Astronaut Health and Performance

Introduction
Helen Lane
Laurence Young

How Humans Adapt to Spaceflight: Physiological Changes

Vision, Orientation, and Balance
William Paloski

Sleep
Laura Barger
Charles Czeisler

Muscle and Exercise
John Charles
Steven Platts
Daniel Feeback
Kenneth Baldwin
Judith Hayes

Cardiovascular
John Charles
Steven Platts

Nutritional Needs in Space
Helen Lane
Clarence Alfrey
Scott Smith

Immunology and Infectious Diseases
Brian Crucian
Satish Mehta
Mark Ott
Duane Pierson
Clarence Sams

Habitability and Environmental Health

Habitability
Janis Connolly
David Fitts
Dane Russo
Vickie Kloeris

Environmental Health
John James
Thomas Limero
Mark Ott
Chau Pham
Duane Pierson

Astronaut Health Care
Philip Stepaniak

Human travel to Mars and beyond is no longer science fiction. Through shuttle research we know how the body changes, what we need to do to fix some of the problems or—better yet—prevent them, the importance of monitoring health, and how to determine the human body's performance through the various sequences of launch, spaceflight, and landing. Basically, we understand how astronauts keep their performance high so they can be explorers, scientists, and operators.

Astronauts change physically during spaceflight, from their brain, heart, blood vessels, eyes, and ears and on down to their cells. Many types of research studies validated these changes and demonstrated how best to prevent health problems and care for the astronauts before, during, and after spaceflight.

*During a shuttle flight, astronauts experienced a multitude of gravitational forces. Earth is 1 gravitational force (1*g*); however, during launch, the forces varied from 1 to 3*g*. During a shuttle's return to Earth, the forces varied from nearly zero to 1.6*g*, over approximately 33 minutes, during the maneuvers to return. In all, the shuttle provided rather low gravitational forces compared with other rocket-type launches and landings.*

The most pervasive physiological human factor in all spaceflight, however, is microgravity. An astronaut perceives weightlessness and floats along with any object, large or small. The microgravity physiological changes affect the human body, the functions within the space vehicle, and all the fluids, foods, water, and contaminants.

We learned how to perform well in this environment through the Space Shuttle Program. This information led to improvements in astronauts' health care not only during shuttle flights but also for the International Space Station (ISS) and future missions beyond low-Earth orbit. Shuttle research and medical care led directly to improved countermeasures used by ISS crew members. No shuttle mission was terminated due to health concerns.

How Humans Adapt to Spaceflight: Physiological Changes

Vision, Orientation, and Balance Change in Microgravity

Gravity is critical to our existence. As Earthlings, we have come to rely on Earth's gravity as a fundamental reference that tells us which way is down. Our very survival depends on our ability to discern down so that we can walk, run, jump, and otherwise move about without falling. To accomplish this, we evolved specialized motion-sensing receptors in our inner ears—receptors that act like biological guidance systems. Among other things, these receptors sense how well our heads are aligned with gravity. Our brains combine these data with visual information from our eyes, pressure information from the soles of our feet (and the seats of our pants), and position and loading information from our joints and muscles to continuously track the orientation of our bodies relative to gravity. Knowing this, our brains can work out the best strategies for adjusting our muscles to move our limbs and bodies about without losing our balance. And, we don't even have to think about it.

At the end of launch phase, astronauts find themselves suddenly thrust into the microgravity environment. Gravity, the fundamental up/down reference these astronauts relied on throughout their lives for orientation and movement, suddenly disappears. As you might expect, there are a number of immediate consequences. Disorientation, perceptual illusions, motion sickness, poor eye-head/eye-hand coordination, and whole-body movements are issues each astronaut has to deal with to some degree.

One thing we learned during the shuttle era, though, is that astronauts' nervous systems adapt very quickly. By the third day of flight, most crew members overcame the loss of gravitational stimulation. Beyond that, most exhibited few functionally significant side effects. The downside to this rapid adaptation was that, by the time a shuttle mission ended and the astronauts returned to Earth, they had forgotten how to use gravity for orientation and movement. So, for the first few days after return, they suffered again from a multitude of side effects similar to those experienced at the beginning of spaceflight. During the Earth-readaptation period, these postflight affects limited some types of physical activities, such as running, jumping, climbing ladders, driving automobiles, and flying planes.

The Space Shuttle—particularly when carrying one of its Spacelab or Spacehab modules and during the human-health-focused, extended-duration Orbiter medical missions (1989 through 1995)—provided unique capabilities to study neurological adaptation to space. By taking advantage of the shuttle's ability to remove and then reintroduce the fundamental spatial orientation reference provided by gravity, many researchers sought to understand the brain mechanisms responsible for tracking and responding to this

Laurence Young, ScD
Principal investigator or coinvestigator on seven space missions, starting with STS-9 (1983).
Alternate payload specialist on STS-58 (1993).
Founding director of the National Space Biomedical Research Institute.
Apollo Program professor of astronautics and professor of health sciences and technology at Massachusetts Institute of Technology.

"The Space Shuttle Program provided a golden era for life sciences research. The difference between science capabilities on spacecraft before and after the Space Shuttle is enormous: it was like doing science in a telephone booth in the Gemini-Apollo era while shuttle could accommodate a school-bus-size laboratory. This significantly added to the kind of research that could be done in space. We had enormous success in life sciences, especially with the Spacelabs, for quality of instrumentation, their size, and opportunity for repeated measurements on the astronauts on different days of flight and over many different flights including Space Life Sciences flights 1 and 2 and ending with Neurolab.

"Our research led to a much more complete understanding of the neurovestibular changes in spaceflight and allowed us to know what issues require countermeasures or treatment, such as space motion sickness, as well as what research needed to continue in Earth laboratories, such as the role of short radius centrifuges for intermittent artificial gravity to support a Mars exploration mission."

stimulus. Other researchers used these stimuli to investigate fundamental and functional aspects of neural adaptation, while others focused on the operational impacts of these adaptive responses with an eye toward reducing risks to space travelers and enabling future missions of longer duration.

Space Motion Sickness

What Is Space Motion Sickness?

Many people experience motion sickness while riding in vehicles ranging from automobiles to airplanes to boats to carnival rides. Its symptoms include headache, pallor, fatigue, nausea, and vomiting. What causes motion sickness is unknown, but it is clearly related to the nervous system and almost always involves the specialized motion-sensing receptors of the inner ear, known as the vestibular system.

The most popular explanation for motion sickness is the sensory-conflict theory. This theory follows from observations that in addition to planning the best strategies for movement control, the brain also anticipates and tracks the outcome of the movement commands it issues to the muscles. When the tracked outcome is consistent with the anticipated outcome, everything proceeds normally; however, when the tracked outcome is inconsistent, the brain must take action to investigate what has gone wrong. Sensory conflict occurs when some of the sensory information is consistent with the brain's anticipated outcome and some information is inconsistent. This might occur in space, for example, when the brain commands the neck muscles to tilt the head. The visual and neck joint receptors would provide immediate feedback indicating that the head has tilted, but because gravity has been reduced, some of the anticipated signals from the inner ear would not arrive. Initially, this would cause confusion, disorientation, and motion sickness symptoms. Over time, however, the brain would learn not to anticipate this inner-ear information during head tilts and the symptoms would abate.

How Often Do Astronauts Have Space Motion Sickness?

Many astronauts report motion sickness symptoms just after arrival in space and again just after return to Earth. For example, of the 400 crew members who flew on the shuttle between 1981 and 1998, 309 reported at least some motion sickness symptoms, such as stomach awareness, headache, drowsiness, pallor, sweating, dizziness, and, of course, nausea and vomiting. For most astronauts, this was a short-term problem triggered by the loss of gravity stimuli during ascent to orbit and, again, by the return of gravity stimuli during descent back to Earth. It usually lasted only through the few days coinciding with neural adaptations to these gravity transitions. While the symptoms of space motion sickness were quite similar to other types of motion sickness, its incidence was not predicted by susceptibility to terrestrial forms, such as car sickness, sea sickness, air sickness, or sickness caused by carnival rides. To complicate our understanding of the mechanisms of space motion sickness further, landing-day motion sickness was not even predicted by the incidence or severity of early in-flight motion sickness. The only predictable aspect was that repeat flyers usually had fewer and less severe symptoms with each subsequent flight.

How Do Astronauts Deal With Space Motion Sickness?

Crew members can limit head movements during the first few days of microgravity and during return to Earth to minimize the symptoms of space motion sickness. For some astronauts, drugs are used to reduce the symptoms. Promethazine-containing drugs emerged as the best choice during the early 1990s, and were frequently used throughout the remaining shuttle flights. Scientists also investigated preflight adaptation training in devices that simulate some aspects of the sensory conflicts during spaceflight, but more work is necessary before astronauts can use this approach.

Some crew members experience height vertigo or acrophobia during extravehicular activities. Astronaut Stephen Robinson is anchored by a foot restraint on the International Space Station Robotic Arm during STS-114 (2005).

Dafydd (Dave) Williams, MD
Canadian astronaut on STS-90 (1998) and STS-118 (2007).

"Humans adapt remarkably well to the physiologic challenges associated with leaving the Earth's gravitational environment. For me, these started at main engine cutoff. After 7 minutes of the 8½-minute ride, G forces pushed me like an elephant sitting on my chest. The crushing pressure resolved as I was thrown forward against my harness when the main engines shut down. This created a sense of tumbling, head over heels, identical to performing somersaults as a child. I pulled myself down in the shuttle seat to re-create the gravitational sense of sitting in a chair and the tumbling stopped. I had experienced my first illusion of spaceflight!

"On the first day, many changes took place. My face felt puffy. I had a mild headache. Over the first few days, I experienced mild low back pain. Floating freely inside the shuttle with fingertip forces gently propelling us on a somewhat graceful path reminded me of swimming underwater—with the notable absence of any resistance.

"During re-entry into the Earth's atmosphere, I felt the forces of gravity gradually building. Standing on the middeck after landing, I felt gravitationally challenged. As I walked onto the crew transfer vehicle I felt as though my arms weighed twice what they normally do. Moving my head created an instant sense of vertigo.

"On my second spaceflight, when I arrived in space it seemed like I had never left and as I floated gracefully, looking back at Earth, it reminded me that I will always remain a spacefarer at heart."

Spatial Disorientation: Which Way Is Down?

Astronauts entering the microgravity environment of orbital spaceflight for the first time report many unusual sensations. Some experience a sense of sustained tumbling or inversion (that is, a feeling of being upside down). Others have difficulty accepting down as being the direction one's feet are pointing, preferring instead to consider down in terms of the module's orientation during preflight training on the ground. Almost all have difficulty figuring out how much push-off force is necessary to move about in the vehicle. While spacewalking (i.e., performing extravehicular activities [EVAs]), many astronauts report height vertigo—a sense of dizziness or spinning—that is often experienced by individuals on Earth when looking down from great heights. Some astronauts also experienced transient acrophobia—an overwhelming fear of falling toward Earth—which can be terrifying.

After flight, crew members also experience unusual sensations. For example, to many crew members everyday objects (e.g., apples, cameras) feel surprisingly heavy. Also, when walking up stairs, many experience the sensation that they are pushing the stairs down rather than pushing their bodies up. Some feel an overwhelming sense of translation (sliding to the side) when rounding corners in a vehicle. Many also have difficulty turning corners while walking, and some experience difficulty while bending over to pick up objects. Early after return to Earth, most are unable to land from a jump; many report a sensation that the ground is coming up rapidly to meet them. For the most part, all of these sensations abate within a few days; however, there have been some reports of "flashbacks" occurring, sometimes even weeks after a shuttle mission.

Eye-Hand Coordination: Changes in Visual Acuity and Manual Control

Manual control of vehicles and other complex systems depends on accurate eye-hand coordination, accurate perception of spatial orientation, and the ability to anticipate the dynamic response of the vehicle or system to manual inputs. This function was extremely important during shuttle flights for operating the Shuttle Robotic Arm, which required high-level coordination through direct visual, camera views, and control feedback. It was also of critical importance to piloting the vehicle during rendezvous, docking, re-entry, and landing.

Clear vision begins with static visual acuity (that is, how well one can see an image when both the person and the image are stationary). In most of our daily activities, however, either we are

Eye-Hand Coordination

Payload specialist James Pawelczyk, STS-90 (1998).

Catching a ball is easy for most people on Earth. Yet, we don't usually realize how much work our brains do to predict when and where the ball will come down, get our hand to that exact place at the right time, and be sure our fingers grab the ball when it arrives. Because of the downward acceleration caused by gravity, the speed of a falling object increases on Earth. Scientists think that the brain must anticipate this to be able to catch a ball. Objects don't fall in space, however. So, scientists wondered how well people could catch objects without gravity. To find out, astronauts were asked to catch balls launched from a spring-loaded canon that "dropped" them at a constant speed rather than a constant acceleration as on Earth. In flight, the astronauts always caught the balls, but their timing was a little bit off. They reacted as if they expected the balls to move faster than they did, suggesting that their brains were still anticipating the effects of gravity. The astronauts eventually adapted, but some of the effects were still evident after 15 days in space. After flight, the astronauts were initially surprised by how fast the balls fell, but they readapted very quickly. This work showed that, over time in microgravity, astronauts could make changes in their eye-hand coordination, but that it took time after a gravity transition for the brain to accurately anticipate mechanical actions in the new environment.

moving or the object we wish to see is moving. Under these dynamic visual conditions, even people with 20/20 vision will see poorly if they can't keep the image of interest stabilized on their retinas. To do this while walking, running, turning, or bending over, we have evolved complex neural control systems that use information from the vestibular sensors of the inner ear to automatically generate eye movements that are equal and opposite to any head movements. On Earth, this maintains a stable image on the retina whenever the head is moving.

Since part of this function depends on how the inner ear senses gravity, scientists were interested in how it changes in space. Many experiments performed during and just after shuttle missions examined the effects of spaceflight on visual acuity. Static visual acuity changed mildly, mainly because the headward fluid shifts during flight cause the shape of the eyes to change. Dynamic visual acuity, on the other hand, was substantially disrupted early in flight and just after return to Earth. Even for simple dynamic vision tasks, such as pursuing a moving target without moving the head, eye movements were degraded. But the disruption was found to be greatest when the head was moving, especially in the pitch plane (the plane your head moves in when you nod it to indicate "yes"). Scientists found that whether pursuing a target, switching vision to a new target of interest (the source of a sudden noise, for instance), or tracking a stationary target while moving (either voluntarily or as a result of vehicle motion), eye movement control was inaccurate whenever the head was moving.

Vision (eye movements) and orientation perceptions are disrupted during spaceflight. Scientists found that some kinds of anticipatory actions are inaccurate during flight. The impact of these changes on shuttle operations was difficult to assess. For example, while it appears that some shuttle landings were not as accurate as preflight landings in the Shuttle Training Aircraft, many confounding factors (such as crosswinds and engineering anomalies) precluded rigorous scientific evaluation. It appears that the highly repetitive training crew members received just before a shuttle mission might have helped offset some of the physiological changes during the flight. Whether the positive effects of this training will persist through longer-duration flights is unknown. At this point, training is the only physiological countermeasure to offset these potential problems.

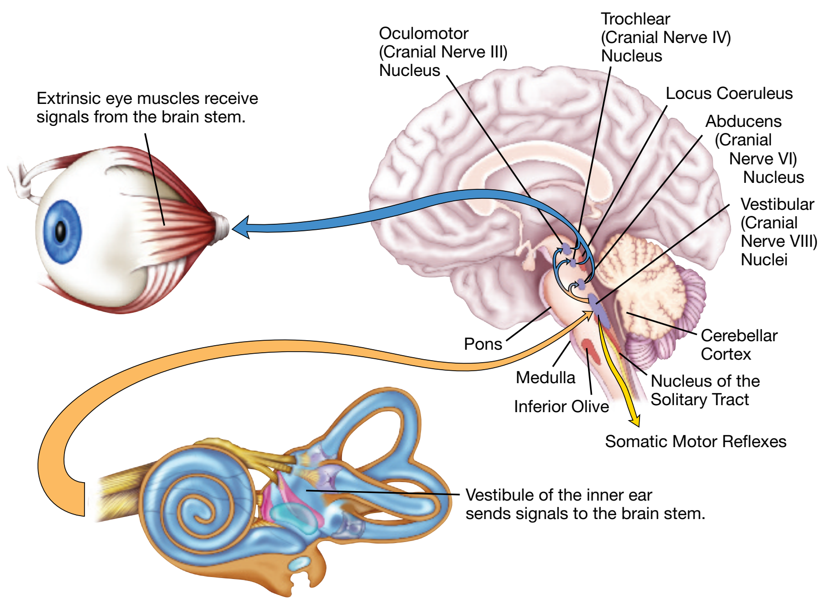
Postflight Balance and Walking

When sailors return to port following a long sea voyage, it takes them some time to get back their "land legs." When astronauts returned to Earth following a shuttle mission, it took them some time to get back their "ground legs." On landing day, most crew members had a wide-based gait, had trouble turning corners, and could not land from a jump. They didn't like bending over or turning their heads independent of their torsos. Recovery usually took about 3 days; but the more time the crew member spent in microgravity, the longer it took for his or her balance and coordination to return to normal. Previous experience helped, though; for most astronauts, each subsequent shuttle flight resulted in fewer postflight effects and a quicker recovery.

