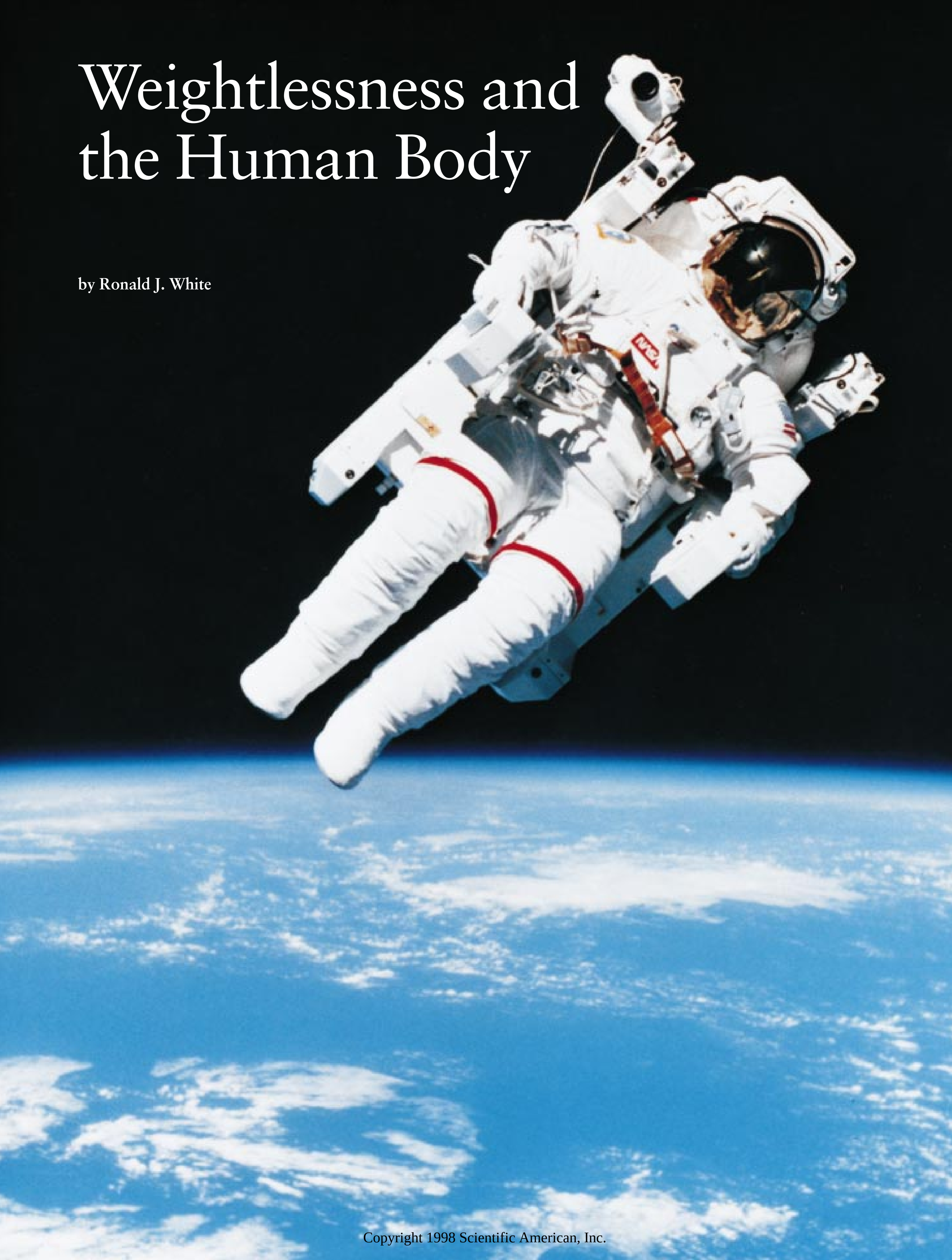

Weightlessness and the Human Body

by Ronald J. White

The effects of space travel on the body resemble some of the conditions of aging. Studying astronauts' health may improve medical care both in orbit and on the ground

When a healthy Valeri Polyakov climbed out of his *Soyuz* capsule on March 22, 1995, after a world-record 438 days on the Mir space station, he had demonstrated that humans can live and work in space for months at a time. It was not always clear that this would be the case.

