2

Interplanetary health care

Exploration class missions (ECMs) will expose astronauts to several unique and hazardous elements. The isolation and great distances mean evacuation will not be an option and the crew and the flight surgeon will need to be prepared to deal with myriad medical situations ranging from motion sickness to death. Compounding the problem of responding to diverse medical situations will be the limited medical capabilities onboard, the cramped living and working quarters, and, of course, the challenges of performing medical procedures in the microgravity environment. Given the limitations of deep space health care, it will be more important than ever to implement effective medical mitigation strategies and new flight surgeon training methods. Here, in Chapter 2, ECM medical capabilities and strategies and the future role of the flight surgeon are discussed.

MEDICAL CAPABILITIES

In February 2008, an undisclosed medical issue among the crew of the Space Shuttle *Atlantis* prompted a 24-hr delay to a scheduled extravehicular activity (EVA). ESA astronaut, Hans Schlegel, was eventually replaced by NASA astronaut, Stanley Love, and later rejoined the EVA rotation. The incident was typical of the many minor medical conditions astronauts suffer during spaceflight. To date, the spectrum of medical conditions (Table 2.1) reported by NASA and ESA astronauts have rarely required serious medical attention and there has been no medical evacuation of any NASA or ESA crewmember. However, given the extreme nature of the space environment combined with the duration of an ECM, it is inevitable that sooner or later, medical intervention will be required.

Since it is not certain that every mission will have a physician-astronaut, the burden of any ECM medical contingency will fall upon the shoulders of the crew medical officer (CMO). At present, the CMO is a pilot or scientist with 34 hr of medical training, whereas other crewmembers receive only 17 hr of pre-flight medical training. However, for ECMs lasting several years, crew medical training may be increased and astronauts selected for these missions will probably follow a schedule similar to that outlined in Table 2.2.

E. Seedhouse, *Trailblazing Medicine: Sustaining Explorers During Interplanetary Missions*,
Springer Praxis Books, DOI 10.1007/978-1-4419-7829-5_2,

Table 2.1. Classification of illnesses and injuries in spaceflight.

Characteristics	*Examples*	*Type of response*
Class I		
Mild symptoms Minimum effect upon performance Non-life-threatening	Space motion sickness Gastrointestinal distress Urinary tract infection Upper respiratory infection Sinusitis	Self care Administration of prescription and/or non-prescription medication
Class II		
Moderate to pronounced symptoms Significant effect upon performance Potentially life-threatening	Decompression sickness Air embolism Cardiac arrhythmia Toxic substance exposure Open/closed chest injury Fracture Laceration	Immediate in-flight diagnosis and treatment Possible evacuation Possible mission termination
Class III		
Immediate severe symptoms Incapacitating Unsurvivable if definitive care unavailable	Explosive decompression Overwhelming infection Massive crush injury Open brain injury Severe radiation exposure	Immediate evacuation following resuscitation and stabilization if necessary Comfort measures applied

Table 2.2. NASA medical training for International Space Station crewmembers [1].

Training session	*Crew*	*Time*	*Time prior to launch*
ISS space medicine overview	Entire crew	0.5 hr	18 months
Crew health care system (CHeCS) overview	Entire crew	2 hr	18 months
Cross-cultural factors	Entire crew	3 hr	18 months
Psychological support familiarization	Entire crew	1 hr	18 months
Countermeasures system operations 1	Entire crew	2 hr	12 months
Countermeasures system operations 2	Entire crew	2 hr	12 months
Toxicology overview	Entire crew	2 hr	12 months
Environmental health system microbiology operations and interpretation	ECLSS	2 hr	12 months
Environmental health system water quality operations	ECLSS	2 hr	12 months
Environmental health system toxicology operations	ECLSS	2 hr	12 months
Environmental health system radiation operations	ECLSS	1.5 hr	12 months
Carbon dioxide exposure training	Entire crew	1 hr	12 months
Psychological factors	Entire crew	1 hr	12 months
Dental procedures	CMOs	1 hr	8 months
ISS Medical diagnostics 1	CMOs	3 hr	8 months
ISS Medical diagnostics 2	CMOs	2 hr	8 months

ISS Medical therapeutics 1	CMOs	3 hr	8 months
ISS Medical therapeutics 2	CMOs	3 hr	6 months
Advanced cardiac life-support (ACLS) equipment	CMOs	3 hr	6 months
ACLS pharmacology	CMOs	3 hr	4 months
ACLS protocols 1	CMOs	2 hr	4 months
ACLS protocols 2	CMOs	2 hr	4 months
Cardiopulmonary resuscitation	Entire crew	2 hr	4 months
Psychiatric issues	Entire crew	2 hr	4 months
Countermeasures system evaluation operations	CMOs	3 hr	4 months
Neurocognitive assessment software	Entire crew	1 hr	4 months
Countermeasures system maintenance	Entire crew	2.5 hr	4 months
Environmental health system Preventive and Corrective Maintenance	Entire crew	1 hr	4 months
ACLS "megacode" practical exercise	Entire crew	3 hr	3 months
Psychological factors 2	Entire crew	2 hr	1 month
Medical refresher	Entire crew	1 hr	2 weeks
CMO computer-based training	CMOs	1 hr/ month	During mission
CHeCS health maintenance system contingency drill	Entire crew	1 hr	During mission

To ensure adequate treatment and rehabilitation during ECMs, space agencies will also rely on instructing the crew using curricula and algorithms such as the one shown in Figure 2.1. In addition to extensive medical training, ECM crews will require a versatile medical system (Table 2.3) designed to stabilize and treat crewmembers. While an astronaut requiring urgent medical attention onboard the ISS can be evacuated to a definitive medical care facility (DMCF) on Earth, an injured crewmember en route to Mars won't have that option. For this reason, the provision of a medical system will present unique challenges to mission planners but Table 2.3 gives you some idea of what the onboard medical inventory might consist of.

Table 2.3. Exploration class mission medical supplies.