Scientists performed many experiments before and after shuttle missions to understand the characteristics of these transient postflight balance and gait disorders. By using creative experimental approaches, they showed that the changes in balance control were due to changes in the way the brain uses inner-ear information during spaceflight. As a result, the crew members relied more on visual information and body sense information from their ankle joints and the bottoms of their feet just after flight. Indeed, when faced with a dark environment (simulated by closing their eyes), the crew members easily lost their balance on an unstable surface (like beach sand, deep grass, or a slippery shower floor), particularly if they made any head movements. As a result, crew members were restricted from certain activities for a few days after shuttle flights to help them avoid injuring themselves. These activities included the return to flying aircraft.

In summary, experiments aboard the Space Shuttle taught us many things about how the nervous system uses gravity, how quickly the nervous system can respond to changes in gravity levels, and what consequences flight-related gravity changes might have on the abilities of crew members to perform operational activities. We know much more now than we did when the Space Shuttle Program started. But, we still have a lot to learn about the impacts of long-duration microgravity exposures, the effects of partial gravity environments, such as the moon and Mars, and how to develop effective physiological countermeasures to help offset some of the undesirable consequences of spaceflight on the nervous system. These will need to be tackled for space exploration.

Balance: Eye, Ear, and Brain Working in Concert



Adapted from an illustration by William Scavone, Kestrel Illustration.

For us to see clearly, the image of interest must be focused precisely on a small region of the retina called the fovea. This is particularly challenging when our heads are moving (think about how hard it is to make a clear photograph if your camera is in motion). Fortunately, our nervous systems have evolved very effective control loops to stabilize the visual scene in these instances. Using information sensed by the vestibular systems located in our inner ears, our brains quickly detect head motion and send signals to the eye muscles that cause compensatory eye movements. Since the vestibular system senses gravity as well as head motion, investigators performed many experiments aboard the shuttle to determine the role of gravity in the control of eye movements essential for balance. They learned that the eye movements used to compensate for certain head motions were improperly calibrated early in flight, but they eventually adapted to the new environment. Of course, after return to Earth, this process had to be reversed through a readaptation process.

Sleep Quality and Quantity on Space Shuttle Missions

Many people have trouble sleeping when they are away from home or in unusual environments. This is also true of astronauts. When on a shuttle mission, however, astronauts had to perform complicated tasks requiring optimal physical and cognitive abilities under sometimes stressful conditions.

Astronauts have had difficulty sleeping from the beginning of human spaceflight. Nearly all Apollo crews reported being tired on launch day and many gave accounts of sleep disruption throughout the missions, including some reporting continuous sleep periods lasting no more than 3 hours. Obtaining adequate sleep was also a serious challenge for many crew members aboard shuttle missions.

Environmental Factors

Several factors negatively affect sleep: unusual light-dark cycles, noise, and unfavorable temperatures. All of these factors were present during shuttle flights and made sleep difficult for crew members. Additionally, some crew members reported that work stress further diminished sleep.

When astronauts completed a daily questionnaire about their sleep, almost 60% of the questionnaires indicated that sleep was disturbed during the previous night. Noise was listed as the reason for the sleep disturbance approximately 20% of the time. High levels of noise negatively affect both slow-wave (i.e., deep sleep important for physical restoration) and REM (Rapid Eye Movement) sleep (i.e., stage at which most dreams occur and important for mental restoration), diminishing subsequent alertness, cognition, and performance. A comfortable ambient temperature is also important for promoting sleep. On the daily questionnaire, approximately 15% of the disturbances were attributed to the environment being too hot and approximately 15% of the disturbances were attributed to it being too cold. Thus, the shuttle environment was not optimal for sleep.

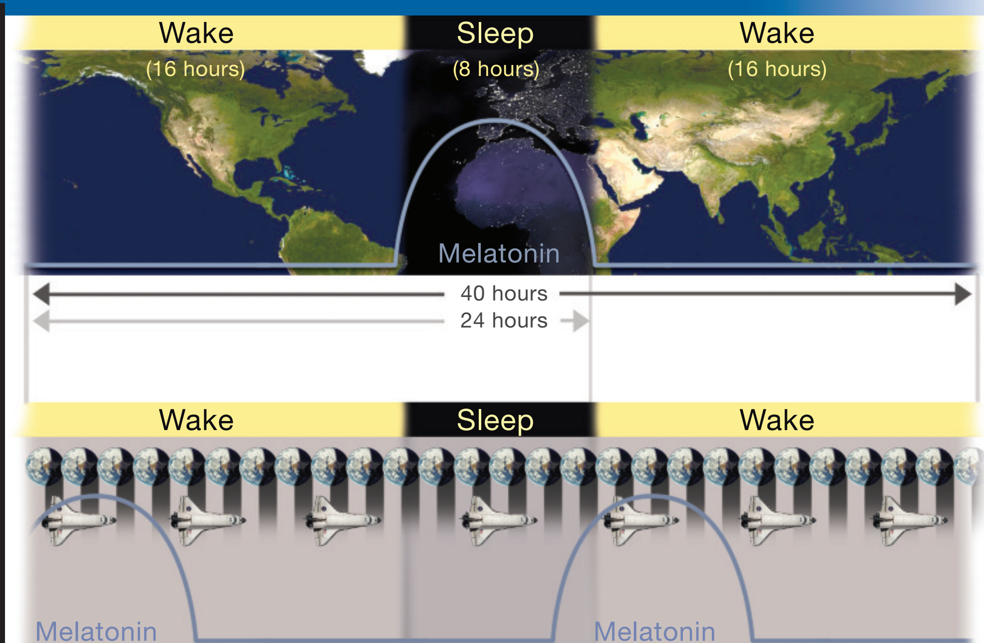
Circadian Rhythms

Appropriately timed circadian rhythms are important for sleep, alertness, performance, and general good health. Light is the most important time cue to the body's circadian clock, which has a natural period of about 24.2 hours. Normally, individuals sleep when it is dark and are awake when it is light.

Comparison of Earth and Space Sleep Cycles

Earth Conditions
On a 24-hour external light-dark cycle, the body's circadian clock remains properly synchronized (e.g., hormones like melatonin are released at the appropriate time).

Space Conditions
On the Orbiter's 90-minute light-dark cycle, weak interior ambient light may not sufficiently cue the body's circadian clock, which may then become desynchronized (e.g., inappropriately timed hormone release).



This 24-hour pattern resets the body's clock each day and keeps all of the body's functions synchronized, maximizing alertness during the day and consolidating sleep at night. Unlike the 24-hour light-dark cycle that we experience on Earth, shuttle crew members experience 90-minute light-dark cycles as they orbited the Earth.

Not only is the timing of light unsuitable, but the low intensity of the light aboard the shuttle may have contributed to circadian misalignment. Light levels were measured in the various compartments of the shuttle during Space Transportation System (STS)-90 Neurolab (1998) and STS-95 (1998) missions. In the Spacelab, light levels were constant and low (approximately 10 to 100 lux) during the working day. In the middeck, where the crew worked, ate, and slept, the light levels recorded were relatively constant and very dim (1 to 10 lux). Laboratory data showed that these light levels are insufficient to entrain the human circadian pacemaker to non-24-hour sleep-wake schedules. Normal room lighting (200 to 300 lux) would be required to keep the circadian system aligned under 24-hour light-dark cycles.

Crew members also were often scheduled to work on 23.5-hour days or had to shift their sleep-wake schedule several hours during flight. Moreover, deviations from the official schedule were frequently required by operational demands typical of space exploration. Therefore, the crew members' circadian rhythms often became misaligned, resulting in them having to sleep during a time when their circadian clock was promoting alertness, much as a shift worker on Earth.

Actually, difficulties with sleep began even before the shuttle launched. Often in the week prior to launch crew members had to shift their sleep-wake schedule, sometimes up to 12 hours. This physiological challenge, associated with sleep disruption, created "fatigue pre-load" before the mission even began.

All US crew members participated in the Crew Health Stabilization Program where they were housed together for 7 days prior to launch to separate them from potential infectious disease from people and food. During this quarantine period, scientists at Harvard Medical School, in association with NASA, implemented a bright-light treatment program for crew members of STS-35 (1990), the first Space Shuttle mission requiring both dual shifts and a night launch. Scheduled exposure to bright light (about 10,000 lux—approximately the brightness at sunrise), at appropriate times throughout the prelaunch period at Johnson Space Center and Kennedy Space Center, was used to prepare shuttle crew members of the Red Team of STS-35 for both their night launch and their subsequent night-duty shift schedule in space. A study confirmed that the prescribed light exposure during the prelaunch quarantine period successfully induced circadian realignment in this crew. Bright lights were installed at both centers' crew quarters in 1991 for use when shuttle flights required greater than a 3-hour shift in the prelaunch sleep-wake cycle.

Studies of Sleep in Space

NASA studied sleep quality and quantity and investigated the underlying physiological mechanisms associated with sleep loss as well as countermeasures to improve sleep and ultimately enhance alertness and performance in space. Scientists conducted a comprehensive sleep study on STS-90 and STS-95 missions using full polysomnography, which monitors brain waves, tension in face muscles, and eye movements, and is the "gold standard" for evaluating sleep. Scientists also made simultaneous recordings of multiple circadian variables such as body temperature and cortisol, a salivary marker of circadian rhythms. This extensive study included performance assessments and the first placebo-controlled, double-blind clinical trial of a pharmaceutical (melatonin) during spaceflight. Crew members on these flights experienced circadian rhythm disturbances, sleep loss, and decrements in neurobehavioral performance.

For another experiment, crew members wore a watch-like device, called an actigraph, on their wrists to monitor sleep. The actigraph contained an accelerometer that measured wrist motion. From that recorded motion scientists were able to use software algorithms to estimate sleep duration. Fifty-six astronauts (approximately 60% of the Astronaut Corps between 2001 and 2010) participated in this study. Average nightly sleep duration across multiple shuttle missions was approximately 6 hours. This level of sleep disruption has been associated with cognitive performance deficits in numerous ground-based laboratory and field studies.

Pharmaceuticals were the most widespread countermeasure for sleep disruption during shuttle flights. Indeed, more than three-quarters of astronauts reported taking sleep medications during missions. Astronauts took sleep medications during flight half the time. Wake-promoting therapeutics gained in popularity as well, improving alertness after sleep-disrupted nights.

Richard Searfoss
Colonel, US Air Force (retired).
Pilot for STS-58 (1993) and STS-76 (1996).
Commander for STS-90 (1998).

Perspectives on Neurolab

"I was privileged to command STS-90 Neurolab, focusing on the effects of weightlessness on the brain and nervous system. Although my technical background is in engineering and flight test, it was still incredibly rewarding to join a dedicated team that included not just NASA but the National Institutes of Health and top researchers in the world to strive with disciplined scientific rigor to really understand some of the profound changes to living organisms that take place in the unique microgravity environment. I viewed my primary role as science enabler, calling on my operational experience to build the team, lead the crew, and partner with the science community to accomplish the real 'mission that mattered.'

"Even though at the time STS-90 flew on Columbia humans had been flying to space nearly 40 years, much of our understanding of the physiological effects was still a mystery. Neurolab was extremely productive in unveiling many of those mysteries. The compilation of peer-reviewed scientific papers from this mission produced a 300-page book, the only such product from any Space Shuttle mission. I'll leave it to the scientists to testify to the import, fundamental scientific value, and potential for Earth-based applications from Neurolab. It's enough for me to realize that my crew played an important role in advancing science in a unique way.

"With STS-90 as the last of 25 Spacelab missions, NASA reached a pinnacle of overall capability to meld complex, leading-edge science investigations with the inherent challenges of operating in space. Building on previous Spacelab flights, Neurolab finished up the Spacelab program spectacularly, with scientific results second to none. What a joy to be part of that effort! It was unquestionably the honor of my professional life to be a member of the Neurolab team in my role as commander."

Although sleep-promoting medication use was widespread in shuttle crew members, investigations need to continue to determine the most acceptable, feasible, and effective methods to promote sleep in future missions. Sleep monitoring is ongoing in crew members on the International Space Station (ISS) where frequent shifts in the scheduled sleep-wake times disrupt sleep and circadian alignment. Sleep most certainly will also be an issue when space travel continues beyond low-Earth orbit. Private sleep quarters will probably not be available due to space and mass issues. Consequently, ground-based studies continue to search for the most effective, least invasive, and least time-consuming countermeasures to improve sleep and enhance alertness during spaceflight. Currently, scientists are trying to pinpoint the most effective wavelength of light to use to ensure alignment of the circadian system and improve alertness during critical tasks.

Spaceflight Changes Muscle

Within the microgravity environment of space, astronauts' muscles are said to be "unweighted" or "unloaded" because their muscles are not required to support their body weight. The unloading of skeletal muscle during spaceflight, in what is known as "muscle atrophy," results in remodeling of muscle (atrophic response) as an adaptation to the spaceflight. These decrements, however, increase the risk of astronauts being unable to adequately perform physically demanding tasks during EVAs or after abrupt transitions to environments of increased gravity (such as return to Earth at the end of a mission).

A similar condition, termed "disuse muscle atrophy," occurs any time muscles are immobilized or not used as the result of a variety of medical conditions, such as wearing a cast or being on bed rest for a long time. Space muscle research may provide a better understanding of the mechanisms underlying disuse muscle atrophy, which may enable better management of these patients. In the US human space program, the only tested in-flight preventive treatment for muscle atrophy has been physical exercise. In-flight exercise hardware and protocols varied from mission to mission, somewhat dependent on mission duration as well as on the internal volume of the spacecraft. Collective knowledge gained from these shuttle missions aided in the evolution of exercise hardware and protocols to prevent spaceflight-induced muscle atrophy and the concomitant deficits in skeletal muscle function.

How Was Muscle Atrophy Measured, and What Were the Results?

Leg and Back Muscle Size Decreases

Loss of muscle and strength in the lower extremities of astronauts was initially found in the Gemini (1962-1966) and Apollo missions (1967-1972) and was further documented in the first US space station missions (Skylab, 1973-1974) of 28, 59, and 84 days' duration. NASA calculated crude muscle volumes by measuring the circumference of the lower and upper legs and arms at multiple sites.

For shuttle astronauts, more sophisticated, accurate, and precise measures of muscle volume were made by magnetic resonance imaging (MRI). MRI is a common diagnostic medical procedure used to image patient's internal organs that was adapted to provide volume measurements of a crew member's lower leg, thigh, and back muscles before and after flight. The leg muscle volume was evaluated in eight astronauts (seven males and one female, age range 31 to 39 years) who flew on either one of two 9-day missions. Scientists obtained MRI scans of multiple leg cross sections prior to flight and compared them to scans obtained at 2 to 7 days after flight. The volumes of various leg muscles were reduced by about 4% to 6% after spaceflight. In another study of longer missions (9 to 16 days' duration—two males and one female, mean age 41 years), the losses were reported to be greater, ranging from 5.5% to 15.9% for specific leg muscles. This study found that daily volume losses of leg muscles normalized for duration of flight were from 0.6% to 1.04% per mission day.

Muscle Strength Decreases

Decreases in muscle strength persisted throughout the shuttle period in spite of various exercise prescriptions. Measurements of muscle strength, mass, and performance helped NASA determine the degree of muscle function loss and assess the efficacy of exercise equipment and determine whether exercise protocols were working as predicted.

Muscle strength, measured with a dynamometry (an instrument that measures muscle-generated forces, movement velocity, and work) before launch and after landing consistently showed loss of strength in muscles that extend the knee (quadriceps muscles) by up to 12% and losses in trunk flexor strength of as much as 23%. The majority of strength and endurance losses occurred in the trunk and leg muscles (the muscle groups that are active in normal maintenance of posture and for walking and running) with little loss noted in upper body and arm muscle strength measurements. In contrast, four STS-78 (1996) astronauts had almost no decrease in calf muscle strength when they participated voluntarily in high-volume exercise in combination with the in-flight, experiment-specific muscle strength performance measurements. This preliminary research suggested that such exercises may prevent loss of muscle function leading to implementation of routine combined aerobic and resistive exercise for ISS astronauts.

