field and prevention of infectious contamination of the surgical site are requisite requirements [43].

The Russian space community built several enclosed systems and tested them in parabolic flights. In 1978, an inflatable Lexan surgical enclosed bubble was proposed by Mutke [56]. Markham and Rock [57] tested several inflatable enclosures and simulated surgical procedures in parabolic flight. These proved to be quite successful at containing floating instruments, solids, and fluids. NASA tested a similar inflatable canopy [58]. Anesthetized animals were used as surgical subjects, and the systems were evaluated for ease of use, portability, and containment. It was noted during these experiments that venous bleeding appeared to be increased. It was surmised to be due to an inability of the venous walls to provide compression in microgravity. Unopposed surface tension caused both arterial and venous areas of bleeding to form large fluid domes[59].

Arterial bleeding was not entrapped by sponges or suction when a large stream of droplets was formed. The overhead canopy placed over the surgical area would be useful in containing uncontrolled bleeding or if copious irrigation was required. Another method of containing contaminants in a surgical field is the use of laminar flow devices. The airflow would direct the fluid or other detritus into a downstream suction collection device. NASA also tested this concept in parabolic flight. Bleeding and debris not restrained by local methods were swept away from the visual field directly over the open wound. Still most bleeding was controlled by surgical sponges, gauze, or suction directly at the site [43].

Surgical Procedures in Space

The Space Shuttle Neurolab mission on STS-90 conducted the first surgical procedures on animals in orbit. A leg wound was created and then closed with Dermabond adhesive. Several other procedures were conducted on that mission and provided insight and verified parabolic experiments of surgical procedures in space. The mission confirmed that the procedures were only as difficult as ones performed on Earth. Spaceflight experience also demonstrated that there were no obvious changes in manual dexterity, proprioception, or fi ne motor control of the hand. It reinforced the principle that restraint of the operator, patient, and surgical equipment was critical. It took a diligent effort to contain equipment in place and immediately discard any trash. Procedures took longer because of the need to assure restraint of the equipment. It was noticeable that fluids coalesced and surface tension predominated in microgravity. Sponging and suction at the site of bleeding controlled the environment and allowed continued visualization of the field. Scalpels and needles required special care, but that restraint on Styrofoam blocks proved adequate. If not restrained, loose needles needed to be called out and identified immediately in order to prevent accidental punctures [43].

Open surgery

For situations in which observation, simple hemostasis or conservative treatment is inadequate, and assuming that the relevant expertise is available, surgical intervention is required. Experimental studies into space surgery have been carried out in simulated microgravity and actual spacecraft [60].

In microgravity, the patient will require absolute restrained position. In addition, surgeons and their equipments may require restrain to ensure sufficient line of sight, access and free movement. These requirements have led to appearance of trauma pod concept, which is an enclosed set offering all necessary facilities and equipments for surgery in adverse habitats [61]. This translated in construction of a dedicated medical module within the spacecraft[62].

Conventional skin preparation has proven to be adequate due to the intrinsic surface tension of antiseptic fluids and adhesive drapes. A notable problem in open surgery in space is the effect of microgravity on exposed internal organs or bleeding sites. The surface tension of blood leads to formation of domes that could be fragmented on disruption by surgical tools. These bloody fragments represent biohazards as it may float off the surface and break up throughout the cabin. The predisposition of internal organs to eviscerate has also been described [63].

To resolve the microgravity actions on exposed body surfaces and fluids, it is mandatory to strictly seal enclosed place over the surgical field. Designs include pressurized air or sterile fluid as a differential between the anatomical site and the cabin atmosphere to prevent evisceration and containing floating debris. Such systems have been examined with certain success. However, remaining unresolved issues include: size and versatility for different surgical maneuvers, visual windows, light refraction in gases or fluids, mixing of blood with a fluid medium, loss of pressure and fogging formation[64].

Robotic surgery

Surgical robots were primary invented for military use in war zones. Modern robots are controlled by a surgeon positioned at a console, sited at a distance from the robot and operating theater. However, the surgeon had a stereoscopic view of the surgical field [65]. Advantages include optimization of conventional endoscopy, greater axial mobility compared with the human hand, reduction of fatigue, and improved ergonomics [66]. Disadvantages include cost, power necessities, loss of haptic [touch] feedback and need for an assistant or scope operator [67].

Although their value over conventional open or endoscopic surgery is disputed, surgical robots allow long-distance telesurgery. Their use could therefore negate the need for an on-board surgeon; they have been used for surgical maneuvers conducted intercontinentally, underwater and in simulated microgravity environments [65]. Their use, however, would be limited to craft whose distance would not confer significant delay of radio signals [68].

In the future, full robotic control may be possible for cannula insertion and diagnostic assessment. This offers some real advantages in deep exploration missions and may reduce the training required for these missions. Tele-robotics and tele-presence are offering an increase in precision and the ability to operate from long distances. They offer the capability to enhance the images and dexterity of the individual surgeon. Telemedicine also has the capability to provide consultation and even surgical procedures to be performed from a distance. Investigations have shown that operating across continents and to undersea environments can be accomplished. While these techniques might be practical in low Earth orbit, they would be inhibited by communication delays outside of that realm. A Mars mission could not avail itself of telemedicine. Electronic delays from 8 to 40 minutes would render this option impossible [69].