Basic medical system

Airway and trauma sub-pack (resuscitator and valve mask)
EENT sub-pack (diagnostic items)
Drug sub-pack (oral and injectable)
Saline bag
Intravenous administration sub-pack
Pharmaceutical sub-pack
Operational bioinstrumentation system to provide downlink
Patient and rescuer restraints
Contaminant clean-up kit
Medical accessory kit
Sharps container
Body bags

Extended medical system

Advanced Life Support (ALS)

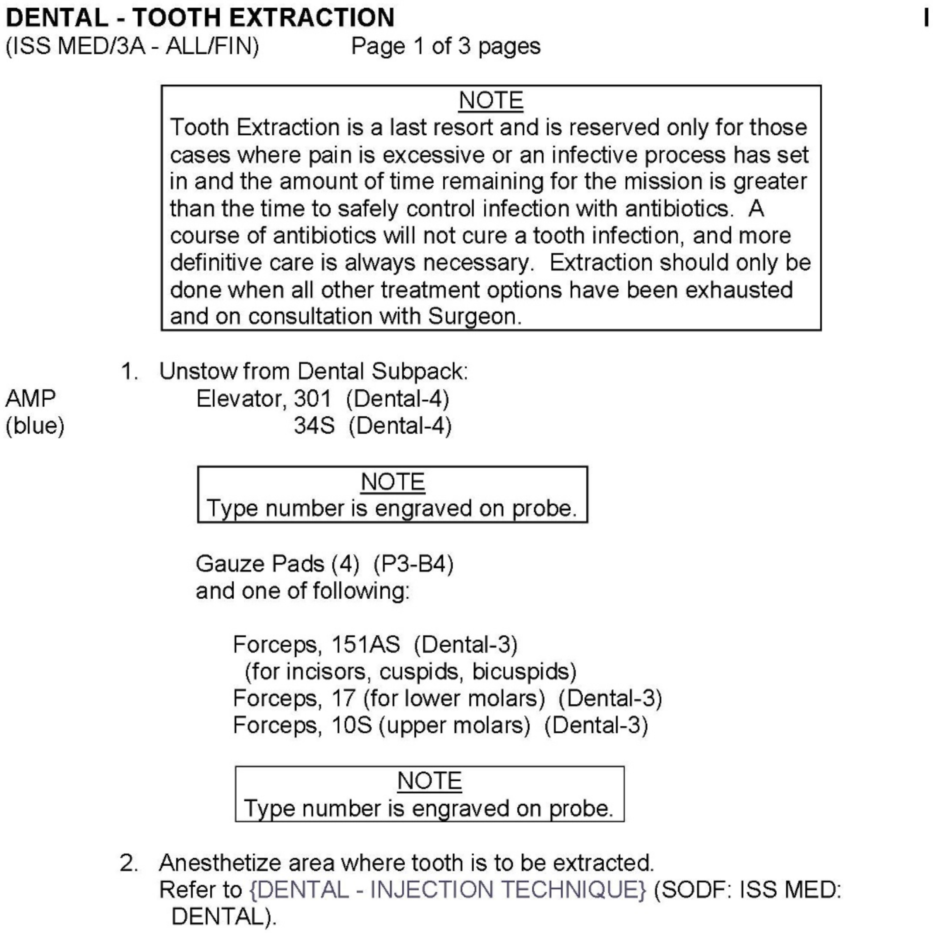
Injectable medications
Intravenous fluid and administration equipment
Airway management equipment
Blood pressure cuff
Stethoscope
Pulse oximeter

Mission medical pack

Oral medications
Topical medications
Bandages
Banked synthetic blood and blood marrow
Portable blood analyzer
Dental hardware
Minor surgical supplies

Systems

System/kit	Description
Crew Medical Restraint System (CMRS)	Provides spinal stabilization of an injured crewmember and provides restraint for CMO treating the patient
Crew Contamination Protection Kit (CCPK)	The CCPK is a multipurpose clean-up kit that protects astronauts from toxic and non-toxic particles
Medical Equipment Computer (MEC)	The MEC is a versatile laptop that is the heart of the medical capability onboard: Displays physiological data from exercise devices Collects and stores medical data Maintains health records Assesses crew health Provides up/downlink capability Stores templates for custom-organ generation
Defibrillator	Also provides heart rate monitoring and analysis
Respiratory Support Pack	This system ventilates an unconscious astronaut automatically and provides oxygen to a conscious crewmember
Blood pressure/ECG	Measures systolic and diastolic blood pressure and also monitors and displays heart rate/ECG during exercise
Countermeasures System	Treadmill, resistive exercise device and bike ergometer
Magnetic Resonance Imaging System (MRIS)	The MRIS is a medical imaging technique used in radiology to visualize the detailed internal structure and function of the body
Autonomous Surgical Robot System (ASRS)	System capable of performing a variety of surgical interventional tasks, ranging from lesion biopsies to foreign body removal
Medical Telepresence System (MTS)	To perform surgery using telepresence, some devices, known as the teleoperated devices, are placed into the patients' internal organs to be operated. Using the MTS, the surgeons manipulate these instruments to see what is happening using small cameras located at the work site
Tissue-engineered Organ Replacement System (TORS)	Engineered biological tissues are customizable and immune-compatible (e.g. heart, limbs, eyes, lungs, pancreas, and bladder)
Interplanetary Bioethics Manual	To provide mission commanders and CMOs guidance with quandaries such as terminally ill crewmembers



DENTAL - TOOTH EXTRACTION I
(ISS MED/3A - ALL/FIN) Page 1 of 3 pages

NOTE
Tooth Extraction is a last resort and is reserved only for those cases where pain is excessive or an infective process has set in and the amount of time remaining for the mission is greater than the time to safely control infection with antibiotics. A course of antibiotics will not cure a tooth infection, and more definitive care is always necessary. Extraction should only be done when all other treatment options have been exhausted and on consultation with Surgeon.

1. Unstow from Dental Subpack:

AMP
(blue)

Elevator, 301 (Dental-4)
34S (Dental-4)

NOTE
Type number is engraved on probe.

Gauze Pads (4) (P3-B4)
and one of following:

Forceps, 151AS (Dental-3)
(for incisors, cuspids, bicuspids)
Forceps, 17 (for lower molars) (Dental-3)
Forceps, 10S (upper molars) (Dental-3)

NOTE
Type number is engraved on probe.

2. Anesthetize area where tooth is to be extracted.
Refer to {DENTAL - INJECTION TECHNIQUE} (SODF: ISS MED: DENTAL).

Figure 2.1 A simple algorithm for tooth extraction. Image courtesy: NASA.

MEDICAL STRATEGIES

Although the crew may be many million kilometers from home, taking care of an injured or ill astronaut during an interplanetary mission will follow the accepted medical strategy of primary, secondary, and tertiary prevention (Table 2.4).

While primary and secondary levels of care won't present too many problems, providing tertiary-level care will be challenging. A loss of pressure in a spacesuit during a spacewalk could result in a nasty injury known as spontaneous pneumothorax. If this were to happen during an ISS mission, it would be considered a mission-terminating event, but en route to Mars, it would require the insertion of a chest tube by the CMO. Another possible event is decompression sickness (DCS), which could easily incapacitate a crewmember. Once again, the CMO would need to

Table 2.4. Levels of prevention.

