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Medical Challenges in Space*

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NASA's Life Science Advisory Committee (LSAC) is comprised of physicians, physicists, physiologists, radiobiologists, and safety engineers as well as scientists in related fields. LSAC is concerned not only with maintaining the health of the astronauts in space but also with the survival and efficient performance of future space inhabitants. The Committee is also interested in the origin of life in the universe.

My experience as a member of LSAC, one of the most interesting of my medical career, enables me to review some of the major medical problems encountered in space travel. I will discuss what can be done about these problems, and describe some of the exciting plans to be implemented in space in the future.

Construction of a manned station in space has long been planned by NASA. In fact, during one of the recent space missions, the astronauts left the spacecraft and actually assembled various portions of prefabricated towers which eventually could be made into space stations. The demonstrated ability of astronauts to work in space outside the protected environment of the spacecraft indicates that space stations can be built in the future.

The proposed size of the initial space station is similar to the dimensions of a football field. The station includes living quarters and laboratory areas with solar panels for power generation and devices to detect both cosmic rays and X-radiation. The space station complex planned for construction in the mid-1990s (Fig 1) may now be delayed due to the recent explosion of the space shuttle Challenger. This space station will rotate in equatorial orbit while coorbiting platforms will occupy both the equatorial and polar orbits. Approximately six to eight people will be accommodated in the main space station with up to two people in the coorbiting platforms. A maneuvering spacecraft will be used to travel between the space station and these platforms. The astronauts will travel to and from earth and the completed space station, between the main space station and the coorbiting platforms, and ultimately to inhabited colonies on the moon and even to the outer planets.

Problems in Space Travel

Acceleration and deceleration

When the spacecraft Apollo re-entered the atmosphere head on, the impact approximated that of hitting a brick wall. This problem of sudden deceleration of the spacecraft has been greatly reduced in the space shuttle Challenger. Being maneuverable, the Challenger glided into the Earth's atmosphere, making the force of deceleration a great deal less than it was in earlier space flights.

The Ames Research Center in California conducts animal experiments relating to the problem of major acceleration during lift-off. A sled used in these experiments weighs over 200 pounds and is separated from a granite bed by an air cushion only one 80 millionth of an inch thick. The sled allows the effects of tremendous acceleration on experimental animals to be measured. Larger sleds of a similar nature are planned for use in humans.

Life support systems

It is relatively easy to maintain adequate concentrations of oxygen and carbon dioxide aboard the spacecraft. Although temperature control usually does not cause any major difficulty, maintaining proper humidity is sometimes a problem. Waste disposal is one of the most important as well as most difficult problems to solve. Recently, solid fecal waste products from animals used in experiments were found circulating in the ventilating system of the spacecraft. This of course was upsetting to all concerned, especially the astronauts. Millions of dollars have been spent trying to improve the waste disposal system on future spacecraft.

Microgravity

Zero gravity in space removes the stresses and strains from the skeletal system which leads to osteoporosis. Cardiac deconditioning along with peripheral muscle atrophy and weakness are other consequences of the loss of gravitational stress.

Radiation

Radiation is one of the most important risks to prolonged healthy survival in space. Radiation is particularly pronounced during solar flares, whose occurrence fortunately can be predicted. Future astronauts may have to enter a special area in the space station to be protected against increased radiation during the solar flares.

Prolonged isolation

Prolonged isolation is a critical problem in space travel. Imagine the difficulties that can occur in a small group of people, six to eight individuals, who travel to Mars. The flight to Mars will take about two years, the work on Mars will involve two to three months, and then the astronauts face two more years for the...
flight back to Earth. The emotional interactions between small
groups of people during such prolonged periods of time is of
great concern to NASA. The isolation experienced by indi­
viduals in the submarine service and by those who have spent the
winters in Antarctica has provided some knowledge, but much
work needs to be done by psychiatrists and psychologists who
study the interaction between small groups of people isolated
over a long period of time.

