VI. MEDICAL CARE SYSTEMS

A. Introduction

An appropriate level of inflight medical care is a critical element in overall mission success. The capability to treat a broad range of medical and surgical conditions is justifiable both for humanitarian reasons and to ensure that the crew is healthy enough to perform their assigned duties. As a general principle, increasing isolation and mission hazard should be countered by an increasingly capable and autonomous health care system, although it is axiomatic to note that not all clinical conditions will be treatable in space. The overarching objective is to provide treatment capabilities for most feasible conditions without imposing an unacceptable burden on the constrained resources available within spacecraft and planetary habitats. Thus, the overarching MCS requirement is research and development needed to determine potential risks and to identify the mission resources required. Studies must include trade-offs between onboard medical capability and rescue capability (e.g., Assured Crew Return Vehicle for SSF).

Countermeasures and medical care systems form a continuum in terms of overall crew health. Countermeasures represent a preventive medicine approach to limit the deleterious medical effects of unopposed space flight deconditioning, where the medical care systems provide clinical treatment for overt illness or injury. Medical care system requirements result from endogenous medical risk (i.e., that which any individual has as a result of hereditary, lifestyle, and prior illness), unopposed physiological deconditioning in microgravity, environmental factors (radiation exposure, atmospheric contamination, or rapid pressure changes) and psychological stress associated with living and working in an isolated, hazardous and confined environment. The body's tremendous ability to acclimate, both: (1) allows humans to exist in a microgravity environment which was not experienced during the evolutionary process; and (2) confounds medical treatment in space. Many physiological parameters change in the flight environment. It is not known whether the degree to which these changes occur are simply appropriate adjustments to a new "normal" homeostatic level suitable to that environment. Consequently, it is not known when or if intervention to adjust parameters toward "Earth normal" is beneficial; and diagnosis and treatment of illness without a clear definition of "normal" is difficult at best.

Exposure to the space environment is known to cause changes in drug kinetics, absorption, and action, increases in size of internal organs (e.g., the spleen), changes in the shape and function of the heart and vessels, and multiple alterations in regulatory physiology. The clinical significance of these alterations is not yet clear due to limited experience with medical observation and care inflight. Furthermore, the broad issue of clinical response of the space-adapted crewmember to pathological conditions (e.g., hemorrhage, fracture or lacerations) has not been addressed. It is possible that modified disease processes will require a different approach for providing medical care.

Table VI-1 identifies the Life Sciences Division disciplines[1] that support solutions in clinical medicine and therapeutic response, and summarizes other requirements for MCS.

TABLE VI-1

PROVISIONS FOR MEDICAL CARE SYSTEMS

ILLNESS AND INJURY EVENTS	SYSTEMS PROVIDING CAPABILITY		
	ENVIRONMENTAL HEALTH & LIFE SUPPORT	COUNTER-MEASURES**	MEDICAL CARE
Occupational Health:			
Endogenous medical risk factors			X
EHLSS failure or degradation			C
CS failure or inadequacy			C
Surgical and medical regimes:			
Cardiopulmonary		X	C
Musculoskeletal		X	C
Metabolic Disorders**		X	C
Radiation Health		X*	C
Cell and Developmental Function		X	C

X — Implies the potential for a solution
C — Contingency capability for limited and temporary intervention or treatment
* — If synergism between microgravity and radiation exists
** — Pathological regulatory physiology

B. Constrained Program — Surgical and Medical Regimes

1. Cardiopulmonary System

Medical care systems for exploration missions will require the ability to diagnose and treat major cardiopulmonary emergencies, including but not limited to:

- Decompression sickness (not exclusively a cardiopulmonary problem)
- Myocardial infarction (heart attack)
- Pulmonary embolus
- Cardiac arrhythmias/angina/congestive heart failure
- Cardiopulmonary arrest.

Footnote 1. Less than one percent of the critical questions in Life Sciences Division Discipline Science Plans support a constrained program in Medical Care Systems. See Volume II, Table 2 for details.