Prevention	*Definition*	*Rationale*	*Methods*
Primary	Measures implemented to avoid disease/illness	Eliminate hazard by selecting astronauts without disease	Estimating the incidence of disease in the astronaut corps Genetic screening
Secondary	Measures aimed at identifying disease, thereby increasing opportunities for interventions to prevent progression of the disease	Protect against a risk that couldn't be controlled by primary prevention (e.g. bone loss)	Countermeasures such as load-bearing exercise and artificial gravity
Tertiary	Measures that reduce the negative impact of an established disease by restoring function and reducing complications	This level is implemented when the first two levels have failed	Injury/illness may result due to an uncontrolled event such as decompression. This is when Advanced Life Support (ALS) would be used

implement tertiary care, possibly by using Advanced Life Support (ALS) techniques. A third possible event is a crewmember suffering acute radiation sickness (discussed in more detail in Chapter 4). Obviously, a high level of skill will be required by those charged with providing tertiary care, especially when it will not be possible to return a crewmember to a DMCF. Not only will interplanetary CMOs have to deal with the challenges of administering ALS with limited resources, but they will also have to face the very real possibility of treating illnesses and injuries from which the crewmember may not survive. In fact, extended treatments for a severely injured crewmember could deplete irreplaceable consumables and jeopardize other crewmembers. In such a case, it may be the CMO's call to "treat with final resolution" and euthanize the astronaut. Needless to say, the job of CMO won't be an easy one.

THE INTERPLANETARY FLIGHT SURGEON

Flight surgeons (Panel 2.1) often say they have the second best job in the space agency because in terms of mission operations, they participate in many, if not all, of the same training as crewmembers. In addition to supporting pre-flight crew selection and training, monitoring on-orbit crew, and supervising post-flight rehabilitation, flight surgeons also evaluate medicines for spaceflight, and talk to the families of crewmembers on orbit. It's a demanding job, the most challenging aspect of which is trying to balance the responsibilities of serving the agency and the patient, in whom millions of dollars have been invested. For example, a major medical event during a mission may not only disrupt work schedules and create

Panel 2.1. Flight surgeon

When most people think of flight surgeons, they think of Dr "Bones" McCoy of *Star Trek* fame, but flight surgeons don't fly in space unless they become astronauts. Take Michael Barratt, for example. Barratt is a doctor-turned-astronaut who spent more than six months as a real-life Dr McCoy onboard the ISS as the station's CMO. A veteran mountaineer and diver, Barratt spent nine years as a ground-based flight surgeon before deciding he wanted to experience the effects of spaceflight for himself. He became an astronaut in 2000 at the age of 41, but had to wait five years before being assigned to long-duration flight training and another four years before his first mission. He finally launched on Soyuz TMA-14 on March 26th, 2009, to the ISS and served as a member of Expeditions 19 and 20. After logging 199 days on orbit, Barratt landed on October 11th, 2009.

family stress, but it may also jeopardize the lives of other crewmembers who may be involved in a de-orbit evacuation, and create political strain between international partners.

Like any occupation, the job of flight surgeon comes with its fair share of administration. For example, flight surgeons meet weekly with medical boards to discuss the flight status of astronauts, they confer with representatives of other space agencies, present papers at conferences, and, more recently, involve themselves in the issues facing the next generation of space explorers.

While the medical challenges faced by planetary-bound astronauts will be much more hazardous than those faced by those confined to low Earth orbit (LEO), the manner in which problems will be resolved will follow a similar pattern. For example, during ISS missions, flight surgeons work in Mission Control and hold daily conferences (although these conferences are private, if the flight surgeon learns of something that might affect the mission, they let the flight director know) with the astronauts. During ECMs, it is likely the CMO will be a flight surgeon who will be in daily contact with flight surgeons in Mission Control. Perhaps the best way to understand what these flight surgeons might do during an interplanetary mission is to imagine a hypothetical medical event during an ECM.

We'll imagine you're a flight surgeon working at Mission Control during an interplanetary mission to Callisto,[1] the fourth of Jupiter's Galilean moons. We'll

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[1] A 2003 NASA-led study identified revolutionary concepts and supporting technologies for Human Outer Planet Exploration (HOPE). Callisto, the fourth of Jupiter's Galilean moons, was chosen as the destination for the HOPE study. Assumptions for the Callisto mission included a launch year of 2045 or later, a spacecraft capable of transporting humans to and from Callisto in less than five years, and a requirement to support three humans on the surface for a minimum of 30 days.

assume you're certified in a variety of aerospace medical disciplines and have received extensive training that qualifies you to intervene in just about any conceivable medical emergency. You've served as a flight surgeon during a previous lunar mission and you have access to dozens of flight surgeons around the world. Your current duties involve providing in-flight health care for three male and three female crewmembers that are onboard the Shackleton, Earth's first electro-magnetic powered[2] spacecraft. The crew is three months into the two-year outbound trip to Callisto. As with all crewmembers assigned to ECMs, the astronauts were subjected to thorough and rigorous medical examinations prior to the flight. So far, everything has been proceeding by the book; you've been monitoring their daily exercise routine, checking their biomedical data, and talking with them on a daily basis. Then, on Mission Day #99, Stewart Hawke, the Shackleton's chief scientist, a 51-year-old Canadian male, requests an unscheduled private medical conference (PMC) with you. The request is received by Mission Control at 4 am on a Sunday morning, so the call is patched through to your house. After a few slugs of coffee, you begin the PMC with Hawke, who is in severe pain. He complains of a sharp stabbing pain in his lower abdominal area, which is now almost unbearable. You conduct the PMC while reviewing his medical history, which reveals that his father suffered from episodes of kidney illness from the age of 45. Hawke also has a sister with a similar history. Hawke has been perfectly healthy throughout the mission and during his previous missions, which included a six-month stay on the surface of the Moon three years previously and a four-week liquid-breathing mission onboard the Atlantica underwater facility in the Challenger Deep. As part of his anti-oxidant regime, he takes a multivitamin together with a biological response modifier as prescribed by mission regulations. He tells you he has not experienced shortness of breath, fatigue, urgency in urinating, vomiting, or diarrhea. The pain is sharp and frequent and usually accompanied by nausea, which prompted Hawke to take two aspirin before making the PMC request. Due to the length of the mission, water is rationed, and Hawke tells you that because of his heavy work schedule, he rarely drinks the prescribed daily two liters of fluid.

Following the PMC, you consider the possible causes of Hawke's symptoms. Potential maladies include appendicitis, but this is immediately ruled out because all ECM crewmembers had their appendices removed before flight as a precaution against just such an event. Inflammation of the stomach is another possibility, as is a small blockage of the bowel. On Earth, a simple diagnostic test could rule out these causes, but medical facilities onboard the Shackleton are limited. On arrival at Mission Control, you request that Petacchi, the Shackleton's CMO, conduct a medical examination of Hawke. You also request that Hawke provide a urine sample. Because of the one-hour time delay in radio transmission, the examination takes almost four hours. At the end of the examination, Hawke is screaming in

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[2] An electromagnetic thruster, such as the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) being developed by former astronaut, Franklin Chang-Diaz, uses radio waves to ionize and heat a propellant and magnetic fields to accelerate the resulting plasma to generate thrust.

agony and demanding he be given something for the pain. The CMO sends a data packet containing the results of the urine test, which tests positive for blood. You advise Petacchi to break out the Mission Medical Pack (MMP) and instruct him to administer morphine. Then, you inform the Flight Director that Hawke's condition is being evaluated for mission impact and request a flight control team be convened for an emergency medical conference.