Medical emergencies
Medical emergencies that will occur in space travelers are
problems that pose more questions than answers. If an astronaut
is injured or has a serious illness such as a heart attack, what type
of medical facility is needed on the space station? We will need
to have a sick bay in the space station and a space ambulance
ready to rescue critically wounded or seriously ill personnel in
space. Various solutions to these medical emergencies are being
considered, but much more planning is needed.

Organ Systems Affected by Space Travel
Important organ systems affected by space travel include the
neurovestibular system with development of space motion sick­
ness, the cardiopulmonary system with the problem of cardiac
deconditioning, and the neuromuscular system with the develop­
of muscle atrophy and weakness. Important changes
also occur in the blood, especially problems in fluid and
electrolyte balance. A reduction of stress and strain on the
skeletal system leads to the development of bone thinning or
osteoporosis.

Neurovestibular system
Space travel seriously affects the neurovestibular system,
with about half of the astronauts developing space motion sick­
ness. Although the symptoms of vertigo, sweating, and vomit­
ning usually disappear within two to four days, the astronaut’s
function may be seriously impaired during these first days after
lift-off. While the mechanism producing space motion sickness
is unclear, one cause may be “sensory overload.” The vestibular
system, receiving input from the eyes, ears, cerebellum, cere­
brum, and various proprioceptive mechanisms throughout the
body during the early stages of space flight, may ultimately be­
come overloaded to the point of dysfunction. Another theory
suggests that fluid shifts from the lower extremities to the upper
part of the body increase fluid pressure within the semicircular
canals, stimulating the otoliths which in turn cause vomiting and
vertigo.

Considerable study is being devoted to the prevention of space
motion sickness. Various types of training, including parabolic
trajectory flights, have been employed. Flying a jet plane at

Fig 1—Space station complex early 1990. (From NASA. Reprinted with permission.)
a certain altitude and trajectory can induce a period of weightlessness for about 20 to 30 seconds. Many experiments are being carried out in this environment to study space motion sickness. Potential astronauts are flown in high performance aircraft, which are put through various aerobatic maneuvers to identify those individuals most susceptible to motion sickness. Various rotating chairs and rooms are also utilized in the study of this problem.

Pharmacologic agents such as antivert, scopolamine, and dextroamphetamine help to alleviate space motion sickness in some subjects. An astronaut who was on Space Lab I described his bout of space motion sickness as the most intense vertigo, vomiting, and sweating that he had ever experienced. His symptoms lasted for a period of 20 hours and virtually immobilized him. The combination of scopolamine and dextroamphetamine appeared to be helpful in alleviating the symptoms.

The employment of biofeedback is also under study to help individuals train themselves to alleviate space motion sickness. The use of various head restraints on board the spacecraft appears to be beneficial.

Research is also being conducted at the Ames Research Center to learn more about the mechanisms of space motion sickness. Experiments with small animals employ a precision tooled centrifuge which is free of noise and vibration. Tiny electrodes are placed in animals' vestibular nerve centers to study the neurovestibular connections and the disturbed functions which bring about space sickness. Various pharmacologic agents are then introduced in an attempt to prevent abnormal neurovestibular responses.

Cardiopulmonary system

Major problems affect the cardiopulmonary system during space travel. Significant orthostatic hypotension occurs soon after the astronauts arrive in space and again when they return to Earth. Changes in cardiac dynamics are readily demonstrated by the echocardiogram, and there are modest changes in pulmonary function and exercise capacity. These changes particularly occur during extravehicular activity outside the spacecraft.

Significant fluid shifts occur within the body during space travel. Approximately 1.5 to 2 litres of fluid move cephalad from the lower extremities to the central veins and the atrial chambers of the heart, which results in facial edema and a decrease in calf girth. Orthostatic intolerance is manifested by an increased heart rate, decreased pulse pressure, and a drop in blood pressure. These changes occur spontaneously but especially when the astronauts move from one position to another. These effects are the result of the fluid shift to and from the upper body as well as decreased plasma volume associated with living in space.