Muscle Fiber Changes in Size and Shape

An "average" healthy person has roughly equal numbers of the two major muscle fiber types ("slow" and "fast" fibers). Slow fibers contract (shorten) slowly and have high endurance (resistance to fatigue) levels. Fast fibers contract quickly and fatigue readily. Individual variation in muscle fiber type composition is genetically (inherited) determined. The compositional range of slow fibers in the muscles on the front of the thigh (quadriceps muscles) in humans can vary between 20% and 95%, a percentage found in many marathon runners. On the other hand, a world-class sprinter or weight lifter would have higher proportions of fast fibers and, through his or her training, these fibers would be quite large (higher cross-sectional diameter or area). Changing the relative proportions of the fiber types in muscles is possible, but it requires powerful stimulus such as a stringent exercise program or the chronic unloading profile that occurs in microgravity. NASA was interested in determining whether there were any changes in the sizes or proportions of fiber types in astronauts during spaceflight.

In the only biopsy study of US astronauts to date, needle muscle biopsies from the middle of the vastus lateralis muscle (a muscle on the side of the thigh) of eight shuttle crew members were obtained before launch (3 to 16 weeks) and after landing (within 3 hours) for missions ranging in duration from 5 to 11 days. Three of the eight crew members (five males and three females, age range 33 to 47 years) flew 5-day missions while the other five crew members completed 11-day flights. Five of the eight crew members did not participate in other medical studies that might affect muscle fiber size and type. NASA made a variety of measurements in the biopsy samples, including relative proportions of the two major muscle fiber types, muscle fiber cross-sectional area by muscle fiber type, and muscle capillary (small blood vessel) density. Slow fiber-type cross-sectional area decreased by 15% as compared to a 22% decrease for fast fiber muscle fibers. Biopsy samples from astronauts who flew on the 11-day mission showed there were relatively more fast fiber types and fewer slow fiber types, and the density of muscle capillaries was reduced when the samples taken after landing were compared to those taken before launch. NASA research suggests that fiber types can change in microgravity due to the reduced loads. This has implications for the type and volume of prescriptive on-orbit exercise.

Research conducted during the shuttle flights provided valuable insight into how astronauts' muscles responded to the unloading experienced while living and working in space. Exercise equipment and specific exercise therapies developed and improved on during the program are currently in use on the ISS to promote the safety and health of NASA crew members.

The "Why" and "How" of Exercise on the Space Shuttle

Why Exercise in Space?

Just as exercise is an important component to maintain health here on Earth, exercise plays an important role in maintaining astronaut health and fitness while in space. While living in space requires very little effort to maneuver around, the lack of gravity can decondition the human body.

Knowledge gained during the early years of human spaceflight indicated an adaptation to the new environment. While the empirical evidence was limited, the biomedical data indicated that microgravity alters the musculoskeletal, cardiovascular, and neurosensory systems. In addition, the responses to spaceflight varied from person to person. Space adaptation was highly individualized, and some human systems adjusted at different rates. Overall, these changes were considered to have potential implications on astronaut occupational performance as well as possible impacts to crew health and safety. There was concern that space-related deconditioning could negatively influence critical space mission tasks, such as construction of the space station, repair of the orbiting Hubble Space Telescope, piloting and landing operations, and the ability to egress in an emergency.

Historically, NASA worked on programs to develop a variety of strategies to prevent space deconditioning, thus migrating toward the use of exercise during spaceflight to assure crew member health and fitness. In general, exercise offered a well-understood approach to fitness on Earth, had few side effects, and provided a holistic approach for addressing health and well-being, both physically and psychologically.

NASA scientists conducted experiments in the 1970s to characterize the effects of exercise during missions lasting 28, 56, and 84 days on America's first orbiting space station—Skylab. This was the first opportunity for NASA to study the use of exercise in space. These early observations demonstrated that exercise modalities and intensity could improve the fitness outcomes of astronauts, even as missions grew in length. Armed with information from Skylab, NASA decided to provide exercise on future shuttle missions to minimize consequences that might be associated with spaceflight deconditioning to guarantee in-flight astronaut performance and optimize postflight recovery.

Benefits of Exercise

Space Shuttle experience demonstrated that for the short-duration shuttle flights, the cardiovascular adaptations did not cause widespread significant problems except for the feelings of light-headedness—and possibly fainting—in about one-fifth of the astronauts and a heightened concern over irregular heartbeats during spacewalks. During the Space Shuttle Program, however, it became clear from these short-duration missions that exercise countermeasures would be required to keep astronauts fit during long-duration spaceflights. Although exercise was difficult in the shuttle, simple exercise devices were the stationary bike, a rowing machine, and a treadmill. Astronauts, like those from Skylab, found it difficult to raise their heart rate high enough for adequate exercise. NASA demonstrated that in-flight exercise could be performed and helped maintain some aerobic fitness, but much research remained to be done. This finding led to providing the ISS with a bicycle ergometer, a treadmill, and a resistive exercise device to ensure astronaut fitness.

Deconditioning due to a lack of aerobic exercise is a concern in the area of EVAs, as it could keep the astronaut from performing spacewalks and other strenuous activities. Without enough in-flight aerobic exercise, astronauts experienced elevated heart rates and systolic blood pressures.

Ken Baldwin, PhD

Principal investigator on three Spacelab missions—STS-40 (1991), STS-58 (1993), and STS-90 (1998)—and a Physiological Anatomical Rodent Experiment. Muscle Team leader, 2001-2009, for the National Space Biomedical Research Institute.

"The space life sciences missions (STS-40, STS-58, and STS-90) provided a state-of-the-art laboratory away from home that enabled scientists to customize their research studies in ways that were unheard of prior to the Space Shuttle Program. In using such a laboratory, my research generated unique insights concerning the remodeling of muscle structure and function to smaller, weaker, fatigue-prone muscles with a contractile phenotype that was poorly suitable to apposing gravity. These unique findings became the cornerstone of recommendations that I spearheaded to redesign the priority of exercise during spaceflight from one of an aerobic exercise focus (treadmill and cycling exercise) to a greater priority of exercise paradigms favoring heavy-resistance exercise in order to prevent muscle atrophy in microgravity. Additionally, our group also made an important discovery in ground-based research supported by NASA's National Space Biomedical Research Institute showing that it is not necessarily the contraction mode that the muscles must be subjected to, but rather it is the amount and volume of mechanical force that the muscle must generate within a given contraction mode in order to maintain normal muscle mass. Thus, the early findings aboard the Space Shuttle have served as a monument for guiding future research to expand humankind's success in living productively on other planets under harsh conditions."

The deconditioned cardiovascular system must work harder to do the same or even less work (exercise) than the well-conditioned system.

Exercise capacity was measured preflight on a standard upright bike. Exercise was stepped up every 3 minutes with an increase in workload. Maximal exercise was determined preflight by each astronaut's maximum volume of oxygen uptake. A conditioned astronaut may have little increase in heart rate above sitting when he or she is walking slowly. The heart rate and systolic blood pressure (the highest blood pressure in the arteries, just after the heartbeats during each cardiac cycle) increase as the astronaut walks fast or runs until the heart rate cannot increase any more.

In-flight exercise testing showed that crew members could perform at 70% of the preflight maximum exercise level with no significant issues. This allowed mission planners to schedule EVAs and other strenuous activities that did not overtax the astronauts' capabilities.

How Astronauts Exercised on the Space Shuttle

Because of the myriad restrictions about what can be launched within a space vehicle, tremendous challenges exist related to space exercise equipment. Systems need to be portable and lightweight, use minimal electrical power, and take up limited space during use and stowage. In addition, operation of exercise equipment in microgravity is inherently different than it is on Earth. Refining the human-to-machine interfaces for exercise in space was a challenging task tested throughout the shuttle missions. Providing exercise concepts with the appropriate physical training stimulus to maintain astronaut performance that operates effectively in microgravity proved to be a complex issue.

Exercise systems developed for shuttle included: treadmill, cycle ergometer, and rower. The devices offered exercise conditioning that simulated ambulation, cycling, and rowing activities. All exercise systems were designed for operations on the shuttle middeck; however, the cycle could also be used on the flight deck so that astronauts could gaze out the overhead windows during their exercise sessions.

Each of the three systems had its own challenges for making Earth-like exercise feasible while in space within the limits of the shuttle vehicle. Most traditional exercise equipment has the benefit of gravity during use, while spaceflight systems require unique approaches to exercise for the astronaut users. While each system had its unique issues for effective space operations, the exercise restraints were some of the biggest challenges during the program. These restraints included techniques for securing an astronaut to the exercise device itself to allow for effective exercise stimuli.

“Shuttle left a legacy, albeit incomplete, of the theory and practice for exercise countermeasures in space.”

William Thornton, MD, astronaut, principal investigator and original inventor of the shuttle treadmill.

The evolution of types of exercise: running, rowing, and cycling from Earth to space configurations. Astronaut Jerry Linenger running during STS-64 (1994), Astronaut Robert Cabana rowing on STS-53 (1992), and Astronaut Catherine Coleman cycling on STS-73 (1995).

In-flight exercise quality and quantity were measured on all modalities using a commercial heart rate monitor for tracking work intensity and exercise duration. This allowed for a common measure across devices. Heart rate is a quality indicator of exercise intensity and duration (time) is a gauge of exercise quantity—common considerations used for generating exercise prescriptions. Research showed that target heart rates could be achieved using each of the three types of exercise during spaceflight.

Treadmill

Running and walking on a treadmill in the gym can be computer controlled with exercise profiles that alter speed and grade. The shuttle treadmill had limits to its tread length and speed and had no means for altering grade. Treadmill ambulation required the astronaut to wear a complex over-the-shoulder bungee harness system that connected to the treadmill and held the runner in place during use. Otherwise, the runner would propel off the tread with the first step. While exercise target heart rates were achieved, the treadmill length restricted gait length and the harness system proved quite uncomfortable. This information was captured as a major lesson learned for the development of future treadmill systems for use in space.

Cycle Ergometer

The shuttle cycle ergometer (similar to bicycling) operated much like the equipment in a gym. It used a conventional flywheel with a braking band to control resistance via a small motor with a panel that displayed the user’s speed (up to 120 rpm) and workload (up to 350 watts). The restraint system used commercial pedal-to-shoe bindings, or toe clips, that held the user to the cycle while leaning on a back pad in a recumbent position. The cycle had no seat, however, and used a simple lap belt to stabilize the astronaut during aerobic exercise. While the cycle offered great aerobic exercise, it was also used for prebreathe operations in preparation for EVAs. The prebreathe exercise protocol allowed for improved nitrogen release from the body tissues to minimize the risk of tissue bubbling during the EVA that could result in decompression sickness or “the bends.” Exercise accelerated, “washout” nitrogen that may bubble in the tissues during EVA, causing decompression sickness and, thereby, terminating the EVA and risking crew health.

Rower

The rower offered total body aerobic exercise, similar to gym rowers. It also had limited capability for resistance exercise. Similar to the cycle, it was seatless since the body floats. The astronaut's feet were secured with a Velcro® strap onto a footplate that allowed for positioning. The rower used a magnetic brake to generate resistance.

Summary

In summary, exercise during Space Shuttle flights had physical and psychological benefits for astronauts. In general, it showed that astronauts could reduce the deconditioning effects that may alter performance of critical mission tasks using exercise in space, even on the relatively short shuttle missions. As a result, a "Flight Rule" was developed that mandated astronauts exercise on missions longer than 11 days to maintain crew health, safety, and performance.

Each device had the challenge of providing an appropriate exercise stimulus without the benefit of gravity and had a unique approach for on-orbit operations. Engineers and exercise physiologists worked closely together to develop Earth-like equipment for the shuttle environment that kept astronauts healthy and strong.

Cardiovascular: Changes in the Heart and Blood Vessels That Affect Astronaut Health and Performance

The cardiovascular system, including the heart, lungs, veins, arteries, and capillaries, provides the cells of the body with oxygen and nutrients and allows metabolic waste products to be eliminated through the kidneys (as urine) and the gastrointestinal tract. All of this depends on a strong heart to generate blood pressure and a healthy vascular system to regulate the pressure and distribute the blood, as needed, throughout the body via the blood vessels.

For our purposes, the human body is essentially a column of fluid; the hydrostatic forces that act on this column, due to our upright posture and bipedal locomotion, led to a complex system of controls to maintain—at a minimum—adequate blood flow to the brain.

On Earth, with its normal gravity, all changes in posture—such as when lying down, sitting, or standing as well as changes in activity levels such as through exercising—require the heart and vascular system to regulate blood pressure and distribution by adjusting the heart rate (beats per minute), amount of blood ejected by the heart (or stroke volume), and constriction or dilation of the distributing arteries. These adjustments assure continued consciousness by providing oxygen to the brain or continued ability to work, with oxygen going to the working muscles.

Removing the effects of gravity during spaceflight and restoring gravity after a period of adjustment to weightlessness present significant challenges to the cardiovascular control system. The cardiovascular system is stressed very differently in spaceflight, where body fluids are shifted into the head and upper body and changes in posture do not require significant responses because blood does not drain and pool in the lower body. Although the cardiovascular system is profoundly affected by spaceflight, the basic mechanisms involved are still not well understood.

During the shuttle era, flight-related cardiovascular research focused on topics that could benefit the safety and well-being of crew members while also revealing the mechanisms underlying the systemic adjustments to spaceflight. NASA researchers studied the immediate responses to the effects of weightlessness during Space Shuttle flights and the well-developed systemic adjustments that followed days and weeks of exposure. Most such research related to the loss of orthostatic tolerance after even brief flights and to the development of potentially detrimental disturbances in cardiac rhythm during longer flights.

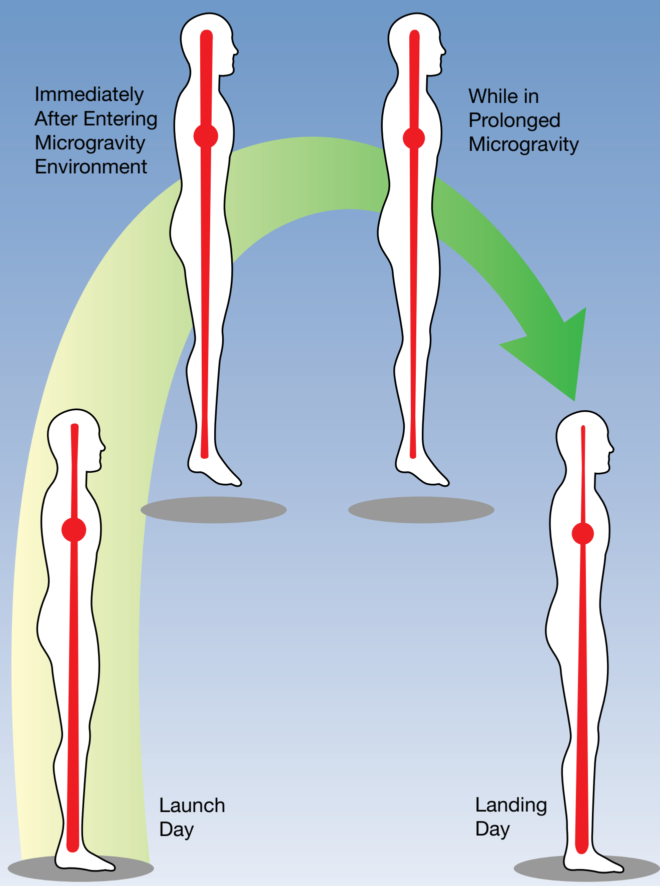
Scientists also evaluated the usefulness of several interventions such as exercise, fluid ingestion, and landing-day gravity suits (g-suits) in protecting the astronauts' capacities for piloting the Orbiter—an unpowered, 100-ton glider—safely to a pinpoint landing, and especially for making an unaided evacuation from the Orbiter if it landed at an alternate site in an emergency.

Orthostatic Intolerance: Feeling Light-headed and Fainting on Standing Upright

One of the most important changes negatively impacting flight operations and crew safety is landing day orthostatic intolerance. Astronauts who have orthostatic intolerance (literally, the inability to remain standing upright) cannot maintain adequate arterial blood pressure and have decreased brain blood levels when upright, and they experience light-headedness and perhaps even fainting. This may impair their ability to stand up and egress the vehicle after landing, and even to pilot the vehicle while seated upright as apparent gravity increases from weightlessness to 1.6*g* during atmospheric re-entry.

The orthostatic intolerance condition is complicated and multifactorial. Its hallmarks are increased heart rate, decreased systolic blood pressure,

Blood Volume Changes During Spaceflight



The distribution of blood changes in microgravity more in the upper torso and less in the legs. At landing, the astronaut is light-headed because of less blood and the pooling of the blood in the feet.

and decreased stroke volume during 5 minutes of standing shortly after landing. The decrease in blood volume frequently observed is an important initiating event in the etiology of orthostatic intolerance, but it is the subsequent effects and the physiological responses (or lack thereof) to those effects that may result in orthostatic intolerance after shuttle flights. This is highlighted by the fact that while all shuttle crew members who were tested had low blood volume on landing day, only one-quarter of them developed orthostatic intolerance during standing or head-up tilting.

