Chapter 1

Introduction to Space Life Sciences

This first chapter describes the hazards that the space environment poses to humans, and how spaceflight affects the human body (where we are). We will then review the historical context of human spaceflight (how we got there), and end with the challenges facing humans in space (where do we go from here) (Figure 1.1).

1.1. Space life sciences: what is it?

1.1.1. Objectives

Life sciences are specifically devoted to the workings of the living world, from bacteria and plants to humans, including their origins, history, characteristics, habits, you name it.

The study of life on Earth ranges from elucidating the evolution of the earliest self-replicating nucleic acids to describing a global ecology comprising over 3 million species, including humans. However, throughout its evolution, organisms on Earth have experienced only a 1-g environment. The influence of this omnipresent force is not well understood, except that there is clearly a biological response to gravity in the structure and functioning of living things. The plant world has evolved gravity sensors; roots grow “down” and shoots grow “up.” Animals have gravity sensors in the inner ear. Many fertilized eggs and developing embryos (amphibians, fish, birds, and mammals) also have clear responses to gravity. For example, the amphibian egg orients itself with respect to gravity within a few minutes after fertilization. During that short time the dorso-ventral and anterior-posterior axes of the future embryo are established. Do we conclude therefore that the gravitational input is a required stimulus for the establishment of these axes?

To better understand a system, the scientific method consists of studying the consequences of its exclusion. This approach has led to considerable advances in the knowledge of human physiology, thanks to the nineteenth century physiologist Claude Bernard, who set out the principles of experimental medicine. Clearly, the removal of gravity is a desirable, even necessary, step toward understanding its role in living organisms. In a sense, removal of gravity for studying the gravity-sensing mechanisms is like switching off the light for studying its role in vision. Transition into weightlessness abolishes the stimulus of gravity by a procedure physiologically equivalent to shutting off the light. What can be accomplished in such an elegant fashion aloft can never be done in Earth-based laboratories.

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Figure 1.1. The Goal of Space Medicine Is to Develop Methods to Keep Humans Healthy in Space for Extended Periods of Time, as Well as Improve Overall Health of People of All Ages on Earth. (Credit Philippe Tauzin).

Space physiology is of basic scientific interest and deals with fundamental questions concerning the role of gravity in life processes. Space medicine is another, albeit more applied, research component concerned with the health and welfare of the astronauts and space travelers. These two objectives complement one another and constitute the field of space life sciences. In short, space life sciences open a door to understanding ourselves, our evolution, and the workings of our world without the constraining barrier of gravity.

Space life sciences are dedicated to the following three objectives:

Enhance fundamental knowledge in cell biology and human physiology – Access to a space laboratory where gravity is not sensed facilitates research on the cellular and molecular mechanisms involved in sensing forces as low as 10^{-3} g and subsequently transducing this signal to a neural or hormonal signal. A major challenge to our understanding and mastery of these biological responses is to study selected species of higher plants and animals through several generations in absence of gravity. How do individual cells perceive gravity? What is the threshold of perception? How is the response to gravity mediated? Does gravity play a determinant role in the early development and long-term evolution of the living organism? These studies of the early development and subsequent life cycles of representative samples of plants and animals in the absence of gravity are of basic importance to the field of developmental biology.

Protect the health of astronauts – As was amply demonstrated by Pasteur, as well as countless successors, investigations in medicine and agriculture contribute to and benefit from basic research. Understanding the effect of gravity on humans and plants has enormous practical significance for human spaceflight. For example, the process of bone demineralization seen in humans and animals as a progressive phenomenon occurring during spaceflight is not only a serious medical problem. It also raises the question of abnormalities in the development of bones, shells, and the otoliths of the inner ear in species developing in the absence of gravity. The study of such abnormalities should provide insight into the process of biomineralization and the control of gene transcription.

Develop advanced technology and applications for space and ground-based research – In addition to the scientific need to study basic plant and animal interactions with gravity, there is a practical need to study their responses. These are essential to our ultimate ability to sustain humans for a year or more on the surface of extraterrestrial bodies or in spaceflight missions of long duration where re-supply is not possible, and food must be produced in situ. Experiments during long-duration space missions will determine which plants and animals are most efficient and best suited for our needs. For instance, can soybeans germinate, grow normally, produce optimum crops of new soybeans for food and new seed for ensuring future crops? All of this biological cycling, plus the development of equipment for water and atmospheric recycling, plus management of waste, will also bring important benefits for terrestrial applications. Also, the absence of gravity is used to eliminate micro convection in crystal growth, in electrophoresis, and in biochemical reactions. The resulting products can be used for both research and commercial application.

Space life sciences include the sciences of physiology, medicine, and biology, and are linked with the sciences of physics, chemistry, geology, engineering, and astronomy. Space life sciences research not only help us to gain new knowledge of our own human function and our capacity to live and work in space but also to explore fundamental questions about gravity's role in the formation, evolution, maintenance, and aging processes of life on Earth (Table 1.1).

Table 1.1. Major Applications of Space Life Sciences Research.

Biology

- Advance understanding of cell behavior
- Improve crop yields using less nutrients and smaller surface and volume

Biotechnology

- Provide information to design a new class of drugs to target specific proteins and cure specific diseases
- Culture tissue for use in cancer research, surgery, bone cartilage, and nerve injuries

Medicine

- Enhance medical understanding of disease processes such as osteoporosis
- Advance fundamental understanding of the nervous system and develop new methods to prevent and treat various neurological disorders
- Develop methods to keep humans healthy in low-gravity environments for extended time periods

Education

- Use science on orbit to encourage and strengthen science education on Earth

1.1.2. The space environment

The space environment (radiation, microgravity, vacuum, magnetic fields) as well as the local planetary environments (Moon, Mars) have been extensively reviewed in Peter Eckart's book *Spaceflight Life Support and Biospherics* (1996). In this section, we will mainly focus on microgravity. The medical issues related to space radiation will be developed in Chapter 8.

1.1.2.1. Microgravity

The presence of Earth creates a gravitational field that acts to attract objects with a force inversely proportional to the square of the distance between the center of the object and the center of Earth. When we measure the acceleration of an object acted upon only by Earth's gravity at Earth's surface, we commonly refer to it as *1 g* or one Earth's gravity. This acceleration is approximately 9.8 m/s^2.

We can interpret the term *microgravity* in a number of ways, depending upon the context [Rogers et al. 1997]. The prefix micro- derives from the original Greek *mikros,* meaning "small." By this definition, a microgravity environment is one that imparts to an object a net acceleration that is small compared with that produced by Earth at its surface. We can achieve such an environment by using various methods, including Earth-based drop towers, parabolic aircraft flights, and Earth-orbiting laboratories. In practice, such accelerations will range from about 1% of Earth's gravitational acceleration (on board an aircraft in parabolic flight) to better than one part in a million (on board a space station). Earth-based drop towers create microgravity environments with intermediate values of residual acceleration.

Quantitative systems of measurement, such as the metric system, commonly use micro- to mean one part in a million. By this second definition, the acceleration imparted to an object in microgravity will be 10^{-6} of that measured at Earth's surface.

The use of the term *microgravity* in this book corresponds to the first definition: small gravity levels or low gravity.