In 1951, more than 10 years before Yuri Gagarin's first short flight (108 minutes), SCIENTIFIC AMERICAN published an article by Heinz Haber of the U.S. Air Force School of Aviation Medicine that anticipated many of the medical effects of space travel and, in particular, of weightlessness [see "The Human Body in Space," January 1951]. Some of his predictions, such as the occurrence of space motion sickness at the beginning of a flight, have been borne out. Others, such as the notion that space travelers would feel as if they were being jerked back and forth or that they would suddenly start to spin around during normal motion in space, have not.

As most doctors can attest, it is difficult to predict what will happen when a brand-new challenge is presented to the human body. Time and again, space travel has revealed its marvelous and sometimes subtle adaptive ability. But only in the past few years have scientists begun to understand the body's responses to weightlessness, as the data—the cumulative experience of nearly 700 people spending a total of 58 person-years in space—have grown in quantity and quality. Pursuit of this knowledge is improving health care not only for those who journey into space but also for those of us stuck on the ground. The unexpected outcome of space medicine has been an enhanced understanding of how the human body works right here on Earth.

Feeling Gravity's Pull

Although many factors affect human health during spaceflight, weightlessness is the dominant and single most important one. The direct and indirect effects of weightlessness precipitate a cascade of interrelated responses that begin in three different types of tissue: gravity receptors, fluids and weight-bearing structures. Ultimately, the whole body, from bones to brain, reacts.

When space travelers grasp the wall of their spacecraft and pull and push their bodies back and forth, they say it feels as though they are stationary and the spacecraft is moving. The reason is embedded in our dependence on gravity for perceptual information.

The continuous and pervasive nature of gravity removes it from our daily consciousness. But even though we are only reminded of gravity's invisible hand from time to time by, say, varicose veins or an occasional lightheadedness on standing up, our bodies never forget. Whether we realize it or not, we have evolved a large number of silent, automatic reactions to cope with the constant stress of living in a downward-pulling world. Only when we decrease or increase the effective force of gravity on our bodies do we consciously perceive it. Otherwise our perception is indirect.

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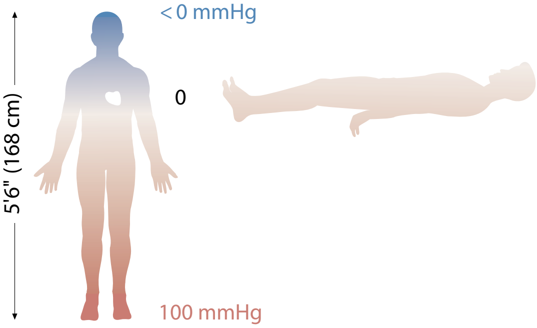
FREEDOM FROM WEIGHT, alluring though it is, has unfortunate side effects, such as motion sickness, head congestion and bone loss. On a space walk in 1984, Bruce McCandless II tried out NASA's new rocket pack—becoming the first astronaut to venture outside a spacecraft without a tether.

Our senses provide accurate information about the location of our center of mass and the relative positions of our body parts. This capability integrates signals from our eyes and ears with other information from the vestibular organs in our inner ear, from our muscles and joints, and from our senses of touch and pressure. Many of these signals are dependent on the size and direction of the constant terrestrial gravitational force.

The vestibular apparatus in the inner ear has two distinct components: the semicircular canals (three mutually perpendicular, fluid-filled tubes that contain hair cells connected to nerve fibers), which are sensitive to angular acceleration of the head; and the otolith organs (two sacs filled with calcium carbonate crystals embedded in a gel), which respond to linear acceleration. Because movement of the crystals in the otoliths generates the signal of acceleration to the brain and because the laws of physics relate that acceleration to a net force, gravity is always implicit in the signal. Thus, the otoliths have been referred to as gravity receptors. They are not the only ones. Mechanical receptors in the muscles, tendons and joints—as well as pressure receptors in the skin, particularly on the bottom of the feet—respond to the weight of limb segments and other body parts.