Table VI-2
Cardiopulmonary

- •• Determine beneficial and harmful delayed or persistent consequences of long-term space flight and identify appropriate short-term (i.e., hours to days) and long-term (i.e., months to years) postflight rehabilitative measures
- •• Identify risks for bubble formation and decompression sickness associated with pre-EVA denitrogenation/decompression schedules and exercises
- •• Determine cardiovascular electrical and mechanical responses to EVA at different levels of gravity (e.g., transit and surfaces of Moon and Mars)
  --Determine what factors influence the occurrence, magnitude, and sequence of these responses
- •• Establish pulmonary life support procedures for protection or resuscitation in the event of loss of EVA suit or cabin pressure, and for cardiopulmonary resuscitation and general anesthesia
- •• Determine whether space flight increases cardiac arrhythmias and identify mechanisms
- •• Determine whether the extent of adaptation to space flight affects postflight orthostatic intolerance
- •• Determine space flight alterations in blood pressure and flows and functional consequences in tissues and organ systems during long-duration flight or after return to Earth

• = Required for Mars
•• = Required for Moon and Mars

Research Requirements. Additional study of decompression sickness (bends) and design of improved space suits is required. Ground EVA simulations suggest that bubbles frequently occur in the pulmonary artery, but that clinical bends occurs much less frequently. While bubbles may be of little consequence in a normal subject, they could be catastrophic in a subject with an undetected arterivenous shunt. Risks of bubble formation and clinical decompression sickness associated with pre-EVA denitrogenation/decompression schedules and exercises must be identified. Standards for crew health and performance, including periodic monitoring of health status, must be developed. The impact of expanded EVA (e.g., constructing SSF) and EHA (base construction and Moon or Mars exploration) on the risk of decompression sickness and suit design must be determined.

Certain types of arrhythmia will incapacitate a crewmember and endanger a mission. Therefore, it is important to know whether the prevalence of cardiac arrhythmias is in fact higher during space flight, and if so, what mechanisms, prevention, and therapy are required. It is important to determine whether space alters pharmacokinetics and dose response curves for beneficial and deleterious effects of anti-arrhythmic and other cardioactive and vasoactive drugs. An understanding of the mechanisms and treatment of orthostatic intolerance that could compromise landing and productivity on the Moon or Mars, and on return to Earth is required. What is the threshold for prevention of intolerance (e.g., will 0.16 or 0.38 Earth gravity prevent its occurrence?), and are there more effective and/or less intrusive methods of therapy than those currently employed (e.g., fluid loading, lower body negative pressure—LBNP)?

2. Musculoskeletal

Major issues (Table VI-3) involve the prevention of excessive deconditioning and the provisions for treatment of acute injuries. There is substantial risk of a crush injury of muscle and bone when moving large masses in space; and muscle and tendon sprains, bruises, and bone fracture with work or exercise. Prevention of excessive deconditioning is necessary because:

1) Excessively deconditioned crewmembers may not be able to respond to inflight or postflight situations requiring physical strength and stamina.
2) Routine EVA activities, which will characterize planetary surface exploration programs, will require normal physical strength and stamina.
3) Crewmembers with excessive deconditioning will be prone to bone fractures, tendon injuries, or muscle tears while doing physical work and/or exercising.

Table VI-3
Musculoskeletal

- Define the risk for bone loss on development of bone fractures, hypercalcemia, metastic calcifications, and renal stone formation
- Determine whether atrophy from unloading makes muscle, tendon and the myotendonous functions more susceptible to injury or damage on resuming normal weight-bearing status
- Determine how well injured muscles repair in microgravity

• = Required for Mars

While prevention will be the primary MCS thrust, diagnosis and treatment must be available for fractures, repair of ruptured tendons and ligaments, and prevention or treatment for complications of fractures (e.g., pulmonary embolus). Diagnosis and treatment must be provided for the secondary effects of muscle and bone tissue wasting which may lead to mineral and electrolyte derangements. These include hypercalcemia (which could cause metastatic calcification), muscle weakness, changes in mental status, hypercalciuria (which leads to kidney stones and dehydration), and hyperkalemia (which could cause cardiac arrhythmia).