Microgravity can be created in two ways. Because gravitational pull diminishes with distance, one way to create a microgravity environment is to travel away from Earth. To reach a point where Earth's gravitational pull is reduced to one-millionth of that at the surface, we would have to travel into space a distance of 6.37 million kilometers from Earth (almost 17 times farther away than the Moon). This approach is impractical, except for automated spacecraft.

However, the act of free fall can create a more practical microgravity environment. Although aircraft, drop tower facilities, and small rockets can establish a microgravity environment, all of these laboratories share a common problem. After a few seconds or minutes of low-g, Earth gets in the way and the free-fall stops. To establish microgravity conditions for long periods of time, one must use spacecraft in orbit. They are launched into a trajectory that arcs above Earth at the right speed to keep them falling while maintaining a constant altitude above the surface.

Newton [1687] envisioned a cannon at the top of a very tall mountain extending above Earth's atmosphere so that friction with the air would not be a factor, firing cannonballs parallel to the ground. Newton demonstrated how additional cannonballs would travel farther from the mountain each time if the cannon fired using more black

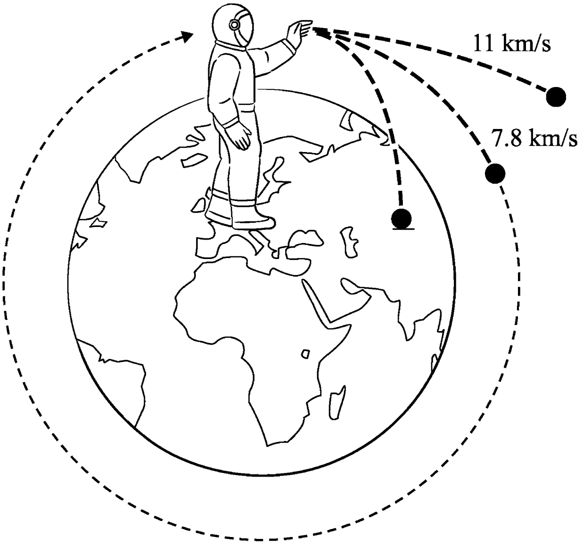

Figure 1.2. Artificial Satellites Are Made to Orbit Earth When Their Velocity Is Equal or Higher Than 7.8 km/s. When in Orbit, the Spacecraft and Its Inhabitants Are in a State of Continuous Free-Fall with No Apparent Perception of Gravity. (Credit Philippe Tauzin).

powder. With each shot, the path would lengthen, and soon the cannonballs would disappear over the horizon. Eventually, if one fired a cannon with enough energy, the cannonball would fall entirely around Earth and come back to its starting point. The cannonball would begin to orbit Earth. Provided no force other than gravity interfered with the cannonball motion, it would continue circling Earth in that orbit (Figure 1.2).

This is how the space shuttle stays in orbit. It launches into a trajectory that arcs above Earth so that the orbiter travels at the right speed to keep it falling while maintaining a constant altitude above the surface. For example, if the space shuttle climbs to a 320-km high orbit, it must travel at a speed of about 27,740 km/h to achieve a stable orbit. At that speed and altitude, due to the extremely low friction of the upper atmosphere, the space shuttle executes a falling path parallel to the curvature of Earth. In other words, the spacecraft generates a centrifugal acceleration that counterbalances Earth's gravitational acceleration at that vehicle's center of mass. The spacecraft is therefore in a state of free-fall around Earth, and its occupants are in a microgravity environment. Gravity *per se* is only reduced by about 10% at the altitude of low Earth orbit (LEO), but the more relevant fact is that gravitational acceleration is essentially canceled out by the centrifugal acceleration of the spacecraft.

1.1.2.2. Other factors of the space environment

Beside microgravity, during spaceflight living organisms are also affected by ionizing radiation, isolation, confinement, and changes in circadian rhythms (the 24-h day-night cycle). In plants, for example, spaceflight offers the unique opportunity to separate the gravitational input from other environmental stimuli known to influence

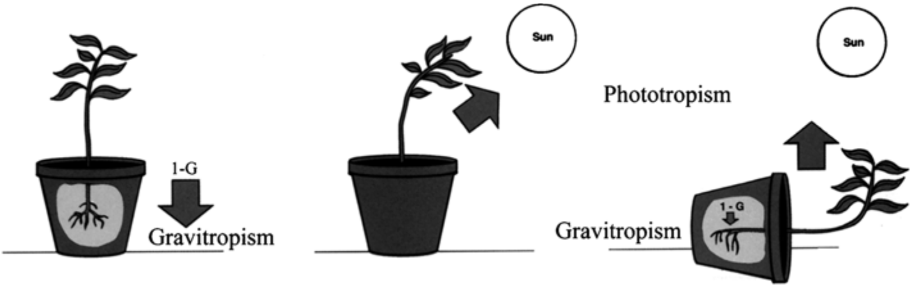

Figure 1.3. Gravitropism Is the Way Plants Grow in Response to the Pull of Gravity. When Placed Near a Window, Plants Exhibit Phototropism (Bending Toward the Light Source). This Behavior Can Be Easily Observed by Placing a Plant on Its Side; Within Minutes the Roots and Stem Begin to Reorient Themselves in Response to Both Gravity and Light. (Credit NASA).

plant growth, for example, phototropism (Figure 1.3), water tropism, and the circadian influences of the terrestrial environment. Spaceflight thus provides the opportunity to distinguish between the various tropic responses and to investigate the mechanisms of stimulus detection and response.

The absence of natural light in spacecraft may have significant effects on humans, too. A typical person spends his days outdoors, exposed to light provided by the Sun's rays (filtered through the ozone layer), including a small but important amount of mid- and near-ultraviolet light, and approximately equal portions of the various colors of visible light. Indoor lighting in most offices and in spacecraft is of a much lower intensity and, if emitted by fluorescent "daylight" or "cool-white" bulbs, is deficient in ultraviolet light (and the blues and reds) and excessive in the light colors (yellow-green) that are best perceived as brightness by the retina.

If the only effect of light on humans was to generate subjective brightness, then this artificial light spectrum might be adequate. It has become clear, however, that light has numerous additional physiological and behavioral effects. For example, light exerts direct effects on chemicals near the surface of the body, photo activating vitamin D precursors and destroying circulating photo-absorbent compounds (melanin). It also exerts indirect effects via the eye and brain on neuroendocrine functions, circadian rhythms, secretions from the pineal organ, and, most clearly, on mood. Many people exhibit major swings in mood seasonally, in particular toward depression in the fall and winter, when the hours of daylight are the shortest. When pathological, the *seasonal affective disorder syndrome* is a disease related to excessive secretion of the pineal hormone, melatonin, which also may be treatable with several hours per day of supplemental light. While not yet proved, it seems highly likely that prolonged exposure to inadequate lighting (that is, the wrong spectrum, or too low an intensity, or too few hours per day of light) may adversely affect mood and performance.

Low-power light emitting diodes (LED) are fast becoming a "green" lighting alternative for conventional lighting. LED are known to use less electricity, to be quieter, last longer, and produce a low amount of heat compared to conventional light sources. Recent studies demonstrated that LED with a spectrum of blue, orange and red provided the exact bandwidth for plants to grow and produce food on the ISS. As in our home, the compact florescent and other legacy lighting sources will be progressively replaced with LED on board the ISS.