The flight control team asks you for your diagnosis based on the PMC. You suggest Hawke may be suffering from a kidney stone infection (Panel 2.2), but until an ultrasound investigation is conducted, it will be impossible to say for sure. You recommend the ultrasound team is brought to Mission Control to conduct the investigation. Petacchi breaks out the mission's ultrasound equipment and performs the examination. The images (Figure 2.2) are transmitted to Mission Control, where they are evaluated by you and a radiologist.

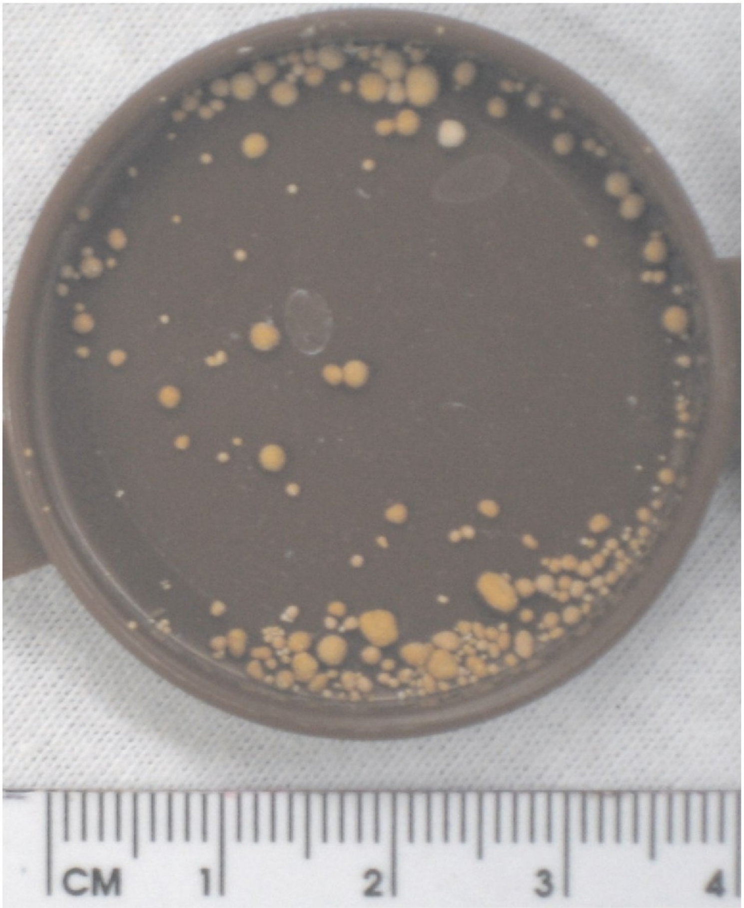

Figure 2.2 Kidney stones. Image courtes

Panel 2.2. Kidney stones

The condition of *kidney stones* results from stones being present in the urethra. Kidney stones can form anywhere within the kidney or bladder and range from tiny microscopic crystals to stones as large as walnuts. They can move from the kidney towards the bladder, causing a number of problems, including excruciating pain. If the stone completely blocks the tube draining the kidney, the kidney could stop functioning. Once renal stones start to move, they can be excruciatingly painful. The stones are solid concretions or calculi (crystal aggregations) formed in the kidneys from dissolved urinary minerals. *Nephrolithiasis* is the medical condition of having kidney stones, while *urolithiasis* refers to the condition of having calculi in the urinary tract (which also includes the kidneys), which may form or pass into the urinary bladder.

Kidney stones often leave the body in the urine stream but if stones grow to sufficient size (two to three millimeters), they may cause obstruction of the urethra. The obstruction causes dilation or stretching of the upper urethra and renal pelvis (the part of the kidney where the urine collects before entering the urethra) as well as muscle spasm of the urethra, trying to move the stone. This leads to pain, most commonly felt in the lower abdomen. There may also be blood in the urine due to damage to the lining of the urinary tract.

Diagnosis can be confirmed by radiological studies or ultrasound examination together with urine and blood tests. The most frequently used procedure for treating kidney stones is extracorporeal shock wave lithotripsy (ESWL), which uses shock waves to break down the stones into small particles, which are passed through the urinary tract in the urine.

For mid and lower-urethra stones, a procedure called *ureteroscopy* may be needed. This involves the surgeon passing a small fiber-optic instrument called a ureteroscope through the urethra and bladder into the urethra. The surgeon locates the stone and either removes it with a cage-like device or shatters it with a special instrument that produces a shock wave.

Astronauts are particularly susceptible to kidney stones because crewmembers lose bone mass during spaceflight and much of the excess calcium ends up in the urine. For example, studies on long-duration crews onboard Mir and the International Space Station (ISS) found astronauts had significantly higher levels of calcium phosphate in urine. The higher calcium levels are probably contributing to the increased calcium-stone-forming potential. They also found fluid intake and urine volume were significantly lower than normal, which means calcium salts are more likely to crystallize and grow into stones.

You examine the ultrasound images and notice a small obstruction in the urethra (the tubes that transport urine from the kidneys to the bladder) – a classic sign of a kidney stone. You send a data packet to Petacchi with instructions on how to commence treatment. Then, you explain the problem to the Flight Director, informing him that it is possible the condition may not be resolved but that treatment has started. Unfortunately, due to the pain, Hawke will be unable to perform any mission duties and will require continuous medical monitoring. If the mission had been onboard the ISS, the default emergency would have been to de-orbit onboard the Dragon capsule. With the crew almost half a billion kilometers away, the options are rather more limited.

Comforted by the fact Hawke has adequate pain control for at least the next 48 hr, you return home in the hope of catching up on some much needed sleep. No sooner are you in the door than your phone rings. It's the Flight Director requesting you return to Mission Control immediately. Hawke's condition has worsened and NASA management has requested an update of the situation because the media are covering the event on television; Fox News has already broadcast an article saying Hawke is just hours from death and the space agency is planning on euthanizing him! You return to Mission Control, where you conduct another PMC with Hawke, who is visibly anxious and deathly pale. Despite the pain killers, Shackleton's chief scientist is complaining that the pain in his stomach is the worst he has ever experienced. You are concerned about the lack of improvement and the deterioration of Hawke's condition. Urine samples are still positive for blood and white cells, suggesting possible urosepsis[3] – a potentially fatal condition. You prescribe narcotics and antibiotics to treat the condition and report to the Flight Director. After you've explained the seriousness of Hawke's condition, the Flight Director asks you for worst and best-case scenarios. Based on the results of the ultrasound and after consulting with Petacchi, you recommend continuing the course of treatment and increasing hydration with intravenous fluids. NASA releases a press statement stating Hawke is expected to make a full recovery and the mission is in no danger. An hour after the press release, CapCom receives word from the Shackleton that Hawke has lapsed into a coma.