Removing gravity transforms these signals. The otoliths no longer perceive a downward bias to head movements. The limbs no longer have weight, so muscles are no longer required to contract and relax in the usual way to maintain posture and bring about movement. Touch and pressure receptors in the feet and ankles no longer signal the direction of down. These and other changes contribute to visual-orientation illusions and feelings of self-inversion, such as the feeling that the body or the spacecraft spontaneously reorients. In 1961 cosmonaut Gherman Titov reported vivid sensations of being upside down early in a spaceflight of only one day. Last year shuttle payload specialist Byron K. Lichtenberg, commenting on his earlier flight experiences, said, "When the main engines cut off, I immediately felt as though we had flipped 180 degrees." Such illusions can recur even after some time in space.

The lack of other critical sensory cues also confuses the brain. Although orbital flight is a perpetual free fall—the only difference from skydiving is that the spacecraft's forward velocity carries it around the curve of the planet—space travelers say they do not feel as if they are falling. The perception of falling probably depends on visual and airflow cues along with information from the direct gravity receptors. This contradicts a prediction made in 1950 by Haber



DMITRY KRASNY

HYDROSTATIC PRESSURE in blood vessels changes dramatically when a person stands up. Pressure increases with depth below the heart, up to 100 millimeters of mercury (mmHg) in a person of average height; above the heart, pressure decreases. As a result, fluid settles into the lower body and blood flow diminishes. Conversely, in a prone position (or in weightlessness), pressure equalizes and fluid sloshes into the upper body.

and his colleague Otto H. Gauer: "In the absence of gravity there would necessarily be a sensation of falling in free space. It is expected that one would gradually get accustomed to this state."

The aggregate of signal changes produces, in half or more of space travelers, a motion sickness that features many of the symptoms of terrestrial motion sickness: headache, impaired concentration, loss of appetite, stomach awareness, vomiting. Space motion sickness usually does not last beyond the first three days or so of weightlessness, but something similar has been reported by cosmonauts at the end of long flights.

At one time, scientists attributed space motion sickness to the unusual pattern of vestibular activity, which conflicts with the brain's expectations. Now it is clear that this explanation was simplistic. The sickness results from the convergence of a variety of factors, including the alteration of the patterns and levels of motor activity necessary to control the head itself. A similar motion sickness can also be elicited by computer systems designed to create virtual environments, through which one can navigate without the forces and sensory patterns present during real motion [see News and Analysis, "Virtual Reality Check," by W. Wayt Gibbs; Scientific American, December 1994].

Over time, the brain adapts to the new signals, and for some space travelers, "down" becomes simply where the feet are. The adaptation probably involves physiological changes in both receptors and nerve-cell patterns. Similar changes occur on the ground during our growth and maturation and during periods of major body-weight changes.

The way we control our balance and avoid falls is an important and poorly understood part of physiology. Because otherwise healthy people returning from space initially have difficulty maintaining their balance but recover this sense rapidly, postflight studies may allow doctors to help those non–space travelers who suffer a loss of balance on Earth.

Bernard Cohen of the Mount Sinai School of Medicine and Gilles Clément of the National Center for Scientific Research in Paris undertook just such a study after the Neurolab shuttle mission, which ended on May 3. To connect this work with patients suffering from balance disorders, Barry W. Peterson of Northwestern University and a team of researchers, supported by the National Aeronautics and Space Administration and the National Institutes of Health, are creating the first whole-body computer model of human posture and balance control.

Space Sniffles

The second set of weightlessness effects involves body fluids. Within minutes of arriving in a weightless environment, a traveler's neck veins begin to bulge, and the face begins to fill out and become puffy. As fluid migrates to the chest and head, sinus and nasal congestion results. This stuffiness, which is much like a cold on Earth, continues for the entire flight, except during heavy exercise, when the changing fluid pressures in the body relieve the congestion temporarily. Even the senses of taste and smell are altered; spicy food retains its appeal best. In the early days of spaceflight, doctors feared that the chest congestion might be dangerous, much as pulmonary edema is to cardiac patients; fortunately, this has not been the case.