The effects of spaceflight on biological specimens might also be related to other factors. Even the gentlest of launch vehicles produces enormous amounts of noise and vibration, plus elevated g forces, until orbital velocity is achieved, or during the re-entry into Earth's atmosphere. Once in orbit, machines and astronauts continue to produce vibrations that are difficult to control. The space environment also exposes animals and individuals to high-energy radiation unlike anything they experience on Earth. To control these and other external factors (for example, fluctuations in atmospheric pressure as astronauts enter and exit a spacecraft), the biologists studying the effects of microgravity *per se* ideally need onboard centrifuges that can expose control specimens to the level of gravity found on Earth's surface [Wassersug, 2001].

1.1.3. Justification for human spaceflight

1.1.3.1. Humans versus robots

The debate over space exploration is often framed as humans versus robots. Some scientists fear that sending humans to the Moon and Mars might preclude the pursuit of high quality science. On the other hand, some proponents of human exploration are concerned that doing as much science as possible using robots would diminish interest in sending humans. Nevertheless, humans will always be in command. The question is where would they most effectively stand?

Space exploration should be thought of as a partnership to which robots and humans each contribute important capabilities. Opposing robotics versus human crews is like comparing apples and oranges. The discussion must be framed in terms of relative strengths of humans and robots in exploring the Moon and Mars. For example, robots are particularly good at repetitive tasks. In general, robots excel in gathering large amounts of data and doing simple analyses. Hence, they can be designed for reconnaissance, which involves highly repetitive actions and simple analysis. Although they are difficult to reconfigure for new tasks, robots are also highly predictable and can be directed to test hypotheses suggested by the data they gather. However, robots are subject to mechanical failure, design and manufacturing errors, and errors by human operators. Also, before robots can explore and find evidence of life on Mars, for instance, their functional capabilities, particularly their mobility, need to be radically improved and enhanced. In addition, the delay in communication between Mars and Earth (in the order of 40 min round trip) poses a serious problem for teleoperation maneuvers.

People, on the other hand, are capable of integrating and analyzing diverse sensory inputs and of seeing connections generally beyond the ability of robots. Humans can respond to new situations and adapt their strategies accordingly. In addition, they are intelligent operators and efficient end-effectors. They may easily do better than automated systems in any number of situations, either by deriving a creative solution from a good first hand look at a problem or by delivering a more brainless kick in the right place to free a stuck antenna. Either may be mission saving. Finally, only humans are adept at field science, which demands all of these properties. Obviously, humans would have a clear role in doing geological fieldwork and in searching for life on Mars.

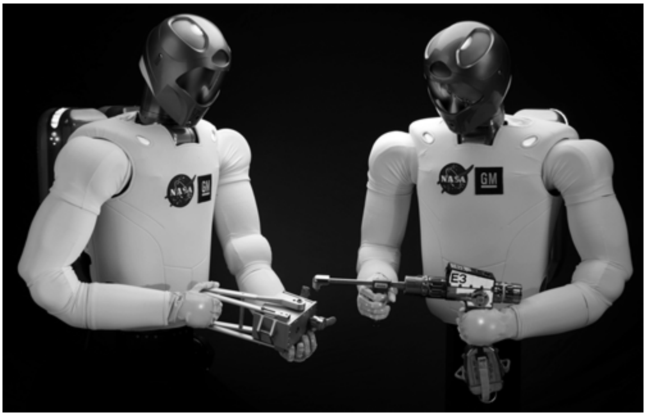

Figure 1.4. Robonaut 2 Is a Dexterous Humanoid Robot Developed Jointly by NASA and General Motors. These Social Robots Are Designed to Use the Same Tools as Humans, Allowing Them to Work Safely Side-by-Side Humans on Earth and in Space. (Credit NASA).

Humans are also less predictable than robots and subject to illness, homesickness, stress resulting from confinement, hunger, thirst, and other human characteristics. They need protective space suits and pressurized habitats. Hence, they require far greater and more complicated and expensive support than robots. The combined potential of humans and robots is a perfect example of the sum equaling more than the parts. It will allow us to go farther and achieve more than we can probably even imagine today. A future generation of robots, the so-called *social robots*, has promise both in space and on Earth, not as replacements for humans but as companions that can carry out key supporting roles. Dexterous robots with human-like hands and arms, able to use the same tools as astronauts, are currently undergoing extensive testing on board the ISS (Figure 1.4). In the future these social robots may assist or stand in for astronauts during space walks and planetary exploration or for tasks too difficult or dangerous for humans.

1.1.3.2. Space science

There is often criticism that human missions are disproportionately costly to their scientific yield as compared to automatic (unmanned) platforms such as those designed for Solar System exploration or Earth's observation. A direct comparison is not justified, however. Automatic probes have indeed returned spectacular results, but it is wrong to compare these directly with human flights. Historically, space life sciences are a rather recent discipline. In most space agencies, at least until recently, the term "space science" refers to space physical sciences, such as astrophysics or search for life on other planets. Perhaps reminiscent of this past, human spaceflight critics often discount the value of space life sciences on the "Discovery Ledger (Big Book)".[1]

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[1] In a February 2003 interview to the *Chicago Tribune,* a physics professor at the University of Maryland and a director at the American Physical Society, a professional organization of physicists, said: "The International Space Station is not exploration; it's going in circles closer to the Earth than Baltimore is to New York". He added: "It is the single greatest obstacle of continued exploration of the Solar System—it's blocking just about everything".

This point of view is often due to the following fundamental differences: physical sciences leads to more concrete discoveries in a relatively unexplored sphere (once a new star is discovered, it is easy to confirm its presence), whereas space life sciences is an inherently inexact science, which must take into account background physiological variability and requires repeated measurements. For instance, large clinical trials are needed to determine the efficacy of a new drug. It may be obvious that space life sciences suffer from the small number of subjects studied and the many confounding factors that are difficult to control. But with all of this, it is likely that the life sciences data obtained in LEO studies will be practically used for going further (such as establishing a Mars base) or for improving our knowledge of clinical and aging disorders on Earth, long before we can make use of the information on the magnetic field of Neptune [Barratt, 1995].

It is true that the cost of human-based space infrastructures, such as the ISS, is much higher than unmanned missions. However, the primary purpose for the ISS was a political one. The ISS is a major accomplishment for all countries involved even in its current incomplete state. It is the largest on-orbit structure ever built and the largest multi-national cooperative project in history. In building the ISS infrastructure and research equipment, aerospace companies are acquiring unique capabilities that make them recognized world players in areas such as space structures, automation, robotics, avionics, fluid handling, advanced life support systems and medical equipment. Both in view of the need to develop advanced technologies and by virtue of the research carried out on board, the ISS can have a significant impact on the competitiveness of aerospace industry. In the same way that one would not charge the cost of a road-system to a single car (or even the first dozen cars), the cost of the ISS cannot be endorsed by the scientific return of its first experiments.

The opportunities for in-depth studies in space life sciences have indeed been sparse. This is simply the nature of the current space program, with much to do and a few flight opportunities that must be shared. Experiments that might take weeks on Earth take years to plan and execute in space. Limitations of the spaceflight environment have also limited the number of control experiments and have often kept the number of specimens studied far from statistical ideal. Often space studies are paralleled by Earth-based simulation studies using centrifuges or clinostats, but results in actual microgravity are somewhat different.