Cardiac changes have been studied intently with electrocardiograms and echocardiograms. The latter demonstrate an actual decrease in heart size when astronauts adjust to the space environment. This is probably due to a decreased work load on the heart. In zero gravity, less work is required of the myocardium to pump blood through the vascular system compared to the situation on Earth in a 1 g environment. After short space flights there has been complete recovery from this cardiovascular dysfunction, but whether there will be such complete recovery after prolonged space flights lasting several years is uncertain.

Blood, fluid, and electrolytes

Coincident with the cephalic shift of fluids from the lower extremities to the central veins and the atrial chambers of the heart, there is a decrease in plasma volume. Osteoporosis, a diuretic, has been interesting to note as a modest denominator for the bone marrow cavity. Bone may be depleted.

Fig 2 shows the fluid shifts from the lower extremities to the great veins entering the heart which results in facial edema and a decrease in calf girth. Orthostatic intolerance is manifested by an increased heart rate, decreased pulse pressure, and a drop in blood pressure. These changes occur spontaneously but especially when the astronauts move from one position to another. These effects are the result of the fluid shift to and from the upper body as well as decreased plasma volume associated with living in space.

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there is a decrease in plasma volume. There is evidence that the volume shift may stimulate secretion of the atrial natriuretic factor, a diuretic causing loss of water and sodium in the urine. An interesting change also occurs in the hematopoietic system, with a modest decrease in the circulating red cell mass. The mechanism for this is unclear; there may be some hypoplasia of the bone marrow, but the possibility exists that red cell survival time may be decreased in space. Further studies are needed.

Fig 2 depicts the fluid changes that occur with passage from 1 g on Earth to zero gravity, a period of adjustment, and then the return to 1 g on Earth. As astronauts enter space, blood and fluid shift from the lower extremities to the upper extremities and great veins entering the heart. Initially, the heart gets larger, then gradually adjusts in size, and ultimately becomes smaller with decreased diastolic filling volume. When the astronauts return to Earth, blood pooling in the lower extremities results in a further decrease in plasma volume and further orthostatic hypotension. Preloading the astronauts with water and salt several hours before their return to Earth can reduce the severity of the orthostatic changes.

Neuromuscular system

In Fig 3, as a dramatic illustration of weightlessness, a payload specialist is holding a mission specialist on one finger. Weightlessness "unloads" the muscular and skeletal systems. Since neither the muscular nor skeletal systems are needed in space, our structural system could possibly turn into an amorphous mass if humans stayed there long enough. Deterioration of muscle function in space is a major concern in prolonged space flights.

The muscle changes are characterized by a breakdown of muscle tissue with an increase in serum enzymes of muscle tissue and a negative nitrogen balance. The decrease in muscle size and strength occurs predominantly in the antigravity muscles. There are characteristic changes in the electromyogram as well as some alteration in the deep tendon reflexes. All these changes occur more severely with prolonged flights. The muscles recover after flights of only one or two months, but there is concern about full recovery after flights lasting for several years.

The changes occurring in the gastrocnemius of a rhesus monkey after a few months in space are illustrated in Figs 4 and 5. Fig 4 shows a normal muscle, while Fig 5 demonstrates a breakdown in the myofibrils. If this breakdown and possible replacement with fibrous tissue occurs in humans, muscle function may not ever fully recover after the astronauts' return to Earth.

When Russian astronauts returned to Earth after being in space approximately eight months, they were so weak they had to be carried from the spacecraft. These men had both deterioration of muscle function and osteoporosis. We are not sure how much recovery they have had, but we do expect to receive this information. The United States and Russia share information about medical problems in space flight.

Skeletal system

Osteoporosis may be one of the most serious biomedical hazards of prolonged space flights. This is particularly true as more older individuals and women, who are especially susceptible to osteoporosis, are sent into space.