The group of astronauts that developed orthostatic intolerance lost comparable amounts of plasma (the watery portion of the blood, which the body can adjust quickly) to the group that did not develop orthostatic intolerance. But, the group that was not susceptible had a more pronounced increase in the functioning of the sympathetic nervous system, which is important in responding to orthostatic stress after returning to Earth. Thus, it is not the plasma volume loss alone that causes light-headedness but the lack of compensatory activation of the sympathetic system.

Another possible mechanism for post-spaceflight orthostatic hypotension (low blood pressure that causes fainting) is cardiac atrophy and the resulting decrease in stroke volume (the amount of blood pushed out of the heart at each contraction). Orthostatic hypotension occurs if the fall in stroke volume overwhelms normal compensatory mechanisms such as an increase in heart rate or constriction in the peripheral blood vessels in the arms, legs, and abdomen.

The vast majority of astronauts have been male. Consequently, any conclusions drawn regarding the physiological responses to spaceflight are male biased. NASA recognized significant differences in how men and women respond to spaceflight, including the effects of spaceflight on cardiovascular responses to orthostatic stress. More than 80% of female crew members tested became light-headed during postflight standing as compared to about 20% of men tested, confirming a well-established difference in the non-astronaut population. This is an important consideration for prevention, as treatment methods may not be equally effective for both genders.

How Can This Risk be Changed?

While orthostatic intolerance is perhaps the most comprehensively studied cardiovascular effect of spaceflight, the mechanisms are not well understood. Enough is known to allow for the implementation of some countermeasures, yet none of these countermeasures have been completely successful at eliminating spaceflight-induced orthostatic intolerance following spaceflight.

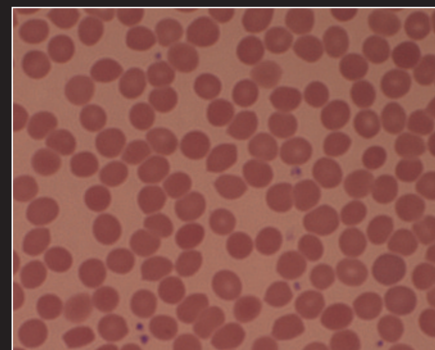
In 1985, ingestion of fluid and salt (or "fluid loading") prior to landing became a medical requirement through a Flight Rule given the demonstrated benefits and logic that any problem caused—at least in part—by a loss in plasma volume should be resolved—at least in part—by fluid restoration. Starting about 2 hours before landing, astronauts ingest about 1 liter (0.58 oz) of water along with salt tablets. Subsequent refinements to enhance palatability and tolerance include the addition of sweeteners and substitution of bouillon solutions. Of course, any data on plasma volume acquired after 1985 do not reflect the unaltered landing day deficit. But, in spite of the fluid loading, astronauts still returned from shuttle missions with plasma volume deficits ranging from 5% to 19% as well as with orthostatic intolerance.

Shuttle astronauts returned home wearing a lower-body counterpressure garment called the anti-g suit. These suits have inflatable bladders at the calves, thighs, and lower abdomen that resist blood pooling in those areas and force the blood toward the head. The bladders can be pressurized from 25 mmHg (0.5 psi) to 130 mmHg (2.5 psi). In addition, ISS crew members landing on the shuttle used recumbent seats (as opposed to the upright seats of the shorter-duration shuttle crews) and only inflated their suit minimally to 25 mmHg (0.5 psi). All astronauts deflated their anti-g suit slowly after the shuttle wheeled to a stop to allow their own cardiovascular systems time to readjust to the pooling effects of Earth's gravity.

Other treatments for orthostatic intolerance were also evaluated during the program. A technique called "lower body negative pressure," which used slight decompression of an airtight chamber around the abdomen and legs to pool blood there and thus recondition the cardiovascular system, showed promise in ground studies but was judged too cumbersome and time consuming for routine shuttle use. A much simpler approach used a medication known as fludrocortisone, a synthetic corticosteroid known to increase fluid retention in patients on Earth. It proved unsuccessful, however, when it was not well-tolerated by crew members and did not produce any differences in plasma volume or orthostatic tolerance.

Thus, the countermeasures tested were not successful in preventing postflight orthostatic intolerance, at least not in an operationally compatible manner. The knowledge gained about spaceflight-induced cardiovascular

How Red Blood Cells Are Lost in Spaceflight



What do astronauts, people traveling from high altitudes to sea level, and renal (kidney) failure patients have in common? All experience changes in red blood cell numbers due to changes in the hormone erythropoietin, synthesized in the kidneys.

Red blood cells bring oxygen to tissues. When astronauts enter microgravity or high-altitude residents travel to sea level, the body senses excess red blood cells. High-attitude residents produce an increased number because of decreased ambient oxygen levels but, at sea level, excess cells are not needed. Astronauts experience a 15% decrease in plasma volume as the body senses an increase in red blood cells per volume of blood. In these situations, erythropoietin secretion from the kidneys ceases. Prior to our research, we knew that when erythropoietin secretion stops, the bone marrow stops production of pre red blood cells and an increase in programmed destruction of these cells occurs.

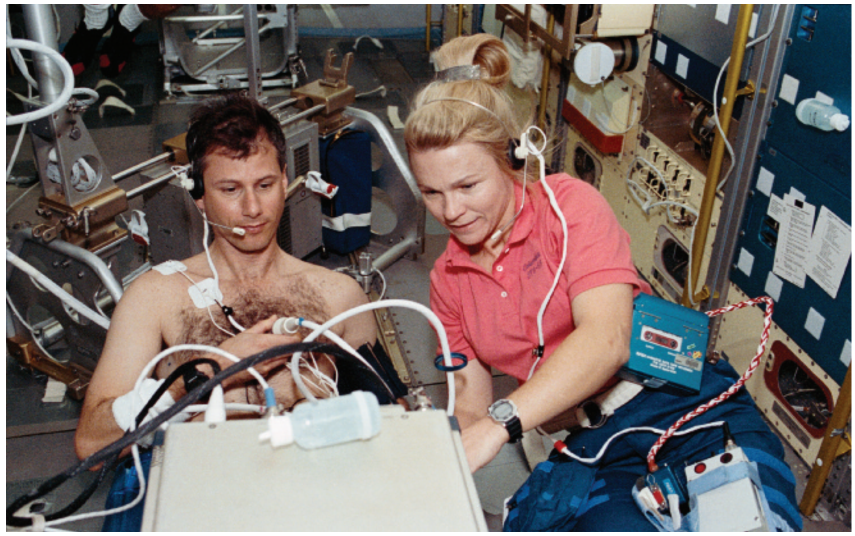
Another function was found in the absence of erythropoietin, the loss of the newly secreted blood cells from the bone marrow—a process called neocytolysis. Since patients with renal failure are unable to synthesize erythropoietin, it is administered at the time of renal dialysis (a process that replaces the lost kidney functions); however, blood levels of erythropoietin fell rapidly between dialysis sessions, and neocytolysis occurs. Thus, the development of long-lasting erythropoietin now prevents neocytolysis in these patients. Erythropoietin is, therefore, important for human health—in space and on Earth—and artificial erythropoietin is essential for renal failure patients.

changes and differences between orthostatic tolerance groups, however, provided a base for development of future pharmacological and mechanical countermeasures, which will be especially beneficial for astronauts on long-duration missions on space stations and to other planets.

Cardiovascular Changes During Spaceflight

Headward fluid shift was inferred from reports containing astronaut observations of puffy faces and skinny legs, and was long believed to be the initiating event for subsequent cardiovascular responses to spaceflight. The documentation of this shift was an early goal of Space Shuttle-era investigators, who used several techniques to do so. Direct measurement of peripheral venous blood pressure in an arm vein (assumed to reflect central venous pressure in the heart, an indication of headward fluid shift) was done in 1983 during in-flight blood collections. Actual measurement of central venous pressure was done on a small number of astronauts on dedicated space life sciences Spacelab missions starting in 1991. These studies, and particularly the direct central venous pressure measurements, demonstrated that central venous pressure was elevated in recumbent crew members even before launch, and that it increased acutely during launch with acceleration loads of up to three times Earth's surface gravity. This increased the weight of the column of blood in the legs "above" the heart and the central venous pressure decreased to below baseline values immediately on reaching orbit. Investigators realized that the dynamics of central blood volume changes were more complex than originally hypothesized.

By measuring and recording arterial blood pressures, heart rate, and rhythm, two-dimensional echocardiography demonstrated the variety of changes in the cardiovascular system in flight. In-flight heart rate and systolic and diastolic blood pressure decreased when compared to the preflight values. During re-entry into Earth's atmosphere, these values increased past their preflight baseline, reaching maximal values at peak deceleration loading. When crew members stood upright for the first time after landing, both systolic and diastolic pressures significantly decreased from their seated values and the decrease in diastolic pressure was greater in crew members who did not fully inflate their g-suits. Systolic pressure and heart rate returned to preflight values within an hour of landing, whereas all other spaceflight-induced cardiovascular changes were reversed within a week after landing. Furthermore, stress hormones such as adrenaline (involved in the primal "fight or flight response") were increased postflight, whether the astronauts were resting supine or standing.



In the Spacelab (laboratory in Orbiter payload bay) Astronaut Rhea Seddon, MD, measures cardiac function on Martin Fettman during Columbia life sciences mission STS-58 (1993) .

So, What Does This Mean?

During weightlessness, there is reduced postural stress on the heart. As expected, the cardiovascular response is muted: blood pressure and heart rate are lower in the resting astronaut than before flight. The volume of blood ejected from the heart with each beat initially increases because of the headward fluid shift, but it becomes lower than preflight levels after that due to the decreased blood volume.

Cardiac Rhythm Disturbances

Contrary to popular opinion, shuttle astronauts were not monitored extensively throughout their flights. Electrocardiograms were recorded and transmitted for crew health assurance only on up to two crew members (out of crews numbering up to seven) and only during launch and landing through the 14th shuttle mission, STS-41G (1984). Subsequently, given the established confidence that healthy astronauts could tolerate spaceflight without difficulty, the requirement for even such minimal medical monitoring was eliminated. Later, a purpose-built system for on-board recording of electrocardiograms and blood pressure was used on select volunteer astronauts between 1989 and 1994.

At present, there is little evidence to indicate that cardiovascular changes observed in spaceflight increase susceptibility to life-threatening disturbances in cardiac rhythms. Certain findings, however, suggest that significant cardiac electrical changes occurred during short and long flights.

NASA systematically studied cardiac rhythm disturbances during some shuttle missions in response to medical reports of abnormal rhythms in nine of 14 spacewalking astronauts between 1983 and 1985. In subsequent studies on 12 astronauts on six shuttle flights, investigators acquired 24-hour continuous Holter recordings of the electrocardiograms during and after altitude chamber training, then again 30 days before launch, during and after each EVA, and after return to Earth. These investigators observed no change in the number of premature contractions per hour during flight compared to preflight or postflight. Given the fact that these data disagreed with other previous reports on astronauts, the investigators recommended that further study was required.

Summary

The Space Shuttle provided many opportunities to study the cardiovascular system due to the high number of flights and crew members, along with an emphasis on life sciences research. This research provided a better understanding of the changes in spaceflight and provided focus for the ISS research program.

Nutritional Needs in Space

Do Astronauts Have Special Nutritional Needs?

If elite athletes like Olympians have special nutritional needs, do astronauts too? During the shuttle flights, nutrition research indicated that, in general, the answer is no. Research, however, provided the groundwork for long-duration missions, such as for the ISS and beyond. Additionally, as the expression goes, while good nutrition will not make you an Olympic-quality athlete, inadequate nutrition can ruin an Olympic-quality athlete.

Nutritional needs drive the types and amounts of food available on orbit. Since shuttle flights were short (1 to 2 weeks), nutritional needs were more like those required for a long camping trip. Accordingly, NASA's research focused on the most important nutrients that related to the physiological changes that microgravity induced for such short missions. The nutrients studied were water, energy (calories), sodium, potassium, protein, calcium, vitamin D, and iron.

Many astronauts eat and drink less in flight, probably due to a combination of reduced appetite and thirst, high stress, altered food taste, and busy schedules. Because the success of a flight is based on the primary mission, taking time for eating may be a low priority. Astronauts are healthy adults, so NASA generally uses Earth-based dietary nutrient recommendations; however, researchers commonly found inadequate food intake and corresponding loss of body weight in astronauts. This observation led to research designed to estimate body water and energy needed during spaceflight.

How Much Water Should an Astronaut Consume?

Water intake is important to prevent dehydration. About 75% of our bodies is water, located mostly in muscles. The fluid in the blood is composed of a noncellular component (plasma) and a cellular component (red blood cells).

NASA measured the various body water compartments using dilution techniques: total body water; extracellular volume (all water not in cells), plasma volume, and blood volume. Because of the lack of strong gravitational force, a shift of fluid from the lower body to the upper body occurs. This begins on the launch pad, when crew members may lie on their backs for 2 to 3 hours for many flights. Scientists hypothesize that the brain senses this extra upper-level body water and adapts through reduced thirst and, sometimes, increased losses through the kidney—urine. An initial reduction of about 15% water (0.5 kg [1.15 pounds]) occurred in the plasma in flight, thus producing a concentrated blood that is corrected by reducing the levels of red blood cells through a mechanism that reduces new blood cells. Soon after entering space, these two compartments (plasma and red blood cells) return to the same balance as before flight but with about 10% to 15% less total volume in the circulation than before flight. Through unknown mechanisms, extracellular fluid is less and total body water does not change or may decrease slightly, 2% to 3% (maximum loss of 1.8 kg [4 pounds]). From this NASA scientists inferred that the amount of intracellular fluid is increased, although this has not been measured. These major fluid shifts affect thirst and, potentially, water requirements as well as other physiological functions. Water turnover decreases due to a lower amount of water consumed and decreased urine volume—both occur in many astronauts during spaceflight. Since total body water does not change much, recommended water intakes are around 2,000 ml/d (68 oz, or 8.5 cups). Astronauts may consume this as a combination of beverages, food, and water.

Because of potentially reduced thirst and appetite, astronauts must make an effort to consume adequate food and water. Water availability on the shuttle was never an issue, as the potable water was a by-product of the fuel cells. With flights to the Russian space station Mir and the ISS, the ability to transfer water to these vehicles provided a tremendous help as the space agencies no longer needed to launch water, which is very heavy.

A much-improved understanding of water loss during EVAs occurred during the shuttle period. This information led to the ISS EVA standards. Dehydration may increase body heat, causing dangerously high temperatures. Therefore, adequate water intake is essential during EVAs. NASA determined how much water was needed for long EVAs (6 hours outside the vehicle, with up to 12 hours in the EVA suit). Due to the concern for dehydration, water supplies were 710 to 946 ml (24 to 32 oz, or 3 to 4 cups) in the in-suit drink bag (the only nutrition support available during EVA).

How Spaceflight Affects Kidney Function

Does the headward fluid shift decrease kidney function? The kidneys depend on blood flow, as it is through plasma that the renal system removes just the right amount of excess water, sodium, metabolic end products like urea and creatinine, as well as other metabolic products from foods and contaminates. So, what is the affect of reduced heart rates and lower blood volumes? Astronauts on several Spacelab flights participated in research to determine any changes in renal function and the hormones that regulate this function. When the body needs to conserve water, such as when sweating or not hydrating enough, a hormone called antidiuretic hormone prevents water loss. Similarly, when the body has too little sodium, primarily due to diet and sweating, aldosterone keeps sodium loss down. All the experiments showed that these mechanisms worked fine in spaceflight. We learned not to worry about the basic functions of the kidney.

Renal Stones

As stated, the kidney controls excess water. But, what happens if a crew member is dehydrated due to sweating or not consuming enough water? During spaceflight, urine becomes very concentrated with low levels of body water. This concentrated urine is doubly changed by immediately entering microgravity, and the bone starts losing calcium salts. Although these losses were not significant during the short shuttle flights, this urinary increase had the potential to form calcium oxalate renal stones. Furthermore, during spaceflight, protein breakdown increases due to muscle atrophy and some of the end products could also promote renal stones. Due to the potential problem of renal stones, crew members were strongly encouraged to consume more water than their thirst dictated. This work led to the development of countermeasures for ISS crew members.

Sodium and Potassium: Electrolytes Important for Health

The electrolytes sodium (Na) and potassium (K) are essential components of healthy fluid balance; Na is a primarily extracellular ion while K is a primarily intracellular ion. They are essential for osmotic balance, cell function, and many body chemical reactions. K is required for normal muscle function, including the heart. With changes in fluid balance, what happens to these electrotypes, especially in their relationship to kidney and cardiovascular function?