Another argument often posed against space life sciences is that no Nobel prizes have been given in this field of research. Although a true statement, there are several instances, however, of Nobel Prizes formerly delivered in life sciences related fields that would presumably not have been presented based on the recent results obtained in space. For example, Robert Bàràny, a Viennese otolaryngologist, received the Nobel Prize of Medicine in 1906 for his discovery of a clinical test aimed at evaluating the functionality of the balance organs in the inner ear (see Chapter 3, Section 3.2.1). During this test, irrigation of the external auditory ear with water or air above or below body temperature generates rhythmic eye movements (nystagmus) and the subject experiences slight vertigo. Bàràny's theory was that the caloric irrigation of the ear canal generated eye movements (the so-called caloric nystagmus) because of the heat, gravity-driven convection within the canal fluid [Barany, 1906]. A space experiment carried out on board *Spacelab* in 1983 proved this theory to be wrong since caloric nystagmus was also observed in microgravity, where no heat current convection is generated. Later studies revealed that it is more likely the changes in pressure or temperature that are at the origin of the eye movement response [Scherer et al., 1986].

1.1.4. Where we are

Human spaceflight began in April 1961 with Yuri Gagarin's single orbit of the Earth on board *Vostok-1*. Exactly 50 years later, in April 2011, a total of 520 astronauts, cosmonauts, and taîkonauts (the name given to Chinese astronauts) will have flown in space,[2] an average of about 10 per year. The total number of days spent in space will be about 36,500 crew days, or 100 years. It is interesting, or rather sad, to note that female astronauts and cosmonauts comprise only 11% of these 520 flown individuals (56 to be exact). Females also contributed to about 11% of all human flights (129) and the total duration of all flights for female astronauts and cosmonauts is less than 8 years.

All together, these 520 humans will have spent about 36,500 days in space. So, the average amount of time spent in space by astronauts and cosmonauts is 36,500 days/520 = 70 days, or a little more than 2 months. If we include the re-flights, the number of flown humans goes up to 1,155 (806 for the shuttle only, nearly 70%!). However, most of them have spent less than 30 days in space, even by cumulating three or four flights. The mean duration of all human spaceflights to date is about 30 days, but the median time spent in orbit is close to 12 days (Figure 1.5). Flight duration longer than 6 months is limited to about 60 individuals, and only four individuals have experienced continuous spaceflight longer than 1 year (Figure 1.6). By counting the re-flights, 25 individuals (including one female) have cumulated the equivalent of 1 year or more in orbit.

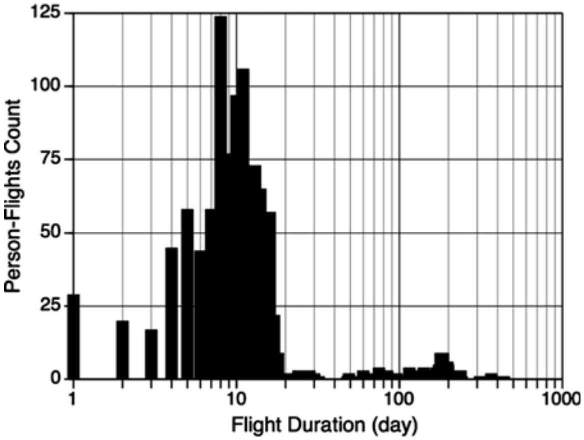

Figure 1.5. Number of Human Spaceflights as a Function of Flight Duration from 1961 to 2010. Note the Logarithmic Scale for Flight Duration. Most Human Flights Were of Short Duration (8–14 days) on Board Soyuz or the Space Shuttle.

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[2] Provided that *STS-133*, *Soyuz TMA-20*, and *STS-134* launch on time (these calculations were made on 13 October 2010).

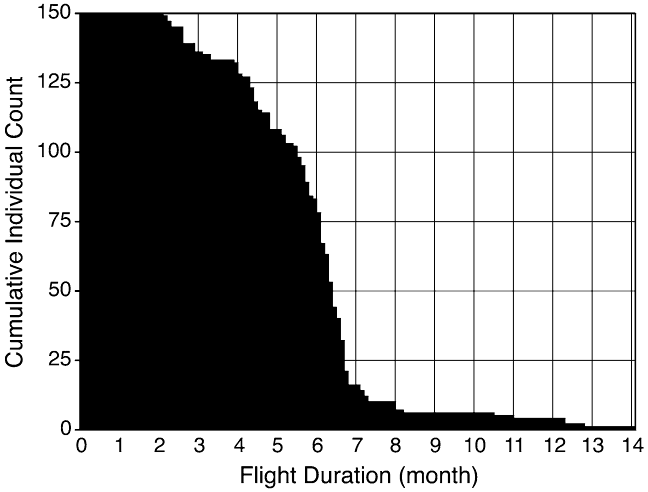

Figure 1.6. Cumulative Histogram Showing the Astronaut and Cosmonaut Count as a Function of (Single) Flight Duration.

Had all the astronauts and cosmonauts been the subjects of space life sciences investigations during their spaceflight, the total amount of collected data would be limited to about one human lifetime. The total amount of collected data on female subjects would be limited to 8 years – the concept of women flying in space is still at its infancy. Yet, since life sciences investigations were not conducted on all astronauts and cosmonauts, and since most of them have flown more than once, the limited number of individuals and observations makes the significance of this data even lower.

This simple arithmetic is to illustrate how little research time – on how few space flyers – is currently available to determine the effects of spaceflight on the human body. A comparison between space research and extreme environment research would undoubtedly show that much more has been accomplished on Mount Everest or during polar expeditions during the same period.[3]

The record of spaceflight duration is currently held by Dr. Valery Polyakov, a Russian physician, who spent 437 days during a single mission on board the space station *Mir* in 1994–1995. This was his second spaceflight, though. In 1989, he had already spent 242 days on board *Mir*, so his total time spent in space actually is 679 days, or about 22 months.

But this is not the longest duration in space for a single individual. Sergey Krikalyov has logged 803 days during six stays on board *Mir*, the space shuttle, and the ISS, and he currently holds the all-time cumulative total for days in space. Beside Polyakov and Krikalyov, eight other cosmonauts have spent more than 500 days in space,

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[3] About 2,700 individuals have successfully climbed to the top of Mount Everest since May 1953. As of 2009 about 4,100 ascents have been made. Over 216 people have died trying. About 440 individuals have completed expeditions to the North Pole or the South Pole since 1865 and 1908, respectively [Source: www.adventurestats.com].

accumulated over two to five spaceflights. This cumulative time in microgravity is about equal to the total exposure to microgravity to be experienced during a mission to Mars. The ISS allows extensive investigations on humans in space. However, the nominal duration of a stay in orbit for Expedition crews on ISS does not exceed 6 months. Therefore, no data is gained anymore during very long spaceflights. Although we know that humans can survive to long duration in space repeatedly, the data collected so far is extremely limited.