Research Requirements. Studies are needed to elucidate the biomechanics of work/exercise in microgravity and partial gravity, both for activity within the vehicle and EVA environments. The nature and mechanism of bone, skin, and muscle healing in microgravity must be determined.

3. Metabolic Disorders (Pathological Regulatory Physiology)

The critical research elements for exploration missions include the effects of microgravity on renal function, endocrine changes that effect the functioning of other homeostatic systems, drug effectiveness, and the combined effects of microgravity and EVA on thermoregulation and heat exchange (Table VI-4). The specific effects of the demonstrated immunological and metabolic alterations of microgravity on the host defense response to severe infection should be investigated. The role of countermeasures in the control of septic processes in microgravity also must be defined and their interactions quantified. Critical care, diagnosis, and treatment should be available for renal failure and common clinical endocrine problems.

Table VI-4
Regulatory Physiology

- • Determine effects of space-induced endocrine changes on the function of other homeostatic systems (e.g., cardiovascular, CNS, immune function, thermoregulation, reproductive system, gastrointestinal system, and energy metabolism, sleep, behavior and performance
- • Determine effects of microgravity on renal function. Are effects progressive or reversible? Are there differences in filtration, reabsorption, secretion, and excretion?
- •• Determine the nature of space flight induced effects of vasoactive, pharmacokinetic and other drugs
- •• Determine effects of space flight and EVA on thermoregulation and heat exchange

• = Required for Mars
•• = Required for Moon and Mars

Research Requirements. A key challenge within the area of regulatory physiology involves the identification of "normal" parameters for the space-adapted individual. These clinical norms are essential to the practice of medicine in the space environment because clinical decisions are often made on the basis of deviations from a baseline value. Both animal and human studies have shown marked variations of endocrine function, examples of which include a tendency towards glucose intolerance (diabetes) and marked decreases of certain regulatory hormones (such as testosterone) in flight. The medical and operational impacts of these changes must be assessed.

4. Radiation Health

The radiation environment for space exploration is not yet sufficiently understood, but on the basis of what is known about exposure to ionizing radiation, it is likely to have serious health implications. The primary research elements for radiation health were presented in Section I (EHLSS). The important research elements from an MCS perspective are discussed below.

Solar particle events (SPEs), commonly referred to as solar flares, pose a life threatening radiation health risk for crewmembers outside the spacecraft and on planetary surfaces. Therefore, the provision of a sanctuary to limit radiation dose is a medical requirement. Determining the degree to which radiation impacts on bone marrow and lymphoid tissue responses will impair the containment of invasive sepsis, thereby preventing generalized septic response, is an important medical question.

Table VI-5
Radiation Health

- •• Develop protocols to manage medical risks associated with acute and chronic exposure to space radiation

•• = Required for Moon and Mars

Determining the long-term medical consequences of exposure to high Z element (HZE) particles present as a component of galactic cosmic radiation (GCR) is critical. The biological hazards associated with HZE particles, i.e, the "late effects," are not adequately known and may pose unacceptable long-term cancer risks. Exposure can result in life-threatening and life-shortening effects, such as cancer, and other detrimental consequences including cataract formation, mutagenesis, and other tissue damage. Neurological and behavioral effects and their consequences on crew performance must also be understood.

Research Requirements. In order to accomplish a realistic risk assessment for radiation exposure during exploration missions, the fluency of GCR, and its biological effects, must be determined prior to establishing medical standards for radiation exposure in space. Other related issues include crew selection standards, personal radiation protection, and medical protocols for treatment of radiation sickness.

5. Environmental Health

The critical issues focus on the treatment of medical problems related to adverse temperature and gaseous environment conditions, procedures to prevent and minimize the risk of decompression sickness, and assessment of EVA risks (Table VI-6). Also included are microgravity effects on the immune system and the degradation or failure of the life support system.