Total body water levels change with changes in body weight. With weight loss, liver glycogen (polymers of glucose) stores that contain significant associate water are lost, followed by tissue water—fat 14% and lean body mass 75% water. Antidiuretic hormone conserves body water. Aldosterone increases the volume of fluid in the body and drives blood pressure up, while atrial natriuretic peptide controls body water, Na, K, and fat (adiposity), thereby reducing blood pressure. In the first few days of spaceflight, antidiuretic hormone is high but it then readjusts to controlling body water. Aldosterone and atrial natriuretic peptide reflect Na and water intakes to prevent high blood pressure.

Research from several Spacelab missions demonstrated that in microgravity, astronauts' bodies are able to adjust to the changes induced by microgravity, high Na intakes, and the stress of spaceflight. During spaceflight, Na intakes are generally high while K intakes are low as compared to needs. The astronauts adjust to microgravity within a few days. Although astronauts have less body water and a headward shift of water, these regulatory hormones primarily reflect dietary intakes.

The implications of these data for long-duration flights, such as the ISS, remain unknown. While on Earth, high Na intakes are most often associated with increasing blood pressure. Such intakes also may exacerbate bone loss, which is a problem for astronauts on long-duration spaceflights.

How Many Calories Do Astronauts Need in Spaceflight?

Because astronauts eat less, research determined the energy level (calories) needed during spaceflight. For selected missions, astronauts completed food records with a bar code reader to obtain good information about dietary intake during spaceflights. These studies showed that most astronauts ate less than their calculated energy needs—on average, about 25% less.

Scientists completed two types of research for measuring astronauts' body energy use. Energy can be determined from the products of energy metabolism: carbon energy sources like carbohydrates, protein, or fat + oxygen (O_2) = heat + carbon dioxide (CO_2). We used two methods for shuttle flights. For most flights, all the expired CO_2 was removed by chemical reaction with lithium hydroxide (LiOH) so the amount of CO_2 produced during a flight could be determined. CO_2 that was absorbed into the LiOH could be measured at the end of the flight to determine the energy use by the crew over the entire mission. The second method was to determine the amount of CO_2 and water loss over 3 to 5 days of time per astronaut. Astronauts consumed two stable isotopes (not radioactive), deuterium and ^{18}O, and the levels of these isotopes in urine were measured over a period of several days. The O_2 occurs in the CO_2 and water, but deuterium is only in the water; thus the method allowed for the determination of the CO_2 produced by an astronaut. Surprisingly for both methods, the levels of energy used were the same in flight as on Earth. As a result of this research, NASA dietitians use gender and weight, along with allowing for moderate activity values, to calculate astronauts' energy needs for spaceflight. This method has worked for many years to ensure adequate provision of space foods.

One of the major contributions of EVA research is the increased ability to predict energy expenditure during spacewalks. EVAs were routinely conducted from the shuttle. Energy expenditure was important for both suit design and dietary intakes before and after a spacewalk. After conducting thousands of EVA hours, NASA knows that the energy expenditure was not high for a short period of time, similar to walking 4 to 6.4 kph (2.5 to 4.0 mph). Nearly all EVAs lasted around 6 hours, however, and thus energy expenditure added up to a fairly high level. The lower energy levels occurred when crew members were within the payload bay, primarily doing less-demanding work for short periods. With the construction of the ISS, EVA activity increased along with duration to about 4 to 8 kJ/hr (250 to 500 kcal/hr). For an 8-hour EVA, this was significant. Of course, as previously described, increased energy expenditure increased water needs.

Protein and Amino Acids: Essential for Maintenance of Muscle Function

Protein and its components (amino acids) are essential for all body chemical reactions, structure, and muscles. In spaceflight, total body protein turnover increases as measured by the loss of the orally ingested stable isotope ^{15}N-glycine, which was measured in body tissues such as saliva and blood. Glycine is an amino acid that occurs abundantly in proteins, so changes in blood levels indicate the amount of glycine moved to the tissues for protein syntheses. Some of the increased turnover may be due to the catabolic state of weight loss found with many astronauts due to lower-than-needed energy intakes. There is evidence, even with short-term shuttle flights, that skeletal muscle function decreases. The mild stress of spaceflight found with hard-working astronauts may increase protein breakdown. Increased stress was determined by increased levels of blood and urinary cortisol. Dietary protein levels are already high in spaceflight. Protein recommendations are the same as ground-based dietary guidelines.

Bones Need Calcium and Vitamin D

Studies with Skylab astronauts in the 1970s and shuttle crew members found calcium (Ca) losses increased during flight, probably through removal from bone. NASA confirmed this initial observation of bone loss in the 1990s by using the latest biological markers technology. In fact, research showed that as soon as the astronauts arrived in space, they started losing bone.

Vitamin D is essential for the body to absorb the dietary Ca that is used for bone and other tissue functions. Vitamin D syntheses occur in the skin during exposure to sunlight. In spacecraft, however, sunlight is not tolerated: the rays are too strong because flights take place above the protective atmosphere. Studies completed during the Shuttle-Mir and European Space Agency research programs showed low vitamin D levels could be a problem for Ca absorption and good bone health. A vitamin D supplement is provided for ISS long-duration spaceflights.

Too Much Iron May Be Toxic

Changes in astronaut's red blood cells and iron (Fe) levels are similar to those of a person who lives at a high altitude (e.g., 3,658 m [12,000 ft]) coming to sea level. Both have too much available Fe (i.e., not bound up in red blood cells).

Fe is an important part of red blood cells that brings oxygen from the lungs to the tissues. Low levels of red blood cells cause fatigue. The initial decrease in plasma volume produces an increased concentration of red blood cells. The body may then perceive too many red blood cells and make adjustments accordingly. A 12% to 14% decrease in the number of red blood cells occurs within a couple of weeks of spaceflight. To maintain the correct percent of red blood cells (about 37% to 51% of the blood), newly formed red blood cells are destroyed until a new equilibrium is achieved. The red blood cell Fe is released back into the blood and tissues, and no mechanism except bleeding can reduce the level of body Fe. Excess Fe could potentially have toxic effects, including tissue oxidation and cardiovascular diseases. Shuttle research showed that the dietary Fe need is below that needed on Earth because of the reduced need for red blood cell production.

Summary of Nutritional Needs Found for Space Shuttle Astronauts

Nutrient	Level
Energy men 70 kg (~154 pounds)	12.147 MJ/d (2,874 kcal/d)
Energy women 60 kg (~132 pounds)	9.120 MJ/d (2,160 kcal/d)
Protein	12% to 15% of energy intake < 85 g/d
Water	2,000 ml/d
Na	1,500 to 3,500 mg/d
K	3,500 mg/d
Fe	10 mg/d
Vitamin D	10 ug/d
Calcium	800 to 1,200 mg

Changes in Immunity and Risk of Infectious Disease During Spaceflight

Humans are healthy most of the time, despite being surrounded by potentially infectious bacteria, fungi, viruses, and parasites. How can that be? The answer is the immune system. This highly complex and evolved system is our guardian against infectious diseases and many cancers. It is essential that astronauts have a robust, fully functional immune system just as it is for us on Earth. Astronauts are very healthy, exquisitely conditioned, and well nourished—all factors promoting healthy immunity. In addition, exposures to potential microbial pathogens are limited by a series of controls. All shuttle consumables (e.g., drinking water and food) and environment (breathing air and surfaces) are carefully examined to ensure the health and safety of the astronauts. Preflight restrictions are in place to limit exposure of astronauts to ill individuals. This system works very well to keep astronauts healthy before, during, and after spaceflight. Since spaceflight is thought to adversely affect the immune system and increase disease potential of microorganisms, the shuttle served as a platform to study immunity and microbes' ability to cause disease.

The Immune System

Your immune system quietly works for you, a silent army within your body protecting you from microorganisms that can make you sick. If it is working well, you never know it. But, when it's not working well, you will probably feel it.

The human immune system consists of many distinct types of white blood cells residing in the blood, lymph nodes, and various body tissues. The white blood cells of the immune system function in a coordinated fashion to protect the host from invading pathogens (bacteria, fungi, viruses, and parasites).

There are various elements of immunity. Innate immunity is the first line of defense, providing nonspecific killing of microbes. The initial inflammation associated with a skin infection at a wound site is an example of innate immunity, which is primarily mediated by neutrophils, monocytes, and macrophages. Cell-mediated immunity provides a specific response to a particular pathogen, resulting in immunologic "memory" after which immunity to that unique pathogen is conferred. This is the part of the immune system that forms the basis of how vaccines work. T cells are part of cell-mediated immunity, while B cells provide the humoral immune response. Humoral immunity is mediated by soluble antibodies—highly specific antimicrobial proteins that help eliminate certain types of pathogens and persist in the blood to guard against future infections. Upon initial exposure to a unique pathogen such as a herpes virus, the number of specific types of T and B cells expands in an attempt to eliminate the infection. Afterward, smaller numbers of memory cells continue to patrol the body, ever vigilant for another challenge by that particular pathogen. An immune response can be too strong at times, leading to self-caused illness without a pathogen. Examples of this are allergies and autoimmune diseases. At other times an immune response is not strong enough to fight an infection (immunodeficiency). Acquired Immunodeficiency Syndrome (AIDS) and cancer chemotherapy are both examples of immunodeficiency conditions caused by the loss of one or more types of immune cells.

Spaceflight-associated Changes in Immune Regulation

Changes in regulation of the immune system are found with both short- and long-duration spaceflight. Studies demonstrated that reduced cell mediated immunity and increased reactivation of latent herpes viruses occur during flight. In contrast, humoral (antibody) immunity was found to be normal when astronauts were immunized during spaceflight. Other shuttle studies showed reduced numbers of T cells and natural killer cells (a type of white blood cell important for fighting cancer and virally infected cells), altered distribution of the circulating leukocyte (white blood cell) subsets, altered stress hormone levels, and altered cytokine levels. Reduced antimicrobial functions of monocytes, neutrophils, and natural killer cells also occur when measured soon after spaceflight. Cytokines are small proteins produced by immune cells; they serve as molecular messengers that control the functions of specialized immune cells. Cytokines are released during infection and serve to shape the immune response. There are many cytokines, and they can be grouped in several ways. Th1 cytokines are produced by specialized T cells to promote cell-mediated immunity, whereas Th2 cytokines promote humoral immunity. One hypothesis to explain immune dysregulation during spaceflight is a shift in the release of cytokines from Th1 toward Th2 cytokines. Data gained from the shuttle research support this theory.

Selected Space Shuttle Immune Studies

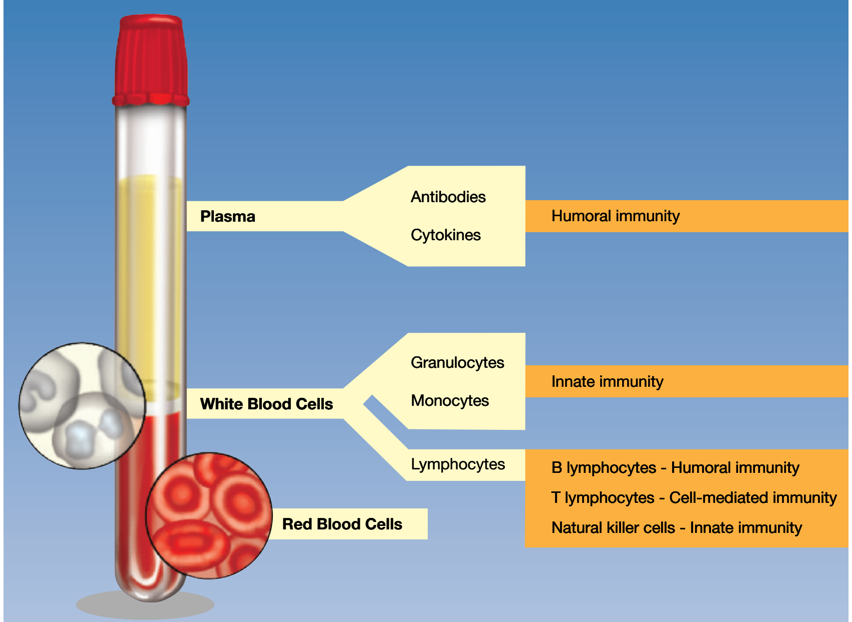
Hypersensitivity

Hypersensitivity occurs when the immune response to a common antigen is much stronger than normal. Usually, this manifests itself as a rash and is commonly measured via skin testing. Briefly, seven common antigens, bacteria, Proteus (common in urinary track infections), Streptococcus, tuberculin and Trichophyton (skin diseases), and yeast, Candida (known to increase in the immune compromised), are injected into the forearm skin. For most normal individuals, the cell-mediated arm of the immune system reacts to these antigens within 2 days, resulting in a visible red, raised area at the site of the injections. These reactions are expected and represent a healthy immune response. The red, raised circular area for each antigen can be quantified. To test astronauts, antigens were injected 46 hours before landing, and the evaluation of the reaction took place 2 hours after landing. Data showed that, as compared to preflight baseline testing, the cell-mediated immunity was significantly reduced during flight. Both the number of reactions and the individual reaction size were reduced during flight. These data indicated for the first time that immunity was reduced during short-duration spaceflight. Any associated clinical risks were unknown at the time. The possibility that this phenomenon would persist for long-duration flight was also unknown. Similar reductions in cell-mediated immunity were reported in Russian cosmonauts during longer missions.

Studies of the Peripheral Mononuclear Cells

Peripheral mononuclear cells are blood immune cells. Their numbers are a measure of the current immune status of a subject. During the latter stages of the 11-day STS-71 (1995) shuttle mission, the shuttle astronauts and the returning long-duration astronauts (from Mir space station) stained samples of their peripheral

Immunity Components of Blood



Innate immunity *comprises the cells and mechanisms that defend the host from infection by other organisms, in a nonspecific manner, and are found in all classes of plant and animal life.*

Humoral immunity *(involving substances found in the humours, or body fluids) is mediated by secreted antibodies that are produced by B lymphocytes and bind to antigens on the surfaces of invading microbes, which marks the microbes for destruction.*

Cell-mediated immunity *is an immune response that involves the activation of macrophages, natural killer cells, antigen-specific cytotoxic T lymphocytes, and the release of various cytokines in response to an antigen.*

Herpes Viruses Become Active During Spaceflight

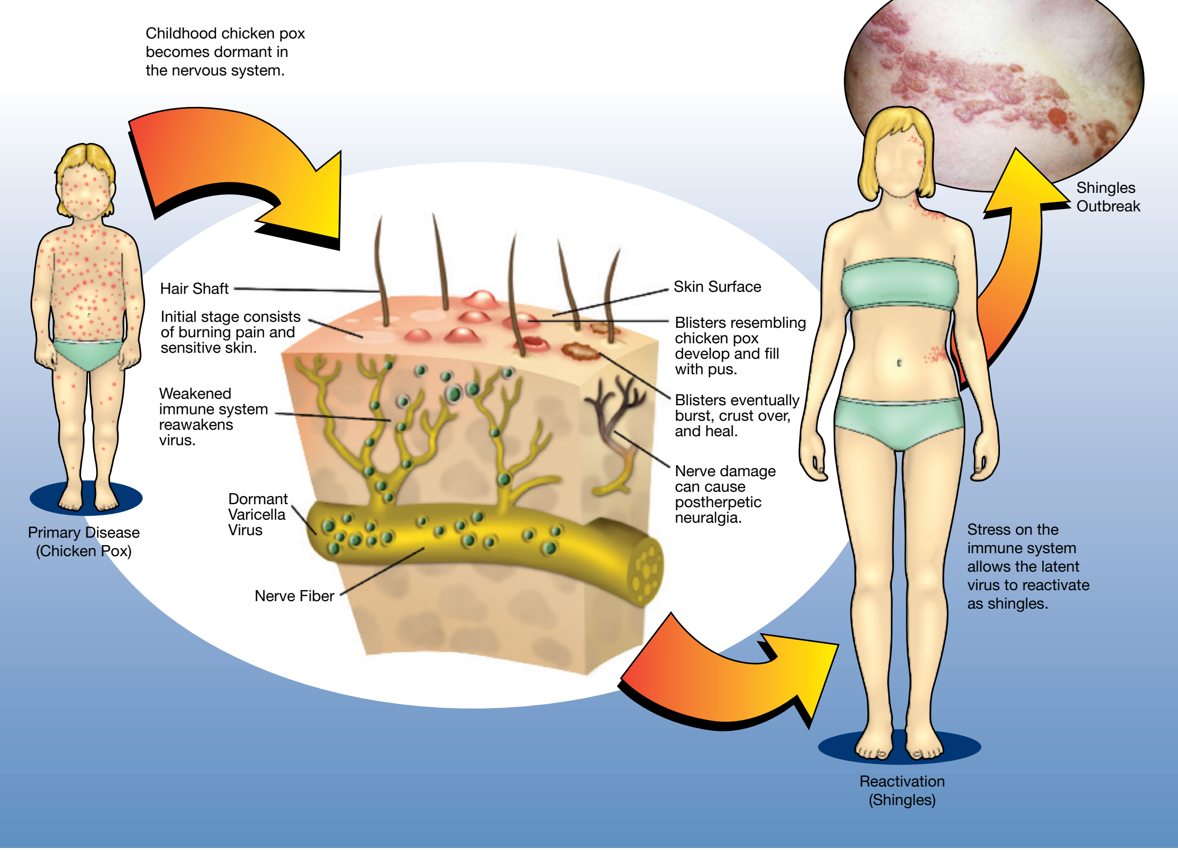
Herpes viruses, the most commonly recognized latent viruses in humans, cause specific primary diseases (e.g., chicken pox), but may remain inactive in nervous tissue for decades. When immune response is diminished by stress or aging, latent viruses reactivate and cause disease (e.g., shingles).