There is a general perception that because a small number of cosmonauts have survived in LEO for as long as 1 year or so, there are no major physiological problems likely to preclude longer-duration human planetary exploration missions. One must admit that, over the years, there has been access only to anecdotal data from the Russian space program. This anecdotal information is, while interesting, not sufficiently reliable for drawing conclusions for a number of reasons. There are differences in the scientific method, the experimental protocols, and the equipment. The results are also not published in peer-reviewed international scientific journals. Fortunately, the increased recent cooperative activities between Russia and its partners of the ISS now allow a standardization of experimental procedures and better data exchange.

1.2. How we got there

1.2.1. Major space life sciences events

1.2.1.1. The pioneers

The first powered flight in 1903 by the Wright Brothers at Kitty Hawk beach in North Carolina is traditionally considered as the milestone in manned flight and aerospace medicine. In mythology, Icarus was the first victim of a flying adventure, when he and his father Daedalus tried to escape their prison on the island of Crete by flying using waxed feathers. The legend says that Icarus, ignoring both advice and warning, flew too close to the Sun. The heat softened the wax and the feathers detached, precipitating a dreadful fall for Icarus.

However, there were no witnesses to the Icarus and Daedalus flight. This was not the case for the second human flight in history, though. In June 1783, two brothers, Jacques Etienne and Joseph Michel Montgolfier, sent a large, smoked-filled bag 35 ft into the air. This first balloon flight was recorded by the French Academy of Sciences. Three months later, a duck, a rooster, and a sheep became the first passengers in a balloon, since no one knew whether a human could survive the flight. All three animals survived the flight, although the duck was found with a broken leg, presumably due to a kick from the sheep after landing. Finally, on November 21, 1783, human flight was attempted before a vast crowd that included the king and queen of France and recognized scientists [Tillet et al., 1783]. Pilatre de Roziers[4] and the Marquis d'Arlandes[5] piloted what became the first known aerial voyage of humankind (Figure 1.7).

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[4] The word "pilot" is derived from his name.

[5] The Marquis d'Arlandes was born in my hometown, Anneyron, a small village in the south of France.

Figure 1.7. Drawing of the First Manned Balloon Flight Taking Off in Front of the Château de la Muette with passengers Pilatre de Roziers and the Marquis d'Arlandes. (Source Unknown).

After this event, ballooning became quite popular for over half a century in Europe. Ten days after the first manned hot air flight, a French physicist named J. A. C. Charles made the first human flight in a hydrogen-filled balloon. When he reached an altitude of 2,750 m, he began to experience physiologically some of the realities of this new environment. He complained of the penetrating cold at this altitude and a sharp pressure pain in one ear as he descended. This is the first description of symptoms experienced in aerospace medicine. In 1784 in England, after several animals were used in free flight tests, Mrs. Elisabeth Tible became the first woman to fly a balloon, and Jean-Pierre Blanchard became the first to cross the Channel from England to France. Feeling outdone, Pilatre de Roziers built a new balloon, using a combination of hot air envelope and a small hydrogen balloon, to fly from France to England. In January 1785, he left France, and after a few minutes in-flight the burner's flame ignited the small hydrogen balloon, creating an inferno. Ironically, the first to fly in a balloon became the first balloon casualty. The hazards of high altitude flight were demonstrated in following flights, where balloonists experienced and described for the first time the symptoms of hypoxia (altitude sickness, increase in heart rate, fatigue) [DeHart, 1985].

1.2.1.2. Animal spaceflight

In the 1950s, as human spaceflight began to be seriously considered, most scientists and engineers projected that if spaceflight became a reality it would build upon logical building blocks. First, a human would be sent into space as a passenger in a capsule (Projects Vostok and Mercury). Second, the passengers would acquire some control over the space vehicle (Projects Soyuz and Gemini). Third, a reusable space vehicle would be developed that would take humans into LEO and return them. Next, a permanent space station would be constructed in LEO through the utilization of the reusable space vehicle. Finally, lunar and interplanetary flights would be launched from the space station using relatively low-thrust and reusable (and thus lower cost) space vehicles.

Just like for balloon flights, animals were sent up in rockets before humans to test if a living being could withstand and survive a journey into space (Figure 1.8). The first successful spaceflight involving living creatures came on September 20, 1951, when the former Soviet Union launched a sounding rocket with a capsule including a monkey and 11 mice. A few attempts to fly animals had been made before (in fact, since 1948 in the nose cones of captured German V-2 rockets during U.S. launch tests), but something always went wrong. These attempts were made with one main purpose: to study the effects of exposure to solar radiation at high altitude, and to determine the effects, if any, of weightlessness [Lujan and White, 1994].

Orbital flight then began on October 4, 1957, when the former Soviet Union sent the *Sputnik-1* satellite into space. This was an unmanned satellite, but before the end of the year a second satellite, *Sputnik-2*, was launched carrying the first living creature into orbit, a dog named Laika. Laika had been equipped with a comprehensive array of telemetry sensors, which gave continuous physiological information to tracking stations. The cabin conditioning system maintained sea-level atmospheric pressure within

Figure 1.8. Rats and Cats Were the First Living Passengers on a Suborbital Flight in a French Rocket in the 60s. (Credit CNES).

the cabin, and Laika survived 6 days before depletion of the oxygen stores caused asphyxiation. Laika's flight demonstrated that spaceflight was tolerable to animals. Twelve other dogs, as well as mice, rats, and a variety of plants were then sent into space for longer and longer duration between 1958 and 1966. In 1996, a Soviet biosatellite *Cosmos* mission carried two dogs in orbit for 23 days. The dogs were observed via video transmission and biomedical telemetry. Their spacecraft landed safely.

In 1959, one rhesus and one squirrel monkey rode in the nose cone of a U.S. missile during a non-orbital flight, successfully withstanding 38 times the normal pull of gravity and a weightless period of about 9 min. Their survival of speeds over 18,000 km/h was the first step toward putting a human into space. Although one of the monkeys died from the effects of anesthesia given to allow the removal of electrodes implanted for the spaceflight, a subsequent autopsy revealed that the monkey had suffered no adverse effects from the flight. Between 1959 and 1961, three other monkeys made suborbital flights in Mercury capsules, and one monkey flew two orbits around Earth in a Mercury capsule in preparation for the next, human flight (Figure 1.9). These experiments paved the way for human expeditions.

A comprehensive list of all the animal species that have flown in space is published in the book *Fundamentals of Space Biology* by Clément and Slenzka [2006, Springer]. While these animals were in space, instruments monitored various physiological responses as the animals experienced the stresses of launch, re-entry, and the weightless environment. The results of these animal flights showed that:

(a) Pulse and respiration rates, during both the ballistic and the orbital flights, remained within normal limits throughout the weightless state. Cardiac function, as evaluated from the electrocardiograms and pressure records, was also unaffected by the flights.