Osteoporosis occurs mainly in the weight-bearing bones, the os calcis, and the spine. It is accompanied by an increase in urinary excretion of calcium, phosphorus, and hydroxyproline and in some instances mild hypercalcemia. If the astronauts stay in space for as long as one year, it is estimated that as much as 25% of the body pool of calcium will be lost. Whether there will be full recovery of this loss after the astronauts return to Earth is not certain.

The bone loss of space-related osteoporosis, which is sometimes called hypogravitational osteoporosis, has been compared to bed-rest osteoporosis. However, bed-rest osteoporosis appears to be different because on Earth the skeletal system and
Fig 4—Normal gastrocnemius muscle of a rhesus monkey. (From NASA. Reprinted with permission.)

Fig 5—Same muscle of rhesus monkey after a few months in space. (From NASA. Reprinted with permission.)
Space-related osteoporosis appears to be more severe and of a different nature than bed-rest osteoporosis. However, there are some similarities, and bed-rest experiments may give us important information that will help us understand space-related osteoporosis. When the astronauts return to Earth there is some recovery, at least a decrease in urinary calcium and hydroxyproline, but whether full recovery of the loss of skeletal mass occurs is not certain. Since astronauts have so many responsibilities after they return from space, it is sometimes difficult to carry out many of the important biomedical tests needed, including repeated measurements of bone mineral content.

Increased urinary calcium and hydroxyproline is evidence of increased bone resorption, but other evidence suggests that decreased bone formation may also be a factor in hypogravitational osteoporosis. This latter information has been derived primarily from studies in rodents. However, rodents are not a good model for studying osteoporosis in humans because the rodent bone remodeling system differs from that of man. In rodents, periosteal new bone growth is continuous, and for this reason, results of osteoporosis studies in rodents may not apply to human space travelers.

Various weightloading exercises have been recommended in an attempt to prevent or reduce the development of space-related osteoporosis. Although isometric exercises are not effective, exercising in the Bungee space suit may be helpful. The Bungee space suit is made in such a way that every body motion is resisted by a spring, inducing stress and strain on the muscles and skeletal system. The Russians found some improvement in muscle strength, with less muscle atrophy and less osteoporosis in the astronauts who used these Bungee suits. Unfortunately, it is difficult for the astronauts to use these space suits for the six to eight hours each day that may be necessary to achieve the desired effect, since the suits require a significant work effort and reduce efficiency. While these suits are a good theoretical approach to preventing space-related osteoporosis, they may not be practical in the long run.

Conceivably, artificial gravitational force can be utilized to prevent the occurrence of space-related osteoporosis. It has been shown that keeping small animals in a centrifuge deters the occurrence of space-related osteoporosis and muscle atrophy. When the space stations are eventually completed, creation of artificial gravity may be the means to avoid space-related muscle atrophy and osteoporosis as well as cardiac deconditioning.

Various types of dietary supplements have had minimal impact on preventing the skeletal complications. Increased concentrations of calcium and phosphorus as well as pharmacologic agents such as vitamin D and some of the diphosphonates have failed to prevent the occurrence of osteoporosis.

Members of the Life Science Advisory Committee have recommended to NASA authorities that bone biopsies need to be performed for essential studies of bone histomorphometric changes. There is considerable reluctance on the part of NASA about following this recommendation. The astronauts are very concerned that as few biomedical studies as possible be performed which might delay their future missions. Recently introduced space scientists, mission specialists, and payload specialists will be more willing to expedite performance of the necessary biomedical experiments needed for further understanding of medical problems in space.

Fig 6 demonstrates what happens to the tibia of an immobilized rhesus monkey which is similar to what may occur in space. Fig 6(A) is the control; and Fig 6(B), the tibia of a rhesus monkey after being immobilized for 10 weeks, illustrates increased resorption cavities in the cortical bone. Fig 6(C) shows the tibia of the monkey several months later, after the recovery process had begun. The resorption cavities have filled in but more dark bone is evident, indicating that this more recently formed bone is poorly mineralized at this point. Whether it will fully mineralize at a later time is uncertain. Further studies of this recovery process on primates and humans are necessary.