You conduct an interview with Petacchi and Everett, Shackleton's commander. Petacchi tells you that Hawke was feverish and disoriented before lapsing into the coma. He is being looked after by the flight engineer and the pilot, which is seriously affecting their duties. You review the latest assessment of Hawke's condition and shake your head. His white blood cell count continues to increase and the course of treatment seems to be having no effect. You present the case to the Multilateral Space Medicine Board (MSMB), who agrees that Hawke probably has less than 48 hr to live. You are about to call the Flight Director to tell him the bad news when you receive a call from Hawke's wife, who has been watching a sensationalist account of her husband's imminent death on Fox News. NASA's public communications officer has told her not to worry, but she wants to hear the truth from you. You tell her that her husband is gravely ill and that everything possible is being done to ensure his

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[3] Urosepsis is a urinary tract infection/bacterial infection. The bacteria causing the infection ascend the urethra and infect the bladder. Once there, the infection poses the risk of further spreading to the kidneys. The worst consequence is the spreading of the infection to the bloodstream, where it can prove fatal.

survival. Then, you excuse yourself and head into the Flight Director's office. The Flight Director has just received a data package from the Shackleton requesting the crew be given permission to euthanize Hawke in light of his imminent demise. Everett has made a strong case that since Hawke's death is inevitable, valuable life-support resources shouldn't be wasted keeping him alive. The Flight Director shakes his head and tells you that he has informed the Washington DC Representative, Jordan James, Chairman of the House Committee on Science, of the matter. It was James's committee that approved the $40 billion Callisto mission and he's understandably concerned that a crew euthanizing one of its own might turn the American public away from funding future missions. You agree, but you have to side with the commander. You refer the Flight Director to the Interplanetary Bioethics Manual (IBM, see Appendix) and point out the reference to euthanization of critically ill crewmembers. You also remind the Flight Director of the crewmembers' waiving their right to life in the event of just such an eventuality. Given the circumstances, Hawke's death is clearly in the mission's best interests and the Flight Director recommends that the chief scientist's life support be withdrawn. He is over-ruled by Jordan James, but half a billion kilometers away, Shackleton's commander decides to put the integrity of the mission above a Washington bean-counter, and orders Petacchi to withdraw Hawke's life support. Hawke is pronounced dead three hours later. Petacchi's wife is understandably distraught when she is told the news and insists her husband's body be cryogenically preserved so an autopsy can be performed when the Shackleton returns in three years' time. Although the IBM makes provision for such a request, the crew doesn't warm to the prospect of sharing a spacecraft with a corpse for the next three years. The crew request Hawke's body be buried in space. The Flight Director, despite the protestations of Jordan James, agrees. Three hours later, in accordance with the "burial in space" procedures described in the IBM, Everett jettisons Hawke's body into deep space.

Obviously, the death of a crewmember represents the extreme end of the spectrum of the myriad issues facing the flight surgeon during an interplanetary mission. However, it is inevitable that, sooner or later, one or more severe emergency medical events will occur. Some medical events may resolve or at least improve quickly with treatment, others may require continuing care, and yet others may require resuscitative measures. Some will end up like Hawke. The flight surgeon's decision to determine end points will be complex and will be based upon the CMO's best judgment and the guidelines described in the IBM or a similar document. Factors the flight surgeon may consider will include whether there are single or multiple incidents, the resources available to treat the patient, and the operational impact upon the crew of the potential loss or extended disability of the patient. In common with 19th-century polar exploration, ingenuity and determination will be used during the treatment of unusual situations. Other factors the flight surgeon will need to consider include resource utilization in the event of multiple illnesses or casualties, identifying specific roles for caregivers, anticipated end points of treatment, and communication with the ground crew to assist in prioritization of care. Given the unique characteristics of the environment (Figure 2.3), the manner in which the flight surgeon administers these medical intervention strategies will be very different from

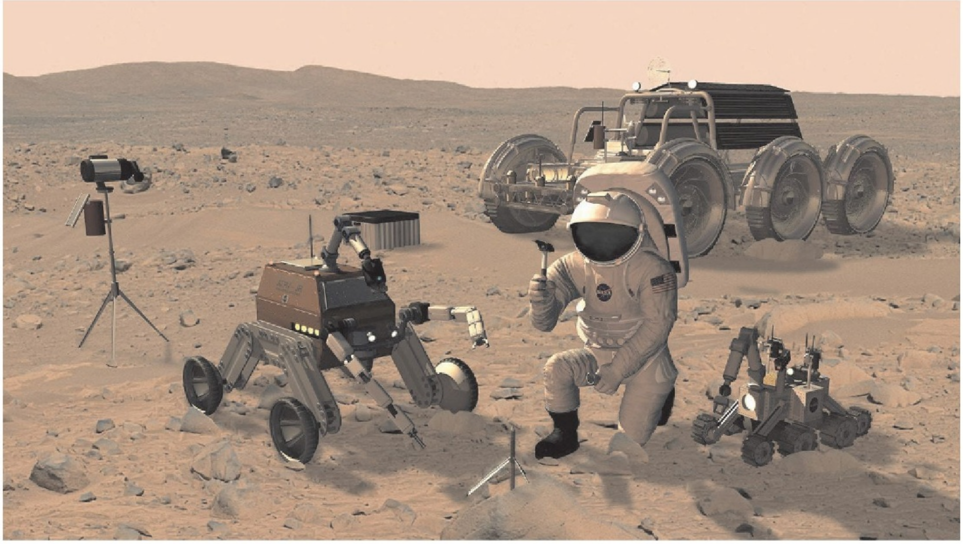

Figure 2.3 Crewmembers embarked upon exploration class missions will work in extreme environments that will influence medical intervention strategies. Image courtesy: NASA.

that on Earth, so it is worthwhile taking a look at some of the medical treatment the CMO will be responsible for.