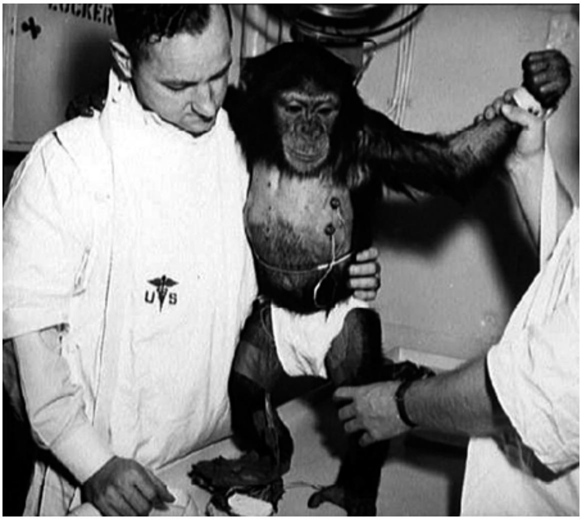

Figure 1.9. Chimpanzee Ham with Biosensors Attached Is Being Prepared for His Trip in the Mercury-Redstone 2 on January 31, 1961. (Credit NASA).

(b) Blood pressures, in both the systemic arterial tree and the low-pressure system, were not significantly changed from preflight values during 3 h of the weightless state.
(c) Performance of a series of tasks of graded motivation and difficulty was unaffected by the weightless state.
(d) Animals trained in the laboratory to perform during the simulated acceleration, noise, and vibration of launch and re-entry were able to maintain performance throughout an actual flight.

On the basis of these results, it was concluded that the physical and mental demands that the astronauts would encounter during spaceflight "would not be excessive," and the adequacy of the life support system was demonstrated [Henry, 1963].

1.2.1.3. Humans in space

Earlier, in late 1958, the new National Aeronautics & Space Administration (NASA) had announced Project Mercury, its first major undertaking. The objectives were threefold: to place a human spacecraft into orbital flight around Earth, observe human performance in such conditions, and recover the human and the spacecraft safely. At this early point in the U.S. space program, many questions remained. Could a human perform normally as a pilot-engineer-experimenter in the harsh conditions of weightless flight? If yes, who were the right people (with the right stuff) for this challenge?

In 1959, NASA received and screened 508 service records of a group of talented test pilots, from which 110 candidates were assembled. One month later, through a variety of interviews and a battery of written tests, the NASA selection committee brought down this group to 32 candidates. Each candidate endured even more stringent physical, psychological, and mental examinations, including total body X-rays, pressure suit tests, cognitive exercises, and a series of unnerving interviews. Of the 32 candidates, 18 were recommended for Project Mercury without medical reservations. At a press conference, NASA introduced the seven Mercury astronauts to the public.

The following year, the Soviet Union announced that 20 fighter pilots had been selected for its space program. Physiological studies and special psychophysiological methods "permitted the selection of people best fitted to discharge the missions accurately and who had the most stable nerves and emotional health," according to the Soviet report. In 1962, 5 female parachutists joined this first group of 20 male cosmonauts.

On April 12, 1961, Yuri Gagarin became the first human to orbit Earth. According to the press release, Gagarin felt "perfectly well" throughout the orbiting phase and also during the period of weightlessness. It was noted, however, that "measures" had been taken to protect the spacecraft from the hazards of space radiation.

Six weeks later, U.S. President Kennedy would announce as a national objective an accelerated space program to accomplish a landing on the Moon before the end of the decade. However, after the suborbital flights of Alan Shepard and Gus Grissom in May and July 1961, respectively, observations made during U.S. orbital spaceflights with monkeys raised some concerns. Variations in cardiac rhythm had been recorded in one chimpanzee during a three-orbit mission [Stringly, 1962]. It was found that the problem came from faulty instrumentation, and that the data were therefore invalid. Accordingly, it was recommended that John Glenn's orbital flight proceed as scheduled.

Figure 1.10. Russian Cosmonauts Yuri Gagarin and Valentina Tereshkova Were the First Male and Female Humans into Space. (Source Unknown).

In August of the same year after Grissom's suborbital flight in July, the USSR launched Cosmonaut Gherman S. Titov into orbit. The following day, Titov successfully landed after 17 orbits in 25 h and 18 min. This was the first human flight of more than one orbit, and the first test of human responses to prolonged weightlessness. Two years later, in 1963, Valentina Tereshkova became the first woman in space (Figure 1.10). She remained in space for nearly 3 days and orbited the Earth 48 times. Unlike earlier Soviet spaceflights, Tereshkova was permitted to operate the controls manually. After her spacecraft reentered Earth's atmosphere, Tereshkova parachuted to the ground, as was typical of cosmonauts at that time. Although her spaceflight was announced as successful, it was 19 years until another woman flew in space, Svetlana Savitskaya, aboard *Soyuz T-7* and *Salyut-7* in 1982. Apparently, something went so wrong during Tereshkova's flight that no further flights included women. Savitskaya must have turned out all right, since she flew twice, and during her second mission on board *Soyuz T-12* and *Salyut-7* in July 1984, was the first woman to ever perform a space walk. The third and last female Russian cosmonaut flew in 1997 on board the space shuttle and *Mir*.

Soviet Cosmonaut Aleksei Leonov made the first space walk during the *Voskhod-2* mission on March 18, 1965. He was followed by U.S. Astronaut Edward White, who stepped out of *Gemini-4* for 20 min. White propelled himself away from the spacecraft with a special gun that gushed out compressed oxygen to move him in any direction. However, because his propulsion gun ran out of fuel, he had to pull on his life support system umbilical line to maneuver around and reenter the spacecraft.

1.2.1.4. Space life sciences investigations

The Mercury flights had made it clear that the body undergoes some real changes during and after spaceflight, such as measurable weight loss. A more complex set of in-flight medical studies was carried out during the Gemini missions, which served as precursors to the lunar missions. Among those missions, *Gemini-7*'s (December 1965) primary objective was to conduct a 2-week mission and evaluate the effects of long-duration exposure to weightlessness on its crew. Many medical experiments were conducted in-flight, including on vision and sleep. Extensive testing, for example on balance, was also performed just after landing. Blood and urine samples were collected throughout the mission for analysis, and astronauts exercised twice daily using rubber bungee cords.

Of particular interest was the visual acuity experiment, which was driven by earlier observations of Mercury astronauts who thought their ability to identify small objects on Earth's surface was enhanced in weightlessness. This experiment used a visual acuity goggle combined with measured optical properties of ground objects and their natural lighting, as well as the atmosphere and spacecraft window. The results failed to show that visual acuity was improved while in space.

Also interesting is the *Gemini-11* flight (September 1966), where artificial gravity was (accidentally) first tested in space. The Gemini spacecraft was tethered to an Agena target vehicle by a long Dacron line, causing the two vehicles to spin slowly around each other. According to the Gemini commander, a TV camera fell "down" in the direction of the centrifugal force, but the crew did not perceive any changes [Clément and Bukley, 2007].

Significant orthostatic hypotension and weight loss were observed in the crewmembers of *Gemini-3*, *-4*, *-5*, and *−6* immediately after flight (see Chapter 4, Section 4.3.4). Also, red blood cell mass losses in the order of 20% were noted after the 8-day Gemini flight. Scientists were concerned that spaceflight might affect the balance of body fluids and electrolytes because fluid losses can contribute to both of these symptoms. This led to a series of ground-based studies to simulate some of the conditions of spaceflight. These studies utilized bed rest and water immersion as a means of simulating microgravity. In addition, *Biosatellite-3* was launched in 1969, 3 weeks before the first men were to land on the Moon, with a monkey passenger. The flight was planned for a full month, but the monkey was brought down, ill from loss of body fluids, after only 9 days. It died shortly after landing. Despite the concern that the same problem could occur to humans, the Apollo missions to the Moon proceeded as planned.