Bone undergoes constant remodeling. In the bone remodeling unit, cutting cones result in bone resorption and are followed by closing cones, which fill in the holes with new bone. A bone remodeling unit is initiated and another finished about every ten seconds in healthy human adults. Bone formation and resorption is normally coupled, and alterations in bone resorption are followed by changes in bone formation. This principle is essential to better understanding osteoporosis of all types and the results of the various therapeutic efforts for prevention. Thus, if we inhibit bone resorption with an agent such as estrogen, we will also inhibit bone formation. The treatment of osteoporosis cannot be limited to agents which reduce bone resorption alone; we also need to administer a substance that will stimulate bone formation.

For further study of space-related osteoporosis, humans and large primates are essential subjects. Interesting studies have been performed in space employing bone tissue cultures. This is interesting science, but it will not tell us much about the cause and correction of human osteoporosis because, again, bone resorption and bone formation are coupled phenomena.

Bone histomorphometric changes must be correlated with measurements of bone mineral content as well as changes in mineral homeostasis. Bone changes must also be correlated with the concentrations of the calcitropic hormones such as vitamin D, parathyroid hormone, and calcitonin. It is hoped that experiments of this kind can be completed in future space flights.

Although not yet proven, I believe that the initial pathologic event after the astronauts enter zero gravity occurs in the bone itself, and that changes in mineral homeostasis and the calcitropic hormones are secondary to this. It appears that zero gravity in some way stimulates bone resorption, possibly through altered bioelectrical fields or altered distribution of tension and pressure on bone cells themselves. It is possible that gravitational and muscular strains on the skeletal system cause friction between bone crystals which creates bioelectrical fields. This bioelectrical effect in some way may stimulate bone cells and affect bone remodeling.

To determine the initial change in bone after entering zero gravity, we need bone biopsies from individuals who have been in space for increasing periods of time. If we can determine the initial nature of the critical change in bone remodeling, we can try to introduce a bone antiresorptive agent at the appropriate time if increased resorption occurs first. Calcitonin or one of the
Fig 6—Cross sections of tibial cortical bone from rhesus monkeys. (A) Control group. (B) After 10 weeks of restraint. Note increased resorption cavities and loss in mass of bone (arrows). (C) Following restraint, and a six-month period of recovery, showing many dark areas of remodeling around osteons (arrows). (From NASA and D.R. Young. Reprinted with permission.)

Fig 7—Artist's impression of 21st century space colony with landscaped interior resembling Earth (From NASA/Science Photo Library. Reprinted with permission.)
diphosphonates may be effective, and estrogen might be benefi­
cial in females. For example, women astronauts could take es­
trogen for the first few weeks when entering space in an attempt
to prevent bone resorption.

We have come a long way in the study of various types of os­
teoporosis, particularly postmenopausal osteoporosis and age­
related osteoporosis. Not only do we better understand the
mechanisms of these forms of osteoporoses, we also know more
about how to prevent them. I believe it is just a matter of time
before we will understand the mechanisms of hypogravitational
osteoporosis and be able to find ways to prevent its occurrence.

In the long run, when artificial gravity can be introduced in the
large space stations, we may no longer have the problems of car­
diac deconditioning, peripheral muscle atrophy and weakness,
and osteoporosis.

The Future in Space

It has been suggested that in a 100 or so years from now as
many as 5,000 individuals may be living in space stations. Fig 7
represents an artist's conception of a future space station com­
plex, and Fig 8 is a model of a 21st century space colony. Ap­
proximately three or four miles in diameter, the space stations
will be turning constantly, providing artificial gravity. Soil ele­
ments will be brought in from either our own planet, the moon,
or from one of the asteroids. There will be fields, crops, animals
such as cows and goats, small communities, roads, and space­
mobiles for transportation. How soon this will all come about is
unknown, but we already have the science and the know-how. It
is just a matter of time and financial support until continuously
manned stations in space become a reality.