IN-FLIGHT HEALTH CARE

At the time of writing, there has not been a life-threatening medical emergency during a space mission, but there have been several medical events, some of which are listed in Table 2.5. However, ECMs, by virtue of the sheer length of the mission, which may be measured in years, means there is a high probability one or more of the health issues listed in Table 2.6 will require intervention by the CMO. Having said that, much of the CMO's time will be spent dealing with common complaints such as overexertion, strains, and sprains. For example, backaches are a common complaint thought to be associated with elongation in vertebral column length and stress placed on intervertebral discs. To get an idea of what other complaints the flight surgeon may have to face, it is worth looking at what has been learned from other isolated environments on Earth, such as Antarctica and submarine missions; by learning about the type and incidence of medical-surgical and behavioral health events that occur in these environments, it's possible for flight surgeons to plan for the future needs during ECMs. We'll start by discussing submarine[4] missions (Figure 2.4).

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[4] Submarine missions serve as good analogs for extended-duration space missions. Until April 2005, NASA's total manned spaceflight amounted to 76.57 man-years. By comparison, one Trident Patrol (10 weeks × 7 days/week × 24 hr/day × 155 crewmen = 260,400 man-hours, or 29.7 man-years!

Figure 2.4 Seawolf-class submarine, USS *Connecticut* (SSN-22). Image courtesy: General Dynamics.

Medical events during submarine missions are instructive, as they occur in a confined, remote environment where there is limited diagnostic and therapeutic support. They also occur in an environment where potentially life-threatening events may end a mission. From January 1st, 1997, through December 31st, 1998, the US Navy described the incidence of illnesses and injuries on 136 submarine patrols. The numbers of acute events were related to the total number of person-days under way, with 2,044 acute events in 1.3 million person-days at sea (or 157 acute events per 100,000 person-days). When it came to the more serious events requiring evacuation, a range of 1.9 to 2.3 medical evacuations per 1,000 person-months was reported for all submarines in the US Atlantic Fleet from 1993 to 1996 and a range of 1.8 to 2.6 evacuations per 1,000 person-months was reported for humane reasons (i.e. death in the family).

Another study reviewed health data from 885 Polaris submarine patrols from 1963 to 1973 – a period equivalent to 4,410,000 person-days of submarine activity. During this time, 1,685 medical events resulted in 6,460 duty days lost. The events with the six highest rates of occurrence were, in descending order, trauma, gastrointestinal disease, respiratory infections, dermal disorders, infection, and genitourinary disorders. However, the range of disorders also included all sorts of other medical events, such as arrhythmia, tachycardia, hepatitis, hemorrhage, schizophrenia, appendicitis, and crush injuries. Based on these data, NASA has estimated there may be one major medical event requiring intervention of the type described in the Hawke scenario during a three-year ECM with a crew of six.

Table 2.5. In-flight medical events for US astronauts (STS-1 through STS-89).[5]

Medical event or system by International Classification of Diseases category	*Number*	*Percent*
Space adaptation syndrome	788	42.2
Nervous system and sense organs	318	17.0
Digestive system	163	8.7
Skin and subcutaneous tissue	151	8.1
Injuries or trauma	141	7.6
Musculoskeletal system and connective tissue	132	7.1
Respiratory system	83	4.4
Behavioral signs and symptoms	34	1.8
Infectious diseases	26	1.4
Genitourinary system	23	1.2

Table 2.6. Major health and medical issues during exploration class missions.

Health issue	*Risk*	*Health issue*	*Risk*
Radiation protection	Severe	Neurovestibular	Severe
Hearing conservation	Moderate	Habitability	Moderate
Cardiovascular	Moderate	Extravehicular activity	Severe
Muscle loss	Moderate	Psychological	Moderate
Bone loss	Severe	Behavioral	Moderate

NASA's prediction has been backed up by similar data compiled from experience in the Antarctic. The Australian National Antarctic Research Expeditions (ANARE) Health Register compiled 1,967 person-years of data from 1988 to 1997. It documented 5,103 illnesses and 3,910 injuries, the distribution and variety of which were similar to spaceflight data. The Health Register also noted several deaths resulting from drowning and exposure, appendicitis, cerebral hemorrhage, acute myocardial infarction, carbon monoxide poisoning, and burns. While it is unlikely an astronaut will drown, each of the other circumstances is a potential medical event on a spacecraft, indicating the wide variety of medical emergencies that a flight surgeon will need to consider when planning for the health care management techniques described in the next section.

Health care management en route to a distant planet will follow many of the procedures here on Earth. For example, the starting point for medical care will be a description of the chief complaint and a physical examination. However, unlike when you visit the doctor here on Earth, the physical examination technique

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[5] Adapted from Billica, R. In-Flight Medical Events for US Astronauts during Space Shuttle Program STS-1 through STS-89. April 1981–January 1998. Presentation to the Institute of Medicine Committee on Creating a Vision for Space Medicine During Travel Beyond Earth Orbit, February 22, Johnson Space Center, Houston (2000).

onboard a spacecraft will be adapted to the microgravity environment. That's because the methods of locating internal organs and other diagnostic methods are affected by the lack of gravity, which means the astronaut, the CMO, and the equipment have to be stabilized.

Within the spectrum of providing health care to the astronauts, the CMO will also be responsible for other factors that may affect the well-being of the crew. For example, he/she will be responsible for ensuring the crew's dietary needs are met and checking crewmembers are drinking enough fluid to prevent the formation of kidney stones, thereby avoiding a situation like Hawke's. He/she will also need to be prepared to deal with the consequences of accidental leaks of chemical elements into the spacecraft atmosphere. Experience in LEO has shown that environmental hazards come from several sources, the dominant source being heat degradation of electronic devices, which produces formaldehyde and ammonia. Needless to say, exposure to these sorts of chemicals could result in multiple casualties that would soon outstrip the finite resources available on the spacecraft, so the CMO will need to be able to identify acute signs and symptoms early. Another monitoring task for the CMO will be checking how much radiation each crewmember has absorbed. This will be particularly important because while much is known about the radiation environment of LEO, little is known about the radiation environment of interplanetary space, where quantities of solar and galactic radiation and the potential for exposure increase. So, when the CMO isn't performing routine check-ups and reminding the crew to drink, they will turn their attention to other daily tasks such as checking how much radiation each crewmember has absorbed, by checking the crew's dosimeters. To protect the crew against excessive radiation exposure, the CMO will no doubt periodically check with the Space Radiation Analysis Group (SRAG)[6] back in Houston.

Other routine check-ups will include making sure astronauts keep up their exercise regime and monitoring crewmembers' cardiovascular integrity, which will mean checking for a whole range of cardiovascular symptoms and abnormalities. For example, astronauts during an ECM may suffer high blood pressure, ventricular premature beats, atrial arrhythmias, tachycardia, chest pain, shortness of breath, syncope, and a host of other heart-related symptoms. Once the CMO has finished those checks, they may turn their attention to the crew's dental health. Although astronauts will be pre-screened, even good teeth and a history of preventive care can't guarantee that no caries will develop in anyone over the course of a multi-year mission. As with most space missions, astronauts will be subject to a heavy work schedule, which means, occasionally, they may not always maintain good dental hygiene (Panel 2.3). This, combined with the lack of foods with natural gingival-cleansing properties, means the CMO will probably have to fill the odd cavity (ANARE data reported dental events accounted for 8.80% of all medical events despite crewmembers having been pre-screened and found to be dentally fit).