During the Apollo missions, a medical program was developed that would make provision for emergency treatment during the course of the mission in case a serious illness occurred. Indeed, during the orbital flights of Mercury and Gemini, it was always possible to abort the mission and recover the astronaut within a reasonable time should an in-flight medical emergency occur. This alternative was greatly reduced during Apollo. The events of *Apollo-13* showed that this medical program proved effective. Biomedical findings of the Apollo program revealed a decrease in postflight exercise capacity and red blood cell number, a loss of bone mineral, and the relatively high metabolic cost of extra-vehicular activity. In addition, symptoms of space motion sickness such as nausea and vomiting, earlier described by Soviet cosmonauts, were experienced. These observations raised another concern for future human spaceflights, and therefore constituted the starting point of detailed life sciences investigations in the *Skylab* program in the 1970's.

The U.S. *Skylab* (Figure 1.11) and the Soviet *Salyut* space stations allowed scientists to conduct investigations on board large orbiting facilities during missions lasting up to 3 months. They gave a basic picture of how the body reacts and adapts to the space environment. The number of subjects was, however, still limited.

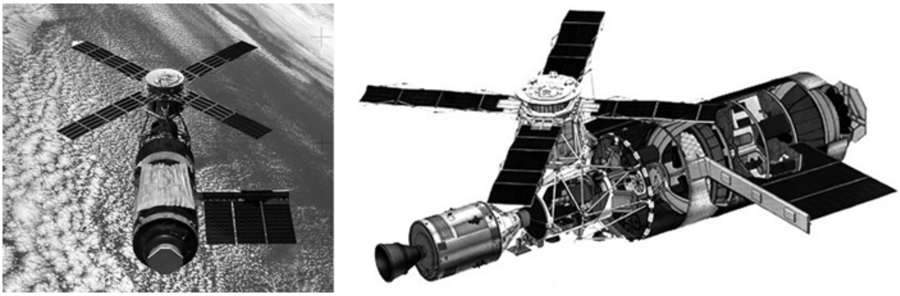

Figure 1.11. Actual Photograph (*Left*) and Drawing (*Right*) of the U.S. Skylab Space Station Showing the Orbital Module Laboratory with "Transparent" Walls and the Apollo Crew Return Vehicle. The Volume of the Laboratory Was About 350 m^3. The Nine Astronauts Visiting Skylab in 1973 and 1974 Logged About 2,000 h of Scientific and Medical Experiments During Three Missions Lasting 28, 59, and 84 days, Respectively. (Credit NASA).

Figure 1.12. Landing of the Space Shuttle at the Kennedy Space Center. (Credit NASA).

The space shuttle (or Space Transportation System, STS), which began flying in 1981, provided the opportunity to test more crewmembers. Also, as the first spacecraft that could be used again and again, the space shuttle has provided space life scientists with a more regular opportunity to conduct experiments, and to repeat and refine those experiments. However, with the space shuttle, other concerns appeared. It was remarkably different from the previous spacecraft because it returned to Earth by landing on a runway (Figure 1.12).

Critical issues existed concerning the ability of crews to perform the visual and manual tasks involved in piloting and landing the shuttle, and their capacity to achieve unaided egress after long exposure to weightlessness. It was later found that the astronaut-pilots were able to pilot and manually land the space shuttle, as long as the flight duration did not exceed 2 weeks. Such critical achievement was in part due to the development of special simulators built to train crews to fly and land the space shuttle, in what is now popularly termed a "virtual reality" setting. In fact, astronauts returning from shuttle missions reported that the simulations were so accurate they felt they had flown the mission many times.

1.2.1.5. Today's access to space

In 134 flights between 1981 and 2010, the space shuttle has repeatedly demonstrated unique capabilities as space transporter, repair ship, scientific platform, and research center. It first accomplished its role of "shuttle" by rendezvous and docking with *Mir* in 1995, a few months after the end of Valery Polyakov's 14-month mission. From February 1994 to June 1998, NASA space shuttles made 11 flights to the Russian space station *Mir*, and U.S. astronauts spent seven residencies, or "increments," on board *Mir*. space shuttles also conducted crew exchanges and delivered supplies and equipment. The space shuttle was then the first spacecraft to dock with the ISS, in May 1999. Since the permanent crew occupation of the ISS in November 2000, the space shuttle has ensured most of the crew transport, together with the *Soyuz*, between Earth and the ISS.

More than four times as large as *Mir*, the ISS consists of 16 pressurized modules with a combined volume of around 1,200 m^3 (Figure 1.13). These modules include laboratories, docking compartments, airlocks, nodes, and living quarters. As of July 2010, 14 of these components were already in orbit. The research laboratories include the Russian *Zvezda* and *Rassvet* modules, the U.S. *Destiny* module, the Japanese *Kibo* module, and the European *Columbus* module. The remaining two laboratories waiting to be launched are the Russian *Nauka* module and the European *Leonardo* module.

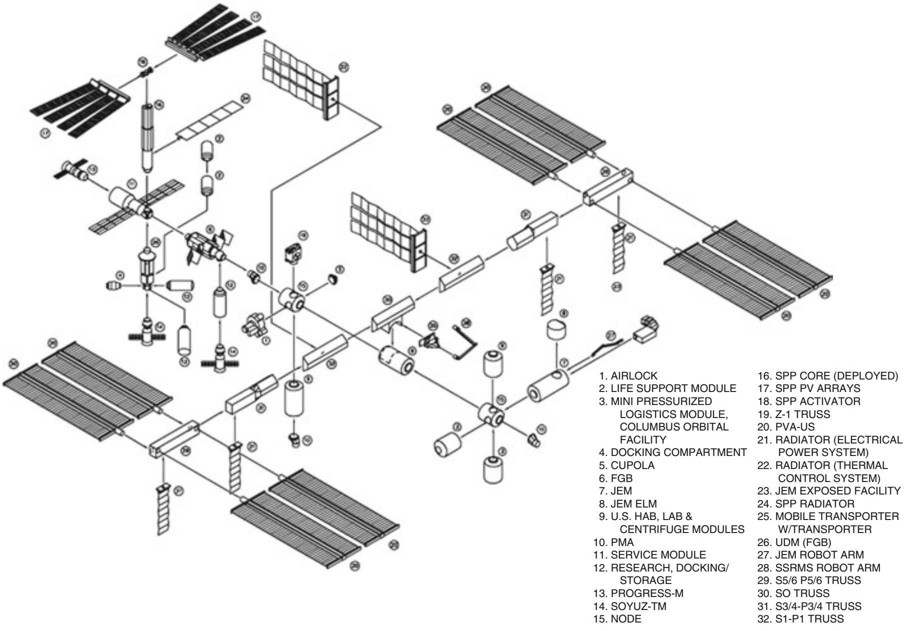

Figure 1.13. The International Space Station. (Credit NASA).

Each module was or will be launched either by the space shuttle, or by Proton or Soyuz rockets. ISS assembly will be completed by 2011, by which point the ISS will have a mass in excess of 400 metric tons.