Epstein-Barr virus reactivated and appeared in astronauts' saliva in large numbers during spaceflight. Saliva collected during the flight phase contained tenfold more virus than saliva collected before or after flight. This finding correlated with decreased immunity in astronauts during flight. The causes of reduced immunity are unknown, but stress associated with spaceflight appears to play a prominent role, as the levels of stress hormones increase during spaceflight. The resulting decreased immunity allows the viruses to multiply and appear in saliva. The mechanism for Epstein-Barr virus reactivation seems to be a reduction in the number of virus-specific T cells leading to decreased ability to keep Epstein-Barr virus inactive.

Cytomegalovirus, another latent virus, also reactivated and appeared in astronaut urine in response to spaceflight. Healthy individuals rarely shed cytomegalovirus in urine, but the virus is commonly found in those with compromised immunity.

Scientists also studied Varicella-Zoster virus, the causative agent of chicken pox and shingles. These astronaut studies were the first reports of the presence of this infectious virus in saliva of asymptomatic individuals. A rapid, sensitive test for use in doctors' offices to diagnose shingles and facilitate early antiviral therapy resulting in reductions in nerve damage was a product of this study.

Role of Varicella-Zoster Virus in Chicken Pox and Shingles



blood immune cells with various dyes using unique and patented equipment developed at Johnson Space Center. These data showed that the major "bulk" levels of peripheral blood immune cells did not appear to be altered during flight.

Summary

The laboratory capabilities of the Space Shuttle allowed our first systematic assessment of the effects of space travel on the human immune system. Most indicators of immunity were altered during short-duration spaceflight, which is a uniquely stressful environment. These stressors were likely major contributors to the observed changes in immunity and the increased viral reactivation. Latent viruses were shown to be sensitive indicators of immune status. Bacterial pathogens were also shown to be more virulent during spaceflight. It is unknown whether these are transient effects or whether they will persist for long-duration missions. These important data will allow flight surgeons to determine the clinical risk for exploration-class space missions (moon, Mars) related to immunology, and to further the development of countermeasures for those risks. These studies and the hardware developed to support them serve as the platform from which new studies on board the ISS were initiated. It is expected that the ISS studies will allow a comprehensive assessment of immunity, stress, latent viral reactivation, and bacterial virulence during long-duration spaceflight.

Habitability and Environmental Health

Habitability

The shuttle contributed significantly to advances in technologies and processes to improve the habitability of space vehicles and enable humans to live and work productively in space. These shuttle-sponsored advances played a key role in our coming to view living and working in space as not only possible but also achievable on a long-term basis.

Habitability can be defined as the degree to which an environment meets an individual's basic physiological and psychological needs. It is affected by multiple factors, including the size of the environment relative to the number of people living and working there and the activities to be undertaken. Other habitability factors include air, water, and food quality as well as how well the environment is designed and equipped to facilitate the work that is to be done.

Resource limitations conspire to severely limit the habitability of space vehicles. Spacecraft usually provide minimal volume in which crew members can live and work due to the high cost of launching mass into space. The spacecraft's environmental control system is usually closed to some degree, meaning that spacecraft air and water are recycled and their quality must be carefully maintained and monitored. It may be several months between when food is prepared and when it is consumed by a space crew. There is normally a limited fresh resupply of foods. Care must be taken to assure the quality of the food before it is consumed.

The following sections illustrate some of the technologies and processes that contributed to the habitability of the shuttle and provided a legacy that will help make it possible for humans to live safely and work productively in space.

On STS-90 (1998), three Space Shuttle Columbia crew members—Astronauts James Pawelczyk, Richard Searfoss, and Richard Linnehan—meet on the middeck, where the crew ate, slept, performed science, prepared for extravehicular activities (spacewalks), exercised, took care of personal hygiene needs, and relaxed.

Innovations Improve Habilitability

Restraints and Mobility Aids

One of the most successful aids developed through the program, and one that will be used on future spacecraft, to support crew member physical stability in microgravity is foot restraints. It is nearly impossible to accomplish tasks in microgravity without stabilizing one's feet. NASA scientists developed several designs to make use of the body's natural position while in space. One design has foot loops and two-point leg/foot restraints used while a crew member works at a glove box. These restraints stabilize a crew member. The effectiveness of a restraint system relates to the simplicity of design, comfort, ease of use, adjustability, stability, durability, and flexibility for the range of the task. Other restraint systems developed include handrails, bungee cords, Velcro®, and flexible brackets. Furthermore, foot restraints aid in meeting other challenges such as limited visibility and access to the activity area. The latter difficulties can lead to prolonged periods of unnatural postures that may potentially harm muscles or exacerbate neurological difficulties.

Cursor Control Devices

The shuttle spacecraft environment included factors such as complex lighting scenarios, limited habitable volume, and microgravity that could render Earth-based interface designs less than optimal for space applications. Research in space human factors included investigating ways to optimize interfaces between crew members and spacecraft hardware, and the shuttle proved to be an excellent test bed for evaluating those interfaces.

For example, while computer use is quite commonplace today, little was known about how, or if, typical cursor control devices used on Earth would work in space. NASA researchers conducted a series of experiments to gather information about the desirable and undesirable characteristics of cursor control devices using high-fidelity environments. Experiments began in ground laboratories and then moved to the KC-135 aircraft for evaluation in a short-duration microgravity environment during parabolic flight. The experiments culminated with flight experiments on board Space Transportation System (STS)-29 (1989), STS-41 (1990), and STS-43 (1991). These evaluations and experiments used on-board crew members to take the devices through the prescribed series of tasks.

Example of a cursor control device with a trackball as used with ungloved and gloved hands.

Anchoring Improves Performance

Without Constraints

On STS-73 (1995) Astronaut Kathryn Thornton works at the Drop Physics Module on board the Spacelab science module located in the cargo bay of the Earth-orbiting shuttle. Notice that Dr. Thornton is anchoring her body by using a handrail for her feet and right hand. This leaves only one free hand to accomplish her tasks at that workstation and would be an uncomfortable position to hold for a long period of time.

With Constraints

Also on STS-73, Astronaut Catherine Coleman uses the advanced lower body extremities restraint at the Spacelab glove box. With Dr. Coleman's feet and knees anchored for body stability, she has both hands free to work for longer periods, providing her stability and comfort.

It cannot be assumed that computer equipment, like cursor control devices (e.g., a trackball, an optical mouse), used on Earth will behave the same way in space. Not only does microgravity make items "float," in general the equipment might be used while a crew member is wearing gloves—and the gloves could be pressurized at the time. For example, a trackball has a certain amount of movement allowed within its casing. In space, the ball will float, making it much more difficult to use the trackball and be accurate. During STS-43, the shuttle crew worked with a trackball that was modified to reduce the "play," and they reported that the mechanism worked well. This modification resulted in the fastest and most accurate responses.

Those tests in the flight environment paved the way for the types of equipment chosen for the International Space Station (ISS). The goal was to provide the best equipment to ensure quick and precise execution of tasks by crew members. As computer technology advances, NASA will continue investigations involving computer hardware as spacecraft and habitats are developed.

Shuttle Food System Legacy

Does NASA have a grocery store in space? The answer is no. One significant change NASA made to the space food system during the Space Shuttle Program, however, was the addition of a unique bar code on each food package to facilitate on-orbit science.

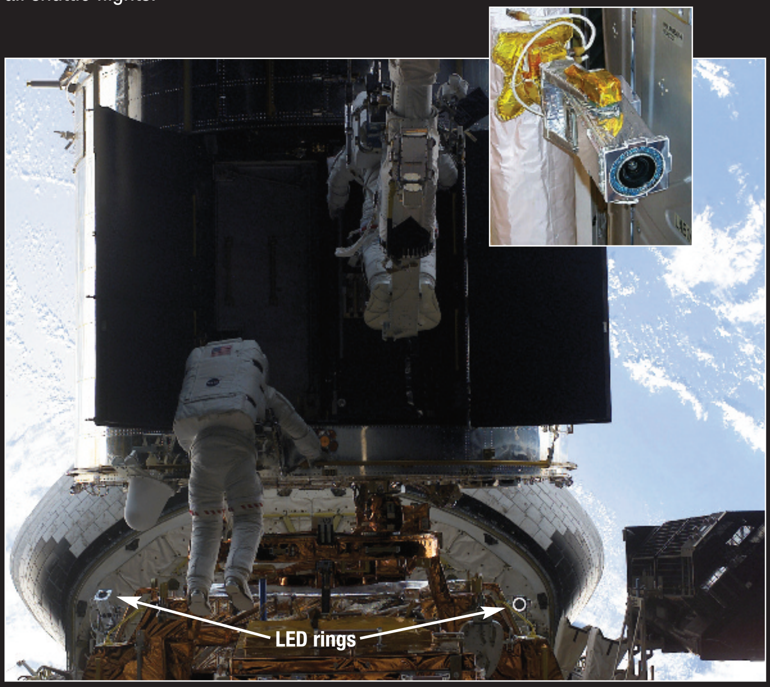
When crew members began participating in experiments on orbit that required them to track their food consumption, a method was needed that would promote accurate data collection while minimizing crew time; thus, the

White Light-emitting Diode Illuminators

As the shuttle orbited Earth, the crew experienced a sunrise and sunset every 45 minutes on average. This produced dramatic changes in lighting conditions, making artificial light sources very important for working in space.

Because of power and packaging constraints during the Space Shuttle Program, most artificial lights were restricted to fixed locations. With the assembly of the International Space Station and the maintenance of the Hubble Space Telescope, NASA felt it would be a great improvement to have lights mounted on all of the shuttle cameras. These light sources had to be durable, lightweight, and low in power requirements—the characteristics of light-emitting diodes (LEDs).

In 1995, NASA began using white LED lights for general illumination in camera systems several years in advance of industry. These early lights were designed as rings mounted around the lens of each camera. The four payload bay cameras were equipped with four LED light systems capable of being pointed with the pan-and-tilt unit of each camera. NASA also outfitted the two robotic arm cameras with LED rings. In June 1998, the first white 40 LED illumination system was flown. In May 1999, white 180 LED illuminators were flown. These lighting systems remained in use on all shuttle flights.



Light-emitting diode (LED) rings mounted on the two shuttle cameras in the aft payload bay of shuttle.

bar code. Crew members simply used a handheld scanning device to scan empty food packages after meals. The device automatically recorded meal composition and time of consumption. Not only did bar codes facilitate science, they also had the additional benefit of supporting the Hazard Analysis and Critical Control Point program for space food.

Hazard Analysis and Critical Control Point is a food safety program developed for NASA's early space food system. Having a unique bar code on each food package made it easy to scan the food packages as they were stowed into the food containers prior to launch. The unique bar code could be traced to a specific lot of food. This served as a critical control point in the event of a problem with a food product. If a problem had arisen, the bar code data collected during the scanning could have been used to locate every package of food from that same lot, making traceability much easier and more reliable. This system of bar coding food items carried over into the ISS food system.

Food preparation equipment also evolved during the shuttle era. The earliest shuttles flew with a portable water dispenser and a suitcase-sized food warmer. The first version of the portable water dispenser did not measure, heat, or chill water, but it did allow the crew to inject water into foods and beverages that required it. This dispenser was eventually replaced by a galley that, in addition to measuring and injecting water, chilled and heated it as well. The shuttle galley also included an oven for warming foods to serving temperature. Ironically, the food preparation system in use on the ISS does not include chilled water and, once again, involves the use of the suitcase-sized food warmer for heating US food products.

On STS-122 (2007), Astronaut Leland Melvin enjoys his dessert of rehydrated peach ambrosia. Also shown is the pair of scissors that is needed to open the pouch. On the pouch is a bar code that is used to track the food. The blue Velcro® allows the food to be attached to the walls.

Food packaging for shuttle foods also changed during the course of the program. The original rigid, rectangular plastic containers for rehydratable foods and beverages were replaced by flexible packages that took up less room in storage and in the trash. The increase in crew size and mission duration that occurred during the program necessitated this change. These improvements continue to benefit the ISS food system.

Environmental

Environmental Conditions

Maintaining a Healthy Environment During Spaceflight

The shuttle crew compartment felt like an air-conditioned room to astronauts living and working in space, and the Environmental Control and Life Support System created that habitable environment. In fact, this system consisted of a network of systems that interacted to create such an environment, in addition to cooling or heating various Orbiter systems or components. The network included air revitalization, water coolant loop, active thermal control, atmosphere revitalization pressure control, management of supply and wastewater, and waste collection.

The Air Revitalization System assured the safety of the air supply by using lithium hydroxide to maintain carbon dioxide (CO_2) and carbon monoxide at nontoxic levels. It also removed odors and trace contaminants through active charcoal, provided ventilation in the crew compartment via a network of fans and ducting, controlled the cabin's relative humidity (30% to 75%) and temperature (18°C [65°F] to 27°C [80°F]) through cabin heat exchangers for additional comfort, and supplied air cooling to various flight deck and middeck electronic avionics as well as the crew compartment.

The water coolant loop system collected heat from the crew compartment cabin heat exchanger and from some electronic units within the crew compartment. The system transferred the excess heat to the water coolant/Freon®-21 coolant loop heat exchanger of the Active Thermal Control System, which then moved excess heat from the various Orbiter systems to the system heat sinks using Freon®-21 as a coolant.

During ground operations, the ground support equipment heat exchanger in the Orbiter's Freon®-21 coolant loops rejected excess heat from the Orbiter through ground systems cooling. Shortly after liftoff, the flash evaporator (vaporization under reduced pressure) was activated and provided Orbiter heat rejection of the Freon®-21 coolant loops through water boiling. When the Orbiter was on orbit and the payload bay doors were opened, radiator panels on the underside of the doors were exposed to space and provided heat rejection. If combinations of heat loads and the Orbiter attitude exceeded the capacity of the radiator panels during on-orbit operations, the flash evaporator was activated to meet the heat rejection requirements. At the end of orbital operations, through deorbit and re-entry, the flash evaporator was again brought into operation until atmospheric pressure, about 30,480 m (100,000 ft) and below, no longer permitted the flash evaporation process to provide adequate cooling. At that point, the ammonia boilers rejected heat from the Freon®-21 coolant loops by evaporating ammonia through the remainder of re-entry, landing, and postlanding until ground cooling was connected to the ground support equipment heat exchanger.

Atmosphere revitalization pressure control kept cabin pressure around sea-level pressure, with an average mixture of 80% nitrogen and 20% oxygen. Oxygen partial pressure was maintained between 20.3 kPa (2.95 pounds per square inch, absolute [psia]) and 23.8 kPa (3.45 psia), with sufficient nitrogen pressure of 79.3 kPa (11.5 psia) added to achieve the cabin total pressure of 101.3 kPa (14.7 psia) +/-1.38 kPa (0.2 psia). The Pressure Control System received oxygen from two power reactant storage and distribution cryogenic oxygen systems in the mid-fuselage of the Orbiter. Nitrogen tanks, located in the mid-fuselage of the Orbiter, supplied gaseous nitrogen—a system that was also used to pressurize the potable and wastewater tanks located below the crew compartment middeck floor.

Three fuel-cell power plants produced the astronauts' potable water, to which iodine was added to prevent bacterial growth, that was stored in water tanks. Iodine functions like the chlorine that is added to municipal water supplies, but it is less volatile and more stable than chlorine. Condensate water and human wastewater were collected into a wastewater tank, while solid waste remained in the Waste Collection System until the Orbiter was serviced during ground turnaround operations.