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[6] SRAG team members examine space weather data, reports, and forecasts for trends or conditions that may produce enhancements to the near-Earth radiation environment; they then report the information to flight management.

Panel 2.3. Toothache in orbit

In 1978, Soviet cosmonaut Yuri Romanenko experienced a toothache during the 96-day flight of *Salyut 6*. To begin with, Romanenko took overdoses of pain killers to deaden a toothache that was causing his eyes to literally roll with pain. Because he considered it would be a disgrace to complain, Romanenko didn't report his discomfort to the ground for two weeks. As his problem worsened, his fellow crewmembers pleaded for help from the ground but the Soviet space program had no contingency plans for dental emergencies. In fact, the only advice from controllers was for Romanenko to take a mouthwash and keep warm! Romanenko suffered for two more weeks before *Salyut 6* touched down on schedule. His ordeal was subsequently the subject of a televised interview in the Soviet Union and featured in published accounts in Russian and US space and dental literature.

Gastrointestinal problems are another common ailment among astronauts, accounting for up to 8% of the recorded medical events on Space Shuttle missions. Many of the problems are caused by the microgravity environment, which causes some astronauts to be constipated and others to suffer from diarrhea. While the CMO will treat these with common over-the-counter medications such as Imodium and Pepto Bismol, other gastrointestinal problems will require more aggressive courses of treatment and, in some cases, even surgery. For example, an obstruction of the gallbladder or appendix that becomes infected can be lethal without operative intervention. Given the seriousness of such an event, astronauts will probably have their appendices removed before flight (an "elective appendectomy" in medical parlance), so this shouldn't be a problem, but other problems such as an inflammation of the pancreas (a life-threatening condition even with the best medical care) may cause the CMO some sleepless nights.

Yet another regular feature of the CMO's job will be handing out pills. Lots of pills. Many of these pills will simply be countermeasures against all the adaptations to microgravity. For example, space missions result in a decreased red blood cell (RBC) mass, which means astronauts become anemic. To combat this, astronauts will probably be given erythropoietin, a hormone that promotes RBC survival. To boost the astronaut's immune systems, the CMO will also hand out immune system boosters such as Eleutherococcus Senticosus (ES), a supplement used by the Russian space program since 1966. ES not only boosts the immune system, but also helps the body adapt to and cope with unfavorable conditions, such as physical and psychological stress, infections, environmental pollutants, radiation, and extreme climatic conditions.

In addition to acting as the mission's dentist, pharmacist, and doctor, the CMO will also be expected to serve as a behavioral health specialist. Astronauts embarked upon multi-year missions will be exposed to the most isolated, hostile, and confined environment in human exploration history and it is inevitable that sooner or later, cracks will appear in even the toughest crewmembers. Some may experience depression, others may become overly anxious, while some may become psychotic. Some of these mental health issues may simply be caused by the cumulative effects of environmental and interpersonal stressors that become magnified by the sheer length of the mission. In either case, it will be up to the CMO to intervene. Most likely, he/she will take advantage of psychiatric expertise on the ground and, if necessary, make use of psychotropic medications (or a straitjacket) onboard.

ANESTHESIA

Inevitably, during ECMs, anesthesia and pain management will be required for unanticipated accidents and various medical conditions. For the CMO, this aspect of health care will present major challenges. For example, little is known about gas diffusion in reduced gravity – a lack of knowledge that may compromise the administration of anesthesia and pain management procedure. Also, in microgravity, fluids and gases do not separate on the basis of differing densities. Consequently, a vial of a drug or a bag of intravenous fluid looks something like shaving foam! Furthermore, many devices that depend on gravity-induced separation of gases and fluids, such as anesthetic vaporizers, simply break down in microgravity. To overcome these challenges, future CMOs will need to adapt current anesthesia techniques and procedures to meet the unique problems that arise when administering anesthesia in space to microgravity-exposed patients.

AIRWAY MANAGEMENT

Another technique CMOs will need to be proficient in administering is airway management. However, success in applying some of the most effective methods of airway management requires frequent and regular practice, especially in the microgravity environment (Figure 2.5).

The types of airway equipment and techniques required will be based on the type of surgery and trauma anticipated. Before such equipment and techniques are selected, it will be necessary to decide which long-term airway care procedures might be needed. For example, to give injured astronauts the best chance of survival, CMOs will almost certainly decide to use anesthetic techniques that do not require endotracheal intubation. You may have seen this procedure in the movies. It refers to the placement of a flexible plastic tube into the trachea to protect the patient's airway and provide a means of mechanical ventilation. Even on Earth, it is a procedure that is potentially dangerous and requires a great deal of clinical experience to master: if performed improperly (in microgravity studies onboard parabolic flights, the procedure was unsuccessful in 15% of situations), complications may lead to the patient's death. Given the potential dangers of such a procedure, flight surgeons will probably recommend that CMOs use a laryngeal

Figure 2.5 This zero-G intubation was performed during parabolic flights conducted on an Airbus 300 over the Atlantic Ocean. The patient's head was gripped between the anesthesiologist's knees, with the torso strapped to the surface. Three personnel with no experience in airway management or microgravity participated in the study, which attempted the procedure seven times. Image courtesy: European Space Agency.

mask, the use of which is technically much easier. The mask also provides an excellent airway and in the simulated atmosphere of microgravity, its use has been more successful.

SURGERY

Surgery also presents interplanetary CMOs with a set of unknowns. For example, the physiological changes that occur in astronauts embarked upon long-duration space missions may affect wound healing and resistance to infection, each of which is crucial for recovery from surgery. Another uncertainty is the response to hemorrhage and fluid resuscitation, which will probably be altered by the effects of microgravity. Then, there's the problem of bleeding in zero gravity. Research onboard parabolic aircraft has shown that bleeding increases during surgery. On Earth, gravitational forces help collapse the veins and help stop the flow of blood, but in microgravity, the gravitational force is absent and external compression must be supplied. No doubt, the CMO will adapt and employ a certain level of ingenuity to overcome these challenges, but what happens if the CMO has to perform a surgical procedure for which there are no instruments? Remember, therapeutic options will be limited by the medical equipment carried onboard and space onboard an interplanetary spacecraft will be at a premium. Fortunately, thanks to computer-assisted design and computer-assisted manipulation (CAD–CAM) technology, it will be possible to fabricate tools to order from specifications contained in an onboard database or transmitted from Earth. So, a CMO requiring a seldom-used surgical instrument a billion kilometers from home could simply custom order the tool using the onboard CAD–CAM equipment. A similar system (Panel 2.4) will be used by CMOs who need to replace the organs or limbs of an injured astronaut.