All these events occur because the fluids in the body no longer have weight. On average, about 60 percent of a person's weight is water, contained in the cells of the body (intracellular fluid), in the arteries and veins (blood plasma) and in the spaces between the blood vessels and cells (interstitial fluid). On Earth, when a person stands up, the weight of this water exerts forces throughout the body. In the vascular system, where the fluid columns are directly connected, blood pressure increases hydrostatically, just as pressure increases with depth in water. For a quietly standing individual, this hydrostatic effect can be quite large. In the feet, both arterial and venous pressures can increase by approximately 100 millimeters of mercury—double the normal arterial pressure and many times the normal venous pressure. At locations above the feet but below the heart, the pressure increases by zero to 100 millimeters of mercury. Above the heart, arterial and venous pressure fall below atmospheric pressure [*see illustration at left*].

The hydrostatic effect has only a small influence on blood flow through tissue because both arterial and venous pressures increase by the same amount. But it does affect the distribution of fluid within the body by increasing the amount of blood that leaks from capillaries into the interstitial space. Going from a prone to a standing position moves fluid into the lower part of the body and reduces the flow of blood back to the heart. If unchecked, quiet standing can lead to fainting; soldiers sometimes swoon when standing at attention. Two other hydrostatic effects are varicose veins, which have become permanently distorted by the extra fluid, and swollen feet after long periods of quiet sitting (such as an airplane flight).

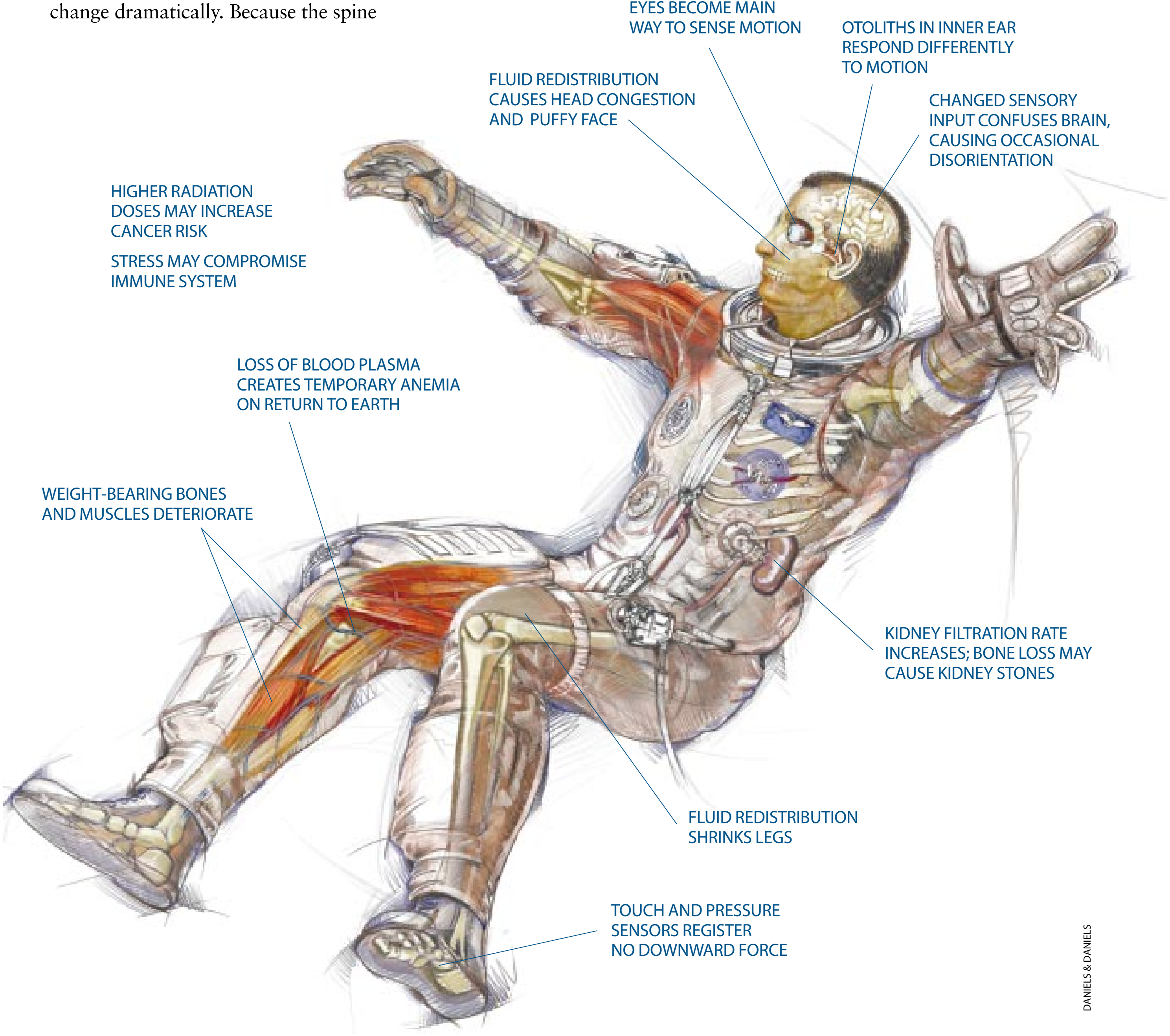
In space, the hydrostatic pressure disappears, causing fluids to redistribute naturally from the lower to the upper body. Direct measurements of leg volumes have shown that each leg loses about one liter of fluid—about a tenth of its volume—within the first day. The legs then stay smaller for the whole time in space. (Actually, fluids begin to shift toward the head while space travelers are still on the launch pad, because they sit for several hours in couches that elevate their feet above their heads.) As fluid moves around, the body adapts by further redistributing water among its compartments. Plasma volume decreases rapidly (by nearly 20 percent) and stays low.