Space Shuttle Environmental Standards

We live on a planet plagued with air and water pollution problems because of the widespread use of chemicals for energy production, manufacturing, agriculture, and transportation. To protect human health and perhaps the entire planet, governmental agencies set standards to control the amount of potentially harmful chemicals that can be released into air and water and then monitor the results to show compliance with standards. Likewise, on the shuttle, overheated electronics, systems leaks, propellants, payload chemicals, and chemical leaching posed a risk to air and water quality. Standards were necessary to define safe air and water, along with monitoring systems to demonstrate a safe environment.

Air

Both standards and methods as well as instruments to measure air quality were needed to ensure air quality. For the shuttle, NASA had a formalized process for setting spacecraft maximum allowable concentrations. Environmental standards for astronauts must consider the physiological effects of spaceflight, the continuous nature of airborne exposures, the aversion to drinking water with poor aesthetic properties, and the reality that astronauts could not easily leave a vehicle if it were to become dangerously polluted.

On Earth, plants remove CO_2—a gas exhaled in large quantities as a result of human metabolism—from the atmosphere. By contrast, CO_2 is one of the most difficult compounds to deal with in spaceflight. For example, accumulation of CO_2 was a critical problem during the ill-fated Apollo 13 return flight. As the disabled spacecraft returned to Earth, the crew had to implement unanticipated procedures to manage CO_2. This involved duct-taping filters and tubing together to maintain CO_2 at tolerable levels. Such extreme measures were not necessary aboard shuttle; however, if the crew forgot to change out filters, the CO_2 levels could have exceeded exposure standards within a few hours.

Although older limits for CO_2 were set at 1%, during NASA's new standard-setting process with the National Research Council it became

Combustion Product Analyzer Ensured Crew Breathed Clean Air After Small Fire in Russian Space Station

The combustion product analyzer flew on every Space Shuttle flight from 1990 through 1999 and proved its value during the Shuttle-Mir Program (1995-1998). On the seventh joint mission in 1998, no harm seemed to have occurred during an inadvertent valve switch on an air-purifying scrubber. In fact, during this time, the crew—including American Andrew Thomas—participated in a video presentation transmitted back to Earth; however, shortly after the valve switch, the crew experienced headaches. As on Earth, when occupants of a house or building experience headaches simultaneously, it can indicate that the air has been severely degraded. The crew followed procedures and activated the combustion product analyzer, designed to detect carbon monoxide (CO), hydrogen cyanide, hydrogen chloride, and hydrogen fluoride. The air contained over 500 parts per million of CO, significantly above acceptable concentrations. This high concentration was produced by hot air flowing through a paper filter and charcoal bed and then into the cabin when the valve was mistakenly switched on. The combustion product analyzer was used to follow the cleanup of the CO. Archival samples confirmed the accuracy of the analyzer's results. The success of this analyzer and its successor—the compound specific analyzer-combustion products—led to the inclusion of four units (compound specific analyzer-combustion products) on the International Space Station and a combustion products analyzer on future crew exploration vehicles.

Commander Robert Gibson and Astronaut Jan Davis check the combustion product analyzer during STS-47 (1992).

clear that 1% was too high and, therefore, the spacecraft maximum allowable concentration was reduced to 0.7 %. Even this lower value proved to be marginal under some conditions. For example, the shuttle vehicle did not have the capability to measure local pockets of CO_2, and those pockets could contain somewhat higher levels than were found in the general air. That was especially true in the absence of gravity where convection was not available to carry warm, exhaled air upward from the astronaut's breathing zone. Use of a light-blocking curtain during a flight caused the crew to experience headaches on awakening, and this was attributed to accumulation of CO_2 because the crew slept in a confined space and the curtain obstructed normal airflow.

Setting air quality standards for astronaut exposures to toxic compounds is not a precise science and is complicated. NASA partnered with the National Research Council Committee on Toxicology in 1989 to set and rigorously document air quality standards for astronauts during shuttle spaceflight.

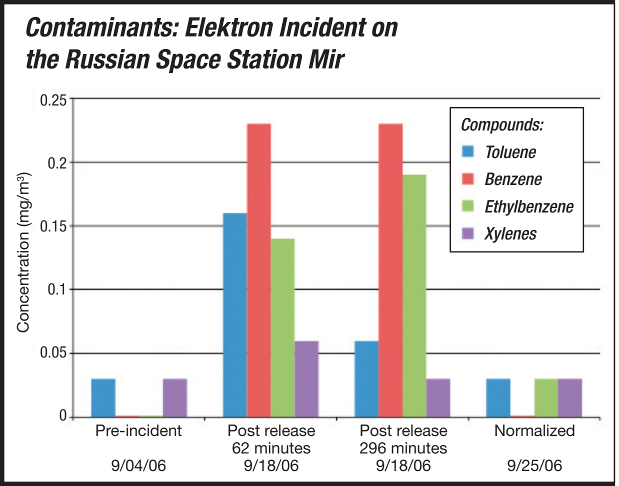
The spaceflight environment is like Earth in that exposure standards can control activities when environmental monitors suggest the need for control. For example, youth outdoor sports activities are curtailed when ozone levels exceed certain standards on Earth. Likewise, spacecraft maximum allowable concentrations for carbon monoxide, a toxic product of combustion, were used to determine criteria for the use of protective masks in the event of an electrical burn. The shuttle Flight Rules provided the criteria. Ranges for environmental monitoring instruments were also based on spacecraft maximum allowable

Measuring Airborne Volatile Organic Compounds

Volatile organic compounds are airborne contaminants that pose a problem in semi-closed systems such as office buildings with contributions from carpets, furniture, and paper products as well as in closed systems such as airplanes and spacecraft. These contaminates cause headaches, eye and skin irritation, dizziness, and even cancer.

NASA needed to be able to measure such compounds for the International Space Station (ISS), a long-term closed living situation. Therefore, in the latter 1990s, the shuttle was used as a test bed for instruments considered for use on the ISS.

Shuttle flights provided the opportunity to assess the performance of a volatile organic analyzer-risk mitigation experiment in microgravity on STS-81 (1997) and STS-89 (1998). Results confirmed component function and improved the instrument built for ISS air monitoring.



This chart plots the course of the Elektron incident showing the concentrations of toluene, benzene, ethylbenzene, and xylenes—all serious toxins—released into the air. In 2004, the levels of the four contaminates were very low, as measured by the volatile organic analyzer and grab samples returned to Earth for analysis. During the incident, the analyzer measured increases in the four compounds. Grab samples confirmed the higher levels for these compounds and verified that the analyzer had worked. The next available data showed the contaminants had returned to very low levels.

The volatile organic analyzer operated episodically on ISS since 2001 and provided timely and valuable information during the Elektron (Russian oxygen generation system) incident in September 2006 when the crew tried to restart the Elektron and saw what appeared to be smoke emanating from the device. The volatile organic analyzer collected and analyzed samples prior to the event and during cleanup. Data showed that the event had started before the crew noticed the smoke, but the concentrations of the contaminants released were not a health hazard.

During the STS-89 shuttle dock with Russian space station Mir, Astronaut Bonnie Dunbar goes through her checklist to start the volatile organic analyzer sample acquisition sequence.

concentrations. For example, the monitoring requirements for hydrogen cyanide, another toxic combustion product, were based on spacecraft maximum allowable concentrations to determine how sensitive the monitor must be. By analogy with Earth-based environmental monitoring, spaceflight monitors needed the ability to indicate when safe conditions had returned so that normal operations could resume.

Water

NASA recognized the need for unique water-quality standards. Although the effort to set specific water-quality standards, called spacecraft water exposure guidelines, did not begin until 2000, NASA quickly realized the value of these new limits. One of the first spacecraft water-exposure guidelines set was for nickel, a slightly toxic metal often found in water that has been held in metal containers for some time. The primary toxic effect of concern was nickel's adverse effect on the immune system. High nickel levels had been observed from time to time in the shuttle water system based on the existing requirements in NASA documents. This sometimes caused expensive and schedule-breaking activity at Kennedy Space Center to deal with these events. When National Research Council experts accepted a new, higher standard, the old standard was no longer applied to shuttle water and the nickel "problem" became history.

Toxicants From Combustion

Fire is always a concern in any environment, and a flame is sometimes difficult to detect. First responders must have instruments to quickly assess the contaminants in the air on arriving at the scene of a chemical spill, fire, or building where occupants have been overcome by noxious fumes. Additionally, these instruments must be capable of determining when the cleanup efforts have made it safe for unprotected people to return. When a spill, thermodegradation, or unusual odor occurs on a spacecraft, crew members are the first responders. They need the tools to assess the situation and track the progress of the cleanup. As a result of shuttle experiments, NASA was able to provide crews with novel instruments to manage degradations in air quality caused by unexpected events.

The combustion products analyzer addressed spacecraft thermodegradations events, which can range from overheated wiring to a full-fledged fire. Fire in a sealed, remote capsule is a frightening event. A small event—overheated wire (odor produced)—occurred on STS-6 (1983), but it wasn't until 1988, when technology advances improved the reliability and shrank the size of monitors, that a search for a combustion products analyzer was initiated. Before the final development of the analyzer, however, a more significant event occurred on STS-28 (1989) that hastened the completion of the instrument. On STS-28, a small portion of teleprinter cable pyrolyzed and the released contaminants could have imperiled the crew if more of the cable had burned. The combustion products analyzer requirements were to measure key contaminants in the air following thermodegradation incidents, track the effectiveness of cleanup efforts, and determine when it was safe to remove protective gear.

Toxic containments may be released from burning materials depending on the type of materials and level of oxygen. For spaceflight, NASA identified five marker compounds: carbon monoxide (odorless and colorless gas) released from most thermodegradation events; hydrogen chloride released from polyvinyl chloride; hydrogen fluoride and carbonyl fluoride associated with Teflon®; and hydrogen cyanide released from Kapton®-coated wire and polyurethane foam. The concentration range monitored for each marker compound was based on the established spacecraft maximum allowable concentrations at the low end and, at the other end of the range, an estimated highest concentration that might be released in a fire.

An upgraded combustion product analyzer is now used on the ISS, demonstrating that the technology and research on fire produced methods that detect toxic materials. The results indicate when it is safe for the astronauts to remove their protective gear.

Safeguarding the Astronauts From Microorganisms—Prevention of Viral, Bacterial, and Fungal Diseases

Certain bacteria, fungi, and viruses cause acute diseases such as upper respiratory problems, lung diseases, and gastrointestinal disease as well as chronic problems such as some cancers and serious liver problems. In space, astronauts are exposed to microorganisms and their by-products from the food, water (both used for food and beverage rehydration, and for personal hygiene), air, interior surfaces, and scientific investigations that include animals and microorganisms. The largest threat to the crew members, however, is contact with their crewmates.

The shuttle provided an opportunity to better understand the changes in microbiological contamination because, unlike previous US spacecraft for human exploration, the shuttle was designed to be used over many years with limited refurbishment between missions. Risks associated with the long-term accumulation of microorganisms in a crewed compartment were unknown at the start of the shuttle flights; however, many years of studying these microorganisms produced changes that would prevent problems for the ISS and the next generation of crewed vehicles. With assistance from industry and government standards (e.g., Environmental Protection Agency) and expert panels, NASA established acceptability limits for bacteria and fungi in the environment (air and surfaces) and consumables (food and water). Preflight monitoring for spaceflight was thorough and included the crew, spaceflight food, potable water, and vehicle air and surfaces to ensure compliance with these acceptability standards. NASA reviewed all flight payloads for biohazardous materials. Space Shuttle acceptability limits evolved with time and were later used to develop contamination limits for the ISS and the next generation of crewed vehicles.

Microbial growth in the closed environment of spacecraft can lead to a wide variety of adverse effects including infections as well as the release of volatile organics, allergens, and toxins. Biodegradation of critical materials, life support system fouling, and bio-corrosion represent other potential microbial-induced problems. Shuttle crew members sometimes reported dust in the air and occasional eye irritation. In-flight monitoring showed increased bacterial levels in the shuttle air as the number of days in space increased. Dust, microbes, and even water droplets from a simple

Adverse Effects of Microorganisms

- *Infectious diseases*
- *Toxin production*
- *Plant diseases*
- *Allergies*
- *Food spoilage*
- *Volatile release*
- *Material degradation*
- *Immune alteration*
- *Environmental contamination*

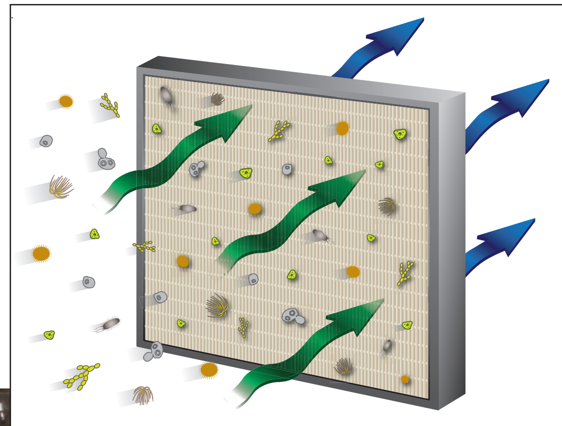
Astronauts Megan McArthur, Michael Massimino (center), and Andrew Feustel prepare to eat a meal on the middeck of Atlantis (STS-125 [2009]).

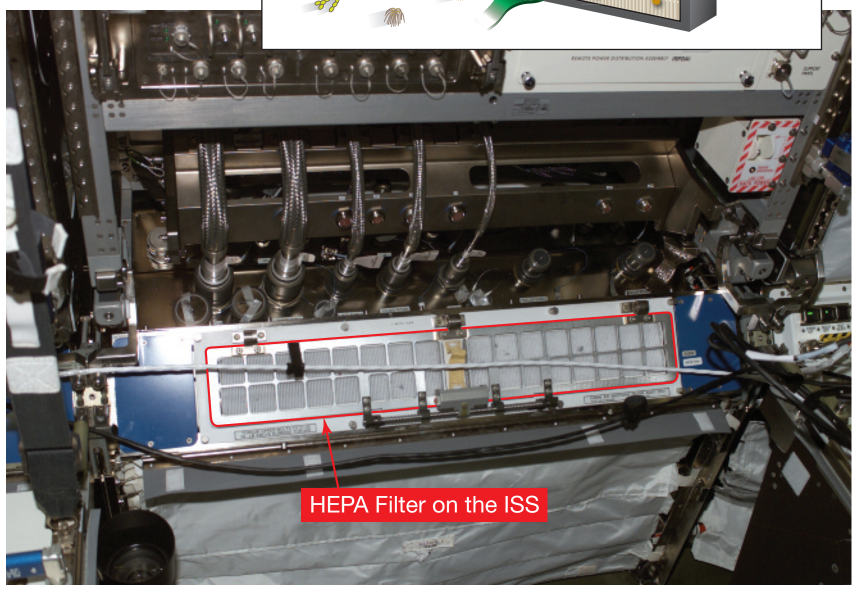
sneeze settle out on Earth. The human body alone sheds about 1 billion skin cells every week. Particles remain suspended in space and carry microorganisms and allergens that pose a health risk to the crew.

The shuttle's air filters were designed to remove particles greater than 70 micrometers. The filters removed most skin cells (approximately 100 micrometers) and larger airborne contaminants (e.g., lint); however, they did not quickly remove smaller contaminants such as bacteria, viruses, and particulates. When the shuttle was modified for longer flights of up to 2 weeks, an auxiliary cabin air cleaner provided filtration that removed particles over 1 micrometer. As the air recirculated through the vehicle, the filter captured skin cells, lint, microorganisms, and other debris. This resulted in much-improved air quality. These high-efficiency particulate air (HEPA) filters (99.97% efficient at removing particles >0.3 micrometers) provide dust- and microbe-free air. This led to the inclusion of HEPA filters in the Air Revitalization System on the ISS where monitoring has shown that air quality has been maintained below stringent microbial requirements. HEPA filters are also planned for other crewed vehicles.

Microbial growth can result in volatile chemicals that can produce objectionable odors or irritants. For example, during the STS-55 (1993) mission, the crew reported a noxious odor that was later found by extensive ground studies to be a mixture of three dimethyl sulfides resulting from the bacterial metabolism of urine in a waste storage container.

As illustrated, a high-efficiency particulate air (HEPA) filter removes particles from recirculated air, resulting in improved air quality. The HEPA filter in the air-purification system on the International Space Station (ISS), as pictured below, is of a higher quality than purification systems used in offices and homes.





These challenges provided opportunities for improvements that served as "lessons learned," which were applied to all future missions. Lessons learned from the shuttle experiences led to NASA's current approach of prevention first and mitigation second. Many microbiological risks associated with living in space can be prevented or mitigated to acceptable levels through engineering approaches. Prevention strategy begins with the design phase and includes steps that discourage excessive microbial growth. Use of antimicrobial materials, maintaining relative humidity below 70%, avoiding condensation buildup, implementing rigorous housekeeping, maintaining air and water filtration, and judicially using disinfectants are effective steps limiting the adverse effects of microorganisms. In all, the microbiological lessons learned from the Space Shuttle era resulted in improved safety for all future spacecraft.