Table VI-6
Environmental Health

- •• Determine treatment of medical problems related to spacecraft inner temperature and adverse effects of the gaseous environment
- •• Determine procedures and approaches to prevent decompression sickness or minimize crew risks
- •• Determine risks and risk relationships among detectable gas emboli, mild limb bend symptoms that impair performance, and both CNS and cardiovascular systems that are life threatening under EVA conditions
- • Determine effects of long-duration space flight on the human immune system

• = Required for Mars
•• = Required for Moon and Mars

Research Requirements. There are several medical concerns related to environmental health which generate research requirements. A key concern relates to the medical consequences of continuous exposure to low level atmospheric contaminants. An obvious difference between Earth-based occupations and extended space missions is that individuals essentially live in the workplace, without the exposure relief that a terrestrial worker gets when leaving the job. Applicable exposure standards, treatment protocols and risk assessment protocols which take into account the changes in the immunological system will have to be developed. The physiological effects of long-term exposure to hypobaric, normoxic environments (should a reduced pressure spacecraft be selected) is an area of great uncertainty in aerospace medicine. The longest hypobaric U.S. mission to date was the 84-day

Skylab 4 mission. A related concern is the medical effects of extended habitation in a spacecraft with a degraded life support system.

6. Cell and Developmental Function

Critical issues in this area focus on providing the scientific knowledge necessary for development of procedures for risk management of pregnancy, osteoporosis, and hemorrhage; determination of whether microgravity effects can be reversed; characterization of the influence of radiation and microgravity effects on development of germ cells; and determination of the effects of gravity on compensatory endocrine, organ, circulatory, regenerative mechanisms, interaction with growth stages, and wound healing (Table VI-7).

Table VI-7
Cell and Development

- • Establish management procedures for premenopausal female crewmembers to minimize risk of pregnancy, osteoporosis, and hemorrhage
  -- What is the role of gravity in developmental biology?
- •• Determine effects of gravity on compensatory mechanisms (e.g., (endocrine, organ, circulatory, regenerative), interaction with growth stages, and wound healing
- •• Determine whether gravity-related effects exist and if they can be reversed
  -- What is the result of gravity-induced desynchronization during development?

• = Required for Mars
•• = Required for Moon and Mars

Estrogen enhances retention of bone minerals and reduces development of heart disease. It is therefore essential to maintain normal estrogen levels in female crewmembers. However, except in postmenopausal females, normal estrogen production is coupled to ovarian cycles and ovulation and thus there is the possibility of ruptured follicles or pregnancy. Both of these conditions entail significant risk and could become life-threatening in space, but could be prevented by oral birth control methods. However, experience on Earth indicates that those methods are not completely reliable. Recently available progesterone-derivative implants (i.e., "Norplant"), or gonadotrophic release hormone agonists coupled with low-dose triphasic steroid replacement, might be improvements. However, these hormone protocols may have changing dose requirements over time in the space environment, and therefore would require monitoring to allow for periodic adjustment of doses. Also, interactions between estrogen levels and microgravity effects may be synergistic in bone.

Research Requirements. Studies done in Soviet biosatellites suggest that embryogenesis is disrupted or altered by microgravity. This concern and the obvious problems of dealing with childbirth and childcare in the space environment make pregnancy contraindicated during space missions. Research concerns, therefore, are focused on the potential medical consequences of contraception in microgravity, i.e., formation of blood clots, osteoporosis, and behavioral effects. Another high level research concern relates to the function of individual cells in microgravity. Most studies have focused upon physiological systems, rather than cellular function. This is an important concern across a broad range of issues, including immune function; wound healing in various tissues (examples being corneal abrasions, skin lacerations, or bone fractures); drug transport across cellular membranes, inflammatory and allergic reactions; blood coagulation (vis a vis the role of cellular elements); and repair of damage from radiation. This is not a comprehensive list, but is a sample of potential concerns. In many cases, the demonstration of competence of cellular function in a given area (such as wound healing) will meet the research requirements. In other areas, such as osteogenesis, it may be necessary to understand the mechanics of cellular function in order to design effective countermeasures.