These fluid shifts in turn initiate a cascade of interacting renal, hormonal and mechanical mechanisms that regulate fluid and electrolyte levels. For example, the kidney filtration rate, normally stable, increases by nearly 20 percent and remains at that level for the first week in space. In addition, returning space travelers have a special form of anemia, even after flights as short as a few days. Over the past few years, Clarence Alfrey of the Baylor College of Medicine has shown that the loss of plasma and the concomitant decrease in vascular space lead to an overabundance of red blood cells. The body responds by stopping production of and destroying new red blood cells—using a mechanism that was not fully appreciated by hematologists before Alfrey's research on space travelers.

A third set of effects caused by weightlessness relates to muscle and bone. People who travel in space for any length of time come home with less of both. Is this a cause for concern?

During weightlessness, the forces within the body's structural elements change dramatically. Because the spine is no longer compressed, people grow taller (two inches or so). The lungs, heart and other organs within the chest have no weight, and as a result, the rib cage and chest relax and expand. Similarly, the weights of the liver, spleen, kidneys, stomach and intestines disappear. As F. Andrew Gaffney said after his 1991 flight: "You feel your guts floating up. I found myself tightening my abdomen, sort of pushing things back."

Meanwhile muscles and bones come to be used in different ways. Skeletal muscle, the largest tissue in the body, evolved to support our upright posture and to move body parts. But in space, muscles used for antigravity support on the ground are no longer needed for that purpose; moreover, the muscles used for movement around a capsule differ from those used for walking down a hall. Consequently, some muscles atrophy rapidly. At the same time, the nature of the muscle itself alters, changing from certain slow-twitch fibers that are useful for support against gravity to



The Effects of Space Travel on the Body

DANIELS & DANIELS

NASA

LYING IN BED mimics weightlessness in its effect on the human body. At the NASA Ames Research Center, volunteers lie head-down at a six-degree angle—which, over a period of weeks, is not as comfortable as it might look. Fluids drain from the legs to the upper body, muscles atrophy and bones weaken. These subjects try out various restorative exercises, diets and drugs. Seated on the right is astronaut Charles Brady, who carried out medical tests during a 1996 Spacelab mission.

faster contractile fibers, useful for rapid response. None of these changes presents a problem to space travelers as long as they perform only light work. But preventing the atrophy of muscles required for heavy work during space walks and preserving muscle for safe return to Earth are the subject of much current experimentation.