Astronaut Health Care

Astronaut health care includes all issues that involve flight safety, physiological health, and psychological health. During the Space Shuttle Program, space medicine was at the "heart" of each issue.

Space medicine evolved during the shuttle's many transitional phases, from the experimental operational test vehicle to pre-Challenger (1986) accident, post-Challenger accident, unique missions such as Department of Defense and Hubble, Spacelab/Spacehab, Extended Duration Orbiter Project, Shuttle–Mir, Shuttle-International Space Station (ISS), post-Columbia (2003) accident and, finally, the ISS assembly completion. All of these evolutionary phases required changes in the selection of crews for spaceflight, preparation for spaceflight, on-orbit health care, and postflight care of the astronauts.

Astronauts maintained their flight status, requiring both ambulatory and preventive medical care of their active and inactive medical conditions. Preflight, on-orbit, and postflight medical care and operational space medicine training occurred for all flights. The medical team worked with mission planners to ensure that all facets of coordinating the basic tenets of personnel, equipment, procedures, and communications were included in mission support. During the shuttle era, the Mission Control Center was upgraded, significantly improving communications among the shuttle flight crew, medical team, and other flight controllers with the flight director for the mission. Additionally, the longitudinal study of astronaut health began with all medical data collected during active astronaut careers. NASA used post-retirement exams, conducted annually, to study the long-term effect of short-duration spaceflight on crews.

Space Adaptation Syndrome

The first thing an astronaut noticed was a fluid shift from his or her lower extremities to his or her torso and upper bodies, resulting in a facial fullness. Ultimately, this fluid shift caused a stretch on the baroreceptors in the arch of the aorta and carotid arteries and the astronaut would lose up to 1.5 to 2 L (1.6 to 2.1 qt) of fluid.

Secondly, over 80% of crew members experienced motion sickness, from loss of appetite to nausea and vomiting. Basic prevention included attempting to maintain an Earth-like orientation to the vehicle. Also, refraining from exaggerated movements helped. If symptoms persisted despite preventive measures, medications in an oral, suppository, or injectable form were flown to treat the condition.

The next thing crew members noticed was a change in their musculoskeletal system. In space, the human body experiences a lengthening and stretching of tendons and ligaments that hold bones, joints, and muscles together. Also, there was an unloading of the extensor muscles that included the back of the neck and torso, buttocks, and back of the thighs and calves. Preventive measures and treatment included on-orbit exercise, together with pain medications.

Additional changes were a mild decrease in immune function, smaller blood cell volume, and calcium loss. Other problems included headache, changes in visual acuity, sinus congestion, ear blocks, nose bleeds, sore throats, changes in taste and smell, constipation, urinary infections and difficulty in urination, fatigue, changes in sleep patterns with retinal flashes during sleep, minor behavioral health adjustment reactions, adverse reactions to medications, and minor injuries.

Astronaut Selection and Medical Standards

Due to increasing levels of flight experience and changes in medical delivery, medical standards for astronaut selection evolved over the shuttle's 30 years, as it was important that the selected individuals met certain medical criterion to be considered as having the "right stuff." The space agency initially adopted these standards from a combination of US Air Force, US Navy, and Federal Aviation Administration as well as previous standards from the other US space programs. The shuttle medical standards were designed to support short-duration spaceflights of as many as 30 days. NASA medical teams, along with experts in aerospace medicine and systems specialties, met at least every 2 years to review and update standards according to a combination of medical issues related to flights and the best evidence-based medicine at that time. These standards were very strict for selection, requiring optimum health, and they eventually led to the ISS medical requirements for long-duration spaceflight.

Preventive medicine was the key to success. Astronauts had an annual spaceflight certification physical exam to ensure they remained healthy for spaceflight, if assigned. Also, if a potential medical condition or problem was diagnosed, it was treated appropriately and the astronaut was retained for spaceflight. Medical exams were completed 10 days prior to launch and again at 2 days prior to launch to ensure that the astronaut was healthy and met the Flight Readiness Review requirements for launch. Preventive health successfully kept almost 99% of the astronauts retained for spaceflight duties during their careers with NASA.

Crew Preparation for Flight

Approximately 9 months prior to each shuttle flight, the medical team and flight crew worked together to resolve any medical issues. The flight medical team provided additional medical supplies and equipment for the crew's active and inactive medical problems.

Spaceflight inspired some exceptional types of medical care. Noise was a hazard and, therefore, hearing needed to be monitored and better hearing protection was included. Due to the presence of radiation, optometry was important for eye health and for understanding the impact of radiation exposure on cataract development. Also, in space visual changes occurred with elongation of the eye, thus requiring special glasses prescribed for flight. All dental problems needed to be rectified prior to flight as well. Behavioral health counseling was also available for the crews and their families, if required. This program, along with on-orbit support, provided the advantage of improved procedures and processes such as a family/astronaut private communication that allowed the astronaut another avenue to express concerns.

Over the course of the Space Shuttle Program, NASA provided improved physical conditioning and rehabilitation medicine throughout the year to keep crews in top physical shape. Before and during all shuttle flights, the agency provided predictions on solar activity and accumulation of the radiation astronauts received during their careers to help them limit their exposure.

Prior to a shuttle mission, NASA trained all astronauts on the effects of microgravity and spaceflight on their bodies to prepare them for what to expect in the environment and during the physiological responses to microgravity. The most common medical concerns were the space adaptation syndrome that included space motion sickness and the cardiovascular, musculoskeletal, and neurovestibular changes on orbit. Other effects such as head congestion, headaches, backaches, gastrointestinal, genitourinary, crew sleep, rest, fatigue, and handling of injuries were also discussed. The most common environmental issues were radiation, the biothermal considerations of heat and cold stress, decompression sickness from an extravehicular activity (EVA), potable water contamination, carbon dioxide (CO_2), and other toxic exposures. Re-entry-day (return to Earth) issues were important because the crew transitioned quickly from microgravity into a hypergravity, then into a normal Earth environment. Countermeasures needed to be developed to overcome this rapid response by the human body. These countermeasures included the control of cabin temperature, use of the g-suit, and entry fluid loading, which helped restore fluid in the plasma volume that was lost on orbit during physiological changes to the cardiovascular system. It was also important to maximize the health and readaptation of the crew on return to Earth in case emergency bailout, egress, and escape procedures needed to be performed.

The addition of two NASA-trained crew medical officers further improved on-orbit medical care. Training included contents of the medical kits with an understanding of the diagnostic and therapeutic procedures contained within the medical checklist. These classes were commonly referred to as "4 years of medical school in three 2-hour sessions." Crew medical officers learned basic emergency and nonemergency procedures common to spaceflight. This training included how to remove foreign bodies from the eye; treat ear blocks and nose bleeds; and start IVs and give medications that included IV, intramuscular, and subcutaneous injections and taught the use of oral and suppository intake. Emergency procedures included training in cardiopulmonary resuscitation, airway management and protection, wound care with Steri-Strip™ and suture repair, bladder catheterization, and needle thoracentesis. NASA taught special classes on how to mitigate the possibility of decompression sickness from an EVA. This incorporated the use of various EVA prebreathe protocols developed for shuttle only or shuttle-ISS docking missions. Crews were taught to recognize decompression sickness and how to medically manage this event by treating and making a disposition of the crew member if decompression sickness occurred during an EVA.

Environmental exposure specialty classes included the recognition and management of increased CO_2 exposure, protection and monitoring in case of radiation exposure from either artificial or solar particle events, and the

Shuttle Medical Kit

The Shuttle Orbiter Medical System had generic and accessory items and provided basic emergency and nonemergency medical care common to spaceflight. The contents focused on preventing illnesses and infection as well as providing pain control. It also provided basic life support to handle certain life-threatening emergencies, but it did not have advanced cardiac life support capabilities. Initially, it included two small kits of emergency equipment, medications, and bandages; however, this evolved into a larger array of sub packs as operational demands required during the various phases of the program. The generic equipment remained the same for every flight, but accessory kits included those mission-specific items tailored for the crew's needs. Overall, the Shuttle Orbiter Medical System included: a medical checklist that helped the on-board crew medical officers diagnose and treat on-orbit medical problems; an airway sub pack; a drug sub pack; an eye, ear, nose, throat, and dental sub pack; an intravenous sub pack; saline supply bags; a trauma sub pack; a sharps container; a contamination cleanup kit; patient and rescue restraints; and an electrocardiogram kit.

biothermal consideration of heat stress in case the Orbiter lost its ability to maintain cooling. Toxicology exposure specialty classes focused on generic toxic compounds unique to the Orbiter and included hypergolic exposure to hydrazines and nitrogen tetroxide, ammonia, and halogenated hydrocarbons such as halon and Freon®. Certain mission-specific toxic compounds were identified and antidotes were flown in case of crew exposure to those compounds. NASA trained crew members on how to use the toxicology database that enabled them to readily identify the exposed material and then provide protection to themselves during cleanup of toxic compounds using a specialty contamination cleanup kit. Astronauts were also trained on fire and smoke procedures such as the rapid quick-don mask for protection while putting out the fire and scrubbing the cabin atmosphere. In such an incident, the atmosphere was monitored for carbon monoxide, hydrogen cyanide, and hydrogen chloride. When those levels were reduced to nontoxic levels, the masks were removed.

The potable water on the shuttle was monitored 15 and 2 days preflight to ensure quality checks for iodine levels, microbes, and pH. Crews were instructed in limiting their iodine (bacteriostatic agent added to stored shuttle water tank) intake by installing/reinstalling a galley iodine-reduction assembly device each day that limited their intake of iodine from the cold water. The crews also learned how to manage the potable water tank in case it became contaminated on orbit.

Over the course of the program, NASA developed Flight Rules that covered launch through recovery after landing and included risky procedures such as EVAs. These rules helped prevent medical conditions and were approved through a series of review boards that included NASA missions managers, flight directors, medical personnel, and outside safety experts. The Flight Rules determined the preplanned decision on how to prevent or what to do in case something went wrong with the shuttle systems. Other controlled activities were rules and constraints that protected and maintained the proper workload, rest, and sleep prior to flight and for on-orbit operations during the presleep, work, and post-sleep periods. The flight-specific sleep and work schedule was dependent on the launch time and included the use of bright and dim lights, naps, medications, and shifts in sleep and work patterns. NASA developed crew schedules to prevent crew fatigue—an important constraint for safety and piloted return.

Although implemented in the Apollo Program, preflight crew quarantine proved to be essential during the Space Shuttle Program to prevent infectious disease exposure prior to launch. The quarantine started 7 days prior to launch. At that point, all crew contacts were monitored and all contact personnel received special training in the importance of recognizing the signs and symptoms of infectious disease, thus limiting their contact with the flight crew if they became sick. This program helped eliminate the exposure of an infectious disease that would delay launch and was successful in that only one flight had to be delayed because of a respiratory illness.

Readiness for Launch and On-orbit Health Care

Launch day is considered the most risky aspect of spaceflight. As such, medical teams were positioned to work directly with mission managers as well as the shuttle crew during this critical stage. On launch day, one crew medical doctor was stationed in the Launch Control Center at Kennedy Space Center (KSC) with KSC medical emergency care providers. They had direct communication with Johnson Space Center Mission Control, Patrick Air Force Base located close to KSC, alternate landing sites at Dryden Flight Research Center/Edwards Air Force Base, White Sands Space Harbor, and transoceanic abort landing medical teams. Another crew medical doctor was pre-staged near a triage site with the KSC rescue forces and trauma teams at a site determined by wind direction. Other forces, including military doctors and US Air Force pararescuers in helicopters, stood on "ready alert" for any type of launch contingency.

Once launch occurred and the crew reached orbit in just over 8 minutes, physiologic changes began. Every crew member was unique and responded to these changes differently on a various scale.

Crew Transport Vehicle

Prior to the 1990s' Extended Duration Operations Program, immediate postflight care was conducted in the "white room" or on a small stairwell platform that mated with the port-side hatch of the shuttle. Typically, astronaut support personnel, a "suit" technician, and the crew medical team entered the shuttle, postlanding. If a medical condition occurred and a crew member had problems readapting to the Earth environment, this care was conducted in the shuttle interior or on the platform of the "white room" stairwell. One major improvement to landing-day medical care was the change to a mobile postflight crew transport vehicle. This vehicle was redesigned to mate with the Orbiter and provided private transport of the crew to a location where they could receive better care, if required. The vehicle was outfitted with lounge chairs, a rest room, gurneys, and medical supplies. The crew could first be stabilized. Then, those who didn't need to remain on board for research testing could perform a crew walk around the Orbiter.

The crew transport vehicle was first used with STS-40 at Dryden Flight Research Center (DFRC), California, in 1991 and supported all subsequent shuttle flights at both DFRC and Kennedy Space Center, Florida.

All medical conditions were discussed during a private medical communication with the crew every flight day. The results at the end of a discussion were one of the following: no mission impact (the majority); possible mission impact; or mission impact. With possible mission impacts, further private discussion with the crew and flight director, other crew members, and other medical care specialists occurred. Fortunately for the program, all possible mission impacts were resolved with adjustments to the timeline and duties performed by the crew so the mission could continue to meet its objectives. If a mission impact were to occur, changes would be made public but not the specifics of those changes. Due to the Medical Privacy Act of 1974, details of these private medical conferences could not be discussed publicly.

Private family communication was another important aspect, psychologically, of on-orbit health care. Early in the program, this was not performed but, rather, was implemented at the start of the Extended Duration Orbiter Medical Project (1989-1996) and involved flights of 11 days or longer.

The second riskiest time of spaceflight was returning to Earth. To overcome hypotension or low blood pressure during re-entry, the crew employed certain countermeasures. The crew would fluid load to restore the lost plasma volume by ingesting 237 ml (8 oz) of water with two salt tablets every 15 minutes, starting 1 hour prior to the time of deorbit ignition and to finish this protocol by entry interface (i.e., the period right before the final return stage) for a total fluid loading time of 90 minutes. Body weight determined the total amount ingested. After the Challenger accident, NASA developed a launch and re-entry suit that transitioned from the standard Nomex® flight suit, to a partial pressure suit, then on to a full pressure suit called the advanced crew escape suit. An incorporated g-suit could be used to compress lower extremities and the abdomen, which prevented fluid from accumulating in those areas. Another post-Challenger accident lesson learned was to cool the cabin and incorporate the liquid cooling within the launch and re-entry suit to prevent heat loads that could possibly compromise the landing performance of the vehicle by the commander and pilot (second in command). Finally, each crew member used slow, steady motions of his or her head and body to overcome the neurovestibular changes that occurred while transitioning from a microgravity to an Earth environment. All items were important that assisted the crew in landing the vehicle on its single opportunity in a safe manner.

Postflight Care

Once the landed shuttle was secured from any potential hazards, the medical team worked directly with returning crew members. Therefore, medical teams were stationed at all potential landing sites—KSC in Florida, Dryden Flight Research Center in California, and White Sands in New Mexico.

When the crew returned to crew quarters, they reunited with their families and then completed a postflight exam and mini debrief. Crew members were advised not to drive a vehicle for at least 1 day and were restricted from aircraft flying duties due to disequilibrium—problems with spatial and visual orientation. NASA performed another postflight exam and a more extensive debrief at return plus 3 days and, if passed, the crew member was returned to aircraft flight duties. Mission lessons learned from debriefs were shared with the other crew medical teams, space medicine researchers, special project engineers, and the flight directors. All of these lessons learned over time, especially during the transitional phases of the program, continued to refine astronaut health and medical care.

Accidents and Emergency Return to Earth

Main engine or booster failures could have caused emergency returns to KSC or transoceanic abort landing sites. NASA changed its handling of post-accident care after the two shuttle accidents. Procedures specific for the medical team were sessions on emergency medical services with the US Department of Defense Manned Spaceflight Support Office and included search and rescue and medical evacuation. This support and training evolved tremendously after the Challenger and Columbia accidents, incorporating lessons learned. It mainly included upgrades in training on crew equipment that supported the scenarios of bailout, egress, and escape.

The Future of Space Medicine

NASA's medical mission continues to require providing for astronaut health and medical care. Whatever the future milestones are for the US space program, the basic tenets of selecting healthy astronaut candidates by having strict medical selection standards and then retaining them through excellent preventive medical care are of utmost importance. Combining these with the operational aspects of coordinating all tenets of understanding the personnel, equipment, procedures, and communications within the training to prepare crews for flight will enhance the success of any mission.

At the closing stages of the Space Shuttle Program, no shuttle mission was terminated or aborted because of a medical condition, and this was a major accomplishment.