C. Advanced Medical Care Systems

U.S. and Soviet space programs have shown that medical contingencies do occur in flight. Most U.S. space flight medical care experience has been limited to minor ailments such as abrasions, contusions, colds, and space motion sickness. The medical care systems aboard Mercury, Gemini, and Apollo were essentially enhanced first aid kits equipped with bandages, ointments, drugs to treat a limited set of medical conditions, and instruments for medical exams. Skylab, an early second generation MCS, included provisions for minor surgery and dental procedures. The medical care facility planned for SSF, the Crew Health Care System (CHeCS), contains three subsystems: clinical care; exercise countermeasures; and environmental monitoring. Mature requirements for surgical facilities in space have not yet been established. This system is an advanced second generation of inflight medical care and requires significant technology development in the following areas (not an all-inclusive listing):

- Compact digital radiography
- Compact clinical chemistry analyzers
- Environmental monitoring technology (based on mass spectrometry)
- Medical data collection, storage, and transmission.

Exploration missions will require an unprecedented level of inflight medical care capability. Because of the extended duration, extreme distance from medical care facilities, hazards associated with operational tasks (EVA, EHA), and the delayed communications because of interplanetary distances. These systems will evolve from and build upon the clinical care systems used on SSF. These "third generation" medical systems will require significant technology development in key areas such as:

- Compact bone density imaging system
- Advanced telemedicine and telemetry capability for medical imaging (x-rays, scans), medical data, and text
- Computer-aided medical diagnostic, monitoring, and therapeutic systems
- Compact soft tissue imaging systems (presumably derivations of existing ultrasound imaging)
- Capacity to conduct major surgical procedures.

Advanced Biotechnology Development. While key elements of advanced hardware can be derived from existing terrestrial medical devices, some applications are unique to extended space flight and will require technology development efforts. For example:

- Extended shelf life (up to three years) pharmaceuticals
- Extended shelf life blood substitutes or blood (e.g., a lyophylized product)
- Research and development of liquid/gas separation devices. (Suction capability is needed for medical, surgical, and dental procedures)
- The ability to bank lymphocytes or derive biological products (lymphokineses). An advanced cell culture device (i.e., bioreactor) will be required. These cells will be required to bolster immune function in space, particularly after infection or radiation exposure
- Development of implanted ion selective electrodes and other sensors that allow continuous monitoring of key physiological parameters.

D. Robust Program

In addition to the constrained program as outlined, a robust program would include the following elements. These elements would limit the risk associated with long duration exploration missions to a greater degree than would the constrained program.

- Renal dialysis
- Skin grafting
- Enhanced major surgical capability (would include more invasive and complex procedures such as pinning bones). The exact menu of procedures included in constrained or robust programs would be determined in a trade study
- Advanced imaging and diagnostic capabilities, such as magnetic resonance imaging (MRI) or computerized tomography (CT) scans would be possible elements of a robust program. This also would be determined by trade studies
- Crew medical personnel would be different across the two programs. While even the constrained program would contain a physician (probably a surgeon), the robust program may be characterized by a second health care specialist, such as a psychologist or psychiatrist
- A robust program would be characterized by the ability to maintain crewmembers as inpatients for longer periods of time (up to six months) and would include the capability for extended parenteral (venous) feedings.

E. Requirements for Moon Exploration Missions

The medical care program for Moon missions would be similar to extended deep space missions, with the exception that provisions for certain types of injuries, more likely in the Moon environment, would be baselined. These might include treatment for crush injuries, electrical burns, or other types of occupational injuries that are more likely given the broad range of planetary surface activities planned for a Moon outpost. The exact set of capabilities would be determined by a detailed trade study and should be matched to the scope of surface activities. Because of the relatively short Moon recovery time (< 4 days). Moon medical care facilities, equipment, procedures, and protocols can build in an evolutionary fashion from SSF capabilities until they incorporate a full scale operational test of Mars mission capabilities.