So far, we've discussed the problems of stopping bleeding, the unavailability of instruments, and wound healing, but what about performing actual surgery? In the microgravity environment of an interplanetary spacecraft or the reduced gravity of a

Panel 2.4. Tissue-engineered Organ Replacement System (TORS)

Tissue engineering has long held promise for building new organs to replace damaged livers, blood vessels, and other body parts. The TORS encapsulates living cells in cubes and arranges them into 3-D structures, just as a child constructs buildings out of Lego blocks. The technique, dubbed "micro-masonry", employs a gel-like material that acts like concrete, binding the cell "bricks" together as it hardens. The tiny cell bricks allow scientists to build artificial tissue such as organs and limbs. To obtain single cells for tissue engineering, researchers first break tissue apart, using enzymes that digest the extracellular material that normally holds cells together. Some scientists have successfully built simple tissues such as skin, cartilage, or bladder on biodegradable foam scaffolds, although the tissues don't have the same complexity as normal tissues. The tissues are built "biological Legos" by encapsulating cells within a polymer called polyethylene glycol (PEG), which is a liquid that becomes a gel when illuminated. So, when the PEG-coated cells are exposed to light, the polymer hardens and encases the cells in cubes. Once the cells are in cube form, they can be arranged in specific shapes using templates made of a silicon-based polymer. Both template and cell cubes are coated again with the PEG polymer, which acts as a glue that holds the cubes together as they pack themselves tightly onto the scaffold surface. Once the cubes are arranged properly, they are illuminated again, and the liquid holding the cubes together solidifies.

It may sound very "Brave New World", but a basic TORS is already on the drawing board and on future HOPE-type ECMs, such an organ printing system may help astronauts grow everything from an artificial liver to a new pancreas.

Jovian moon, problems such as anchoring both the patient (just look at Figure 2.5) and the operating team, maintaining a sterile field, and controlling blood and body fluids can be expected. To minimize these problems, CMOs will opt for minimally invasive procedures such as laparoscopic surgery. Laparoscopic surgery is a modern surgical technique in which operations are performed through small incisions (usually 0.5–1.5 cm) within the abdominal or pelvic cavities. Because the incisions are so small, recovery is quick and body fluids are contained more effectively than in traditional surgery. The procedure has been tested successfully on pigs during parabolic flight.

While laparoscopic surgery may be an effective procedure for many types of surgery, there are some injuries that may exceed the medical capabilities of the spacecraft and the capacities of the CMO to intervene medically. For example, closed head injuries and spinal cord injuries may represent severe life-threatening events, since management and treatment of astronauts with these types of injuries would likely be beyond the capability of even the most experienced CMO. Individuals with mild or moderate closed head injuries may survive but remain disabled because of residual neurological deficits. Terrestrial management issues today include placement of burr holes for evacuation of subdural hematomas, feeding and airway control, spinal cord stabilization, and management of bowel and bladder functions and infections, none of which will be available in the cramped confines of an interplanetary spacecraft or surface habitat.

REHABILITATING ASTRONAUTS

When the astronauts finally make it to the surface of Callisto or Mars and eventually back to Earth – hopefully without any medical emergencies – they will begin a post-flight rehabilitation program. The program will be similar to the plan described in Table 2.7. As you can see, the CMO will play a prominent role in ensuring deconditioned astronauts restore their preflight muscle strength and aerobic capacity.

Table 2.7. Post-flight rehabilitation plan.

Description	The post-flight rehabilitation plan is a three-phase plan designed to protect the health and safety of astronauts following landing and on returning from interplanetary missions and to actively assist in the crewmembers' return to preflight health and fitness levels		
Schedule	*Outbound post landing*		
	Duration	*Schedule*	*Personnel*
	Rehabilitation Phase I 120 min/day Proprioceptive neuromuscular facilitation (PNF) techniques, massage, and light manual resistance exercises	0–3 days post landing	CMO, crewmembers, and crew surgeon via groundlink

Rehabilitation Phase II 120–150 min/day Agility and coordination tasks, light cardiovascular exercise. Massage, PNF techniques, flexibility, and strength exercise	4–10 days post landing	CMO, crewmembers, and crew surgeon via groundlink
Rehabilitation Phase III 150–180 min/day Agility and coordination tasks. Cardiovascular exercise. PNF techniques, massage, and strength exercises	11–14 days post landing	CMO, crewmembers, and crew surgeon via groundlink
Rehabilitation Phase IV 90–120 min/day Cardiovascular and strength training. Massage. Fitness testing once per week	15–21 days post landing	CMO, crewmembers, and crew surgeon via groundlink
	Inbound post landing	
Rehabilitation Phase I 120 min/day Assisted walking. Hydrotherapy, proprioceptive neuromuscular facilitation (PNF) techniques, massage, and light manual resistance exercises	0–7 days post landing	Astronaut Strength Conditioning & Rehabilitation Staff (ASCR), crewmembers, and crew surgeon
Rehabilitation Phase II 120–150 min/day Assisted walking. Hydrotherapy, agility, and coordination tasks, light cardiovascular exercise. Massage, PNF techniques, flexibility and strength exercise	8–30 days post landing	ASCR, crewmembers, and crew surgeon
Rehabilitation Phase III 150–180 min/day Agility and coordination tasks. Cardiovascular exercise. PNF techniques, massage, hydrotherapy and strength exercises	31–60 days post landing	ASCR, crewmembers, and crew surgeon
Rehabilitation Phase IV 90–120 min/day Cardiovascular and strength training. Massage. Fitness testing once per week	61–120 days post landing	ASCR, crewmember, and crew surgeon

Special requirements	Crewmembers will perform rehabilitation on duty days only (5 day/week) Medical status checks will be performed once per week The ASCR and Exercise Physiology Laboratory will make recommendations to the crew surgeon regarding rehabilitation progress and exercise certification of crewmembers
Notes	During each rehabilitation phase, crewmembers will be assessed using fitness tests to evaluate isokinetic function, oxygen uptake, agility, and coordination and flexibility

Astronaut health during ECMs will require a continuum of preventive, therapeutic, and rehabilitative care on the ground, during the mission, and upon return to Earth. The continuum will include normal health maintenance and care for the physiological adaptations astronauts will be exposed to as a result of the extreme environment of space. Each of these phases will require the skills of an experienced CMO and ground-based flight surgeons capable of responding to the myriad minor and major medical problems that can develop among members of a group of individuals over extended periods of time in an extreme environment.

REFERENCES

[1] Dehart, R.L.; Davis, J.R. (eds). *Fundamentals of Aerospace Medicine*, 3rd edn, pp. 617–618. Lippincott Williams and Williams, Philadelphia (2002).

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