Bone metabolism, too, changes substantially. One of the strongest known biological materials, bone is a dynamic tissue. Certain cells, the osteoblasts, have the job of producing it, whereas others, the osteoclasts, destroy it. Both usually work harmoniously to rebuild bones throughout life. These cellular systems are sensitive to various hormones and vitamins in the blood and to mechanical stress on the bone.

Bone contains both organic materials, which contribute strength and stability, and inorganic materials, which contribute stiffness and serve as a mineral reservoir within the body. For example, 99 percent of the calcium in the body is in the skeleton. Stabilized calcium levels in the body's fluids are necessary for all types of cells to function normally.

Joint Russian-American studies have shown that cosmonauts have lost bone mass from the lower vertebrae, hips and upper femur at a rate of about 1 percent per month for the entire duration of their missions. Some sites, such as the heel, lose calcium faster than others. Studies of animals subjected to spaceflight suggest that bone formation also declines.

Needless to say, these data are indeed cause for concern. During spaceflight, the loss of bone elevates calcium levels in the body, potentially causing kidney stones and calcification in soft tissues. Back on the ground, the bone calcium loss stops within one month, but scientists do not yet know whether the bone recovers completely: too few people have flown in space for long periods. Some bone loss may be irreversible, in which case ex-astronauts will always be more prone to broken bones. A 1996 Spacelab mission was partly devoted to these questions; a team of scientists from Italy, Sweden, Switzerland and the U.S. carried out eight investigations related to muscle and bone changes.

These uncertainties mirror those in our understanding of how the body works here on Earth. For example, after menopause women are prone to a loss of bone mass—osteoporosis. Scientists understand that many different factors (activity, nutrition, vitamins, hormones) can be involved in this loss, but they do not yet know how the factors act and interact. This complexity makes it difficult to develop an appropriate response. So it is with bone loss in space, where the right prescription still awaits discovery. Up to now, various types of exercise have been tried [see "Six Months on Mir," by Shannon W. Lucid; Scientific American, May] with little verified success.

NASA MARSHALL SPACE FLIGHT CENTER

VIGOROUS EXERCISE, typically lasting several hours, is a daily routine for astronauts. Terence T. Henricks works out on the shuttle *Atlantis* in 1991, while Mario Runco, Jr., wired with medical sensors, waits on deck. Although such exertion may slow atrophy of muscles, its effectiveness is still not clear.

Heavy Breathing

Disorientation, fluid redistribution, and muscle and bone loss are not the only consequence of weightlessness. Other body systems are affected directly and indirectly. One example is the lung.

John B. West and his group at the University of California at San Diego, along with Manuel Paiva of the Free University of Brussels, have studied the lung in space and learned much they could not have learned in earthbound laboratories. On the ground the top and bottom parts of the lung have different patterns of airflow and blood flow. But are these patterns the result only of gravity or also of the nature of the lung itself? Only recently have studies in space provided unequivocal evidence for the latter. Even in the absence of gravity, different parts of the lung have different levels of airflow and blood flow.

Not everything that affects the body during spaceflight is related solely to weightlessness. Also affected, for example, are the immune system (the various physical and psychological stresses of spaceflight probably play roles in the immunodeficiency experienced by astronauts) and the multiple systems responsible for the amount and quality of sleep (lighting levels and work schedules disrupt the body's normal rhythms). Looking out the spacecraft window just before retiring (an action difficult to resist, considering the view) can let enough bright light into the eye to trigger just the wrong physiological response, leading to poor sleep. As time goes on, the sleep debt accumulates.