Trauma Care in Space

Trauma stabilization and care on long-duration or long distance mission presents unique difficulties in management. In these situations, the need for rapid evacuation can be a disastrous situation. Physiological alterations of microgravity, diminished immune systems, inexperienced or ill-equipped care providers, limited equipment, and extreme distance can conspire against a reasonable survival in traumatic injuries. The advantage to space exploration is that advanced procedures, training, and advanced technology can be incorporated into the design of these missions. These missions are analogous to rural trauma or trauma in undeveloped countries. Rural trauma in the United States shows that in distant populations, mortality can be up to 50 % greater than urban populations. Trauma in rural populations accounts for 60 % of deaths in the US, despite only 20 % of the population reside in these areas[70].

Crewmembers in orbit are hemodynamically challenged after 72 h in a microgravity environment. They have about a 15 % decrease in circulating red blood cell and plasma volume. This is defined as a class I hemorrhage terrestrially. Another factor in space physiology that is unique is the blunting of cardiovascular reflexes. These combined result in a decreased ability for a crewmember in microgravity to respond to blood loss. This can result in a shortened time in which intervention can have the greatest effect. They immediately move in to a class II type of hemorrhagic shock. The initial response to trauma must be rapid and consideration to fluid resuscitation must be given priority. As we have seen, ATLS procedures can be readily accomplished in the microgravity environment [71].

Intravenous access has been demonstrated experimentally and aboard the ISS. Securing an airway has also been established in parabolic flight using endotracheal intubation, laryngeal mask insertion, or surgical tracheostomy. A FAST [focused assessment with sonography for trauma] ultrasound can be utilized to evaluate for traumatic injury as well as confirm the endotracheal tube position [72].

The truncal region requires surgical intervention to control internal bleeding. External pressure is not efficacious to control hemorrhage in this area. Ninety nine percent of deaths are due to thoracic or abdominal bleeding [73]. Ultrasound has been used to localize intrapleural, intraperitoneal, and retroperitoneal bleeding terrestrially, in parabolic flight and onboard space vehicles. It is as sensitive as terrestrial- based applications [28].

Management of these injuries has changed due to rapid diagnostic procedures. No longer, is explorative surgery required and it has given way to observation and repeated scanning techniques. This also implies that surgical or intensive monitoring must be available in case there is recurrent hemorrhage. Observation may also be complicated by and require interventions in the cases of abscesses, pseudoaneurysms, urinomas, or biliomas. Many of these can be treated with percutaneous interventions and have been demonstrated in parabolic as well as actual spaceflights [32].

These conditions still require surgical expertise if severe recurrent hemorrhage occurs. This would require specialized training and physician intervention. In the space environment, it may be better to intervene in a staged fashion rather than going directly to open procedures. In all of these cases, anesthetics would be required. Gaseous anesthetics have innumerable problems in a closed-loop environment. Re-inhalation and intoxication of the ones performing the interventions is a real risk. Also the incorporation of anesthetic decontamination equipment into the environmental control system may be space and cost prohibitive. Intravenous anesthetic techniques are preferable and have been demonstrated in parabolic flights [74].

Immediate Damage Control Procedures

Severe shock and sepsis may demand an immediate surgical intervention before extensive diagnostics can localize the condition. A group of flight surgeons, trauma surgeons, and biomedical engineers emphasized that a laparotomy may be required to stabilize a patient prior to further procedures or deorbiting to Earth [75].

The paradigm of only completing the necessary components via limited procedures is referred to as damage control [DC] surgery. These methods do not require prolonged procedures that tax the patient’s physiological reserves. In addition, these procedures do not require extensive equipment outlays. These procedures are not significantly different from the terrestrial environment. Solid-organ bleeding can be arrested with packs around the offending organ. The abdominal wall can be left open for further procedures to follow. An open abdominal wall facilitates converting non-compressible bleeding into compressible visceral bleeding by direct methods. Fibrin glue and tissue sealants can also be used easily in these DC surgeries. These procedures have been demonstrated by physician extenders and non-surgeons [76].

These types of procedures would allow immediate DC surgery to be performed to stabilize the crewmembers condition. Then planning and further diagnostics can take place with consultation with ground control. Then long distance training or reviews and simulations can be undertaken to perform a definitive surgical procedure. Orthopedic injuries lend themselves to damage control procedures. Fixation devices are easy to use and may be the most viable option. Plaster casting requires mixing plaster with water and this takes up a valuable resource. Fiberglass casting materials produce large amounts of off-gassed products that must be accommodated by the environmental control system. These may not be easily removed. Flexible aluminum splints and elastic bandages can be used on the simpler fractures. Numerous fractures require gravity to heal the break or maintain reduction. Manual traction is difficult to apply in microgravity. Another concern is that bone healing is likely to be delayed in spaceflight [44].

External fixation offers numerous advantages. The techniques for the most part are simple and rapid. They are not physiologically stressing and do not require extensive anesthesia applications. Their application will allow early mobilization, and if placed under tension, they may substitute for gravity and manual traction. US can be used to diagnose and evaluate the reduction [77].

This has been demonstrated in previous studies. The use of US can also be accomplished with external fixation in place. Addressing these surgical challenges has led to unique solutions that have been incorporated into terrestrial care [78].

CT and MRI are not done in microgravity environments. MRI is possible as high-power magnets have been incorporated into the ISS particle physics experiments. The AMS-2 superconducting magnet has two coils of niobium-titanium producing a central field of 0.87 teslas. Numerous investigations are undergoing evaluation in the use of advanced US techniques that could be incorporated in the treatment of critically injured patients. These cover a range of subjects from diagnostic studies to addressing the crew training in advanced US techniques [79].

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