For long space voyages, travelers must also face confinement in a tight volume, unable to escape, isolated from the normal life of Earth, living with a small, fixed group of companions who often come from different cultures. These challenges can lead to anxiety, insomnia, depression, crew tension and other interpersonal issues, which affect astronauts just as much as weightlessness—perhaps even more. Because these factors operate at the same time the body is adapting to other environmental changes, it may not be clear which physiological changes result from which factors. Much work remains to be done.

Finally, spaceflight involves high levels of radiation. An astronaut spending one year in a moderately inclined, low-Earth orbit would receive a radiation dose 10 times greater than the average dose received on the ground. A year's stay on the moon would result in a dose seven times higher still, whereas a flight to Mars would be even worse. Sudden outflows of particles from the sun, of the type that occurred in August 1972, can deliver a dose more than 1,000 times the annual ground dose in less than a day. Fortunately, such events are rare, and spacecraft designers can guard against them by providing special shielded rooms to which astronauts can temporarily retreat.

Obviously, the radiation hazard to long-duration space travelers—and the consequent cancer risk—is disconcerting. The problems of space radiation are difficult to study because it is nearly impossible to duplicate on Earth the radiation environment of space, with its low but steady flux of high-energy cosmic rays. Even so, researchers generally believe that with proper shielding and protective drugs, the risks can be brought within acceptable limits.

Down to Earth

When space travelers return to the world of weight, complementary changes occur. If the effects of weightlessness are completely reversible, everything should return to its normal condition at some time after the flight. We now know that most systems in the body do work reversibly, at least over the intervals for which we have data. We do not yet know whether this is a general rule.

Space travelers certainly feel gravitationally challenged during and just after their descent. As one person said after nine days in space: "It's quite a shock. The first time I pushed myself up, I felt like I was lifting three times my weight." Returning space travelers report experiencing a variety of illusions—for example, during head motion it is their surroundings that seem to be moving—and they wobble while trying to stand straight, whether their eyes are open or closed.

Most of the body's systems return to normal within a few days or weeks of landing, with the possible exception of the musculoskeletal system. So far nothing indicates that humans cannot live and work in space for long periods and return to Earth to lead normal lives. This is clearly good news for denizens of the upcoming International Space Station and for any future interplanetary missions. In fact, the station, assembly of which should begin late this year or early next year, will provide researchers with a new opportunity to investigate the effects of space travel on humans. On its completion in five years, the station will have 46,000 cubic feet of work space (nearly five times more than the Mir or Skylab stations) and will include sophisticated laboratory equipment for the next generation of medical studies. Recognizing the need for a comprehensive attack on all the potential human risks of long-duration space travel, NASA has selected and funded a special research body, the National Space Biomedical Research Institute, to assist in defining and responding to those risks.

Many of the "normal" changes that take place in healthy people during or just after spaceflight are outwardly similar to "abnormal" events occurring in ill people on Earth. For example, most space travelers cannot stand quietly for 10 minutes just after landing without feeling faint. This so-called orthostatic intolerance is also experienced by patients who have stayed in bed for a long time and by some elderly people. Prolonged bed rest also results in muscle and bone wasting. The parallel is so close that bed rest is used to simulate the effects of spaceflight [*see top illustration on opposite page*].

Other age-related changes in function also seem to match changes caused by spaceflight. The wobbliness following flight resembles the tendency of the elderly to fall; the loss of bone during flight is analogous to age-related osteoporosis; immunodeficiency, poor sleep quality and loss of motor coordination afflict both astronauts and the elderly. Although parallels in symptoms do not imply parallels in cause, the data are so striking that NASA and the National Institute on Aging began an investigative collaboration in 1989. The flight in October of Senator John Glenn of Ohio, the oldest person ever scheduled to fly in space, should draw more attention to the ongoing research in this area. SA

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JOHN GLENN, astronaut turned senator turned astronaut again, emerges from a shuttle-training mock-up in 1989. Glenn is due to fly on board the shuttle *Discovery* in late October. Some of the medical effects of space travel resemble the symptoms of aging, such as poor sleep quality; Glenn, 77, will participate in sleep experiments.

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Further Reading

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