The gravity environment on the station is described as "micro-gravity," as the weightlessness is imperfect. This is caused by four separate effects: (a) the drag resulting from the residual atmosphere; (b) vibratory acceleration caused by mechanical systems and the crew; (c) orbital corrections by the on-board gyroscopes or thrusters; and (d) the distance from the real center of mass of the ISS.

Normal air pressure on the ISS is 101.3 kPa (14.7psi), the same as at sea level on Earth. The time zone used on board the ISS is Coordinated Universal Time (UTC, also called GMT). In general, the crew works 10 h/day on a weekday, and 5 h on Saturdays, with the rest of the time their own for relaxation, games, or work catch-up. The ISS does not feature a shower. Instead, crewmembers wash using a water jet and wet wipes, with soap dispensed from a toothpaste tube-like container. Crews are also provided with rinseless shampoo and edible toothpaste to save water. There are two space toilets on the ISS, located in *Zvezda* and *Destiny*.

Most of the space food eaten by station crews is frozen, refrigerated, or canned. Menus are prepared by the astronauts, with the help of a dietitian, before their flight to the ISS. Each crewmember has individual food packages and cooks them using the onboard galley, which features two food warmers, a refrigerator, and a water dispenser that provides both heated and unheated water. Drinks are provided in dehydrated powder form, and are mixed with water before consumption. Drinks and soups are sipped from plastic bags with straws, while solid food is eaten with a knife and fork, which are attached to a tray with magnets to prevent them from floating away.

Each permanent station crew is given a sequential Expedition number. Expeditions have an average duration of 6 months. *Expeditions-1* through *−19* consisted of three-person crews (except for *Expeditions-7* to *−12*, which led to a reduction to two crewmembers following the space shuttle *Columbia* disaster). In May 2009, *Expedition-20* was the first ISS crew of six. The ISS is the most visited spacecraft in the history of spaceflight. As of September 2010, it had 294 visitors (195 individuals) from 15 different nationalities (Table 1.2). *Mir* had 137 visitors (104 individuals).

Emergency crew return vehicles will always be docked with the ISS while it is inhabited, to assure the return of all crewmembers. The *Soyuz* spacecraft, which has a crew capacity of three, is presently used. Following the retirement of the space shuttle, a number of other spacecraft are expected to fly to the station. Two, the *Orbital Sciences Cygnus* and *SpaceX Dragon* will fly under contracts with NASA, delivering cargo to the ISS until at least 2015. In addition, the *Orion* spacecraft, developed as a space shuttle replacement as part of NASA's Constellation program, was re-tasked by U.S. President Barack Obama on April 15, 2010, to provide lifeboat services to the ISS.

It is important to realize that the ISS is far more than a science platform alone. The ISS constitutes a highly visible signature in the sky for human endeavor, courage, spirit, and international peaceful collaboration, and it is the greatest technological challenge the human race has tackled so far. To a large part this was the early political motivation that led to its conception. In addition, and looking more towards the future, the ISS provides the gateway for human exploration of the Solar System. The ISS has also the potential for becoming an ideal tool to support educational activities.

Table 1.2. International Space Station Statistics as of September 2010. Sources: http://space.kursknet.ru/cosmos/english/other/siss.sht; http://en.wikipedia.org/wiki/List_of_International_Space_Station_visitors.

Total Residents and Visitors Since Start of Assembly	
Trips	294
Flyers	195
Women	30
ISS crewmembers	60
Tourists	7
Flights Since Start of Assembly (1999)	
American	34 Shuttle
Russian	4 Proton
	23 Soyuz
	37 Progress
European	1 ATV
Japanese	1 H-II TV
Space Walks (1999–2010)	
Number of astronauts	96
Number of EVA	292
Total duration (man-EVA hours)	1,829

In particular, educational programs encouraging and supporting the study of science, mathematics, technology, and engineering can be implemented on board the ISS, making use of its facilities and resources. Other education projects can be implemented that focus not only on science and technology but also on a larger variety of subjects, such as languages, composition, and art.

In April 2001, an American engineer and millionaire flew on a *Soyuz* and spent 8 days on board the ISS. His trip erupted in a controversy when NASA and the other ISS partners objected to a tourist visit in the middle of a critical series of assembly operations at the ISS. The ISS partners reluctantly gave their approval for a visit that was going to happen with or without their approval, in return for a promise by the Russian Space Agency to meet new standards for paying visitors in the future. Between April 2002 and October 2009 six other orbital space tourists flew to and from the ISS on *Soyuz* spacecraft through the space tourism company, Space Adventures, for a cost ranging from $25 to $30 million.

As a matter of fact, orbital “space tourists” “space participants,” or “commercial astronauts,” according to the new title awarded by the U.S. Federal Aviation Administration, had already flown on several occasions. A senator, a congressman, a teacher, and a prince from Saudi Arabia have flown on U.S. missions. A reporter, an engineer from a chocolate company, and guests from allied countries have flown on Soviet, now Russian, space missions. Before being a full ISS partner, Europe took the opportunity of a paying visitor on the *Soyuz* to allow its astronauts to have a regular access to *Mir* and the ISS for 1 week at a time, the so-called “Taxi” missions.

More affordable space tourism will be the result of new vehicles that make suborbital flights peaking at an altitude of 100–160 km (Figure 1.14). Passengers will experience 3–6 min of weightlessness, a view of a twinkle-free starfield, and a vista of

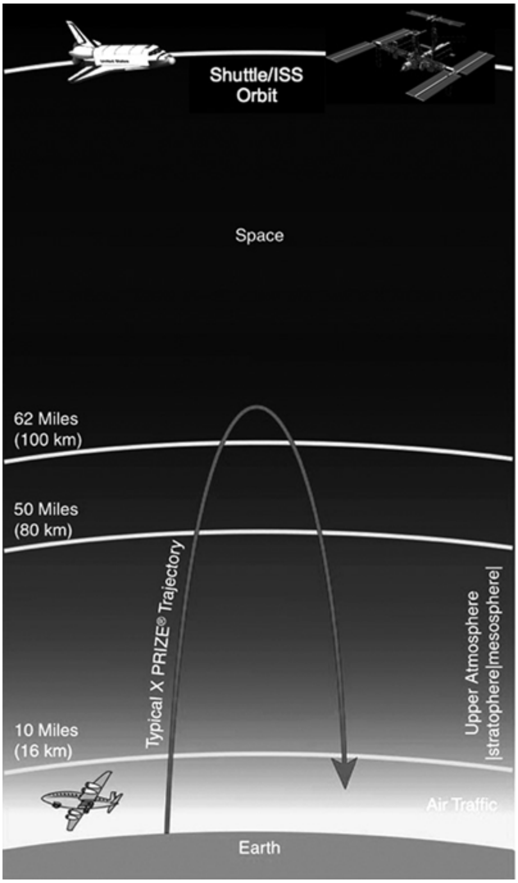

Figure 1.14. Suborbital Spaceflight Will Typically Go Above 100 km, Which Is Considered the Beginning of Space and Thus Entitles the Passengers of These Flights To Be Called "Astronauts." Although at a Much Lower Altitude Than the ISS, the Space Participants Will BeAble to Enjoy a Spectacular View of Earth and Microgravity for a Few Minutes. They Will Also Experience Considerable Accelerations During Launch and Re-entry, Presumably More So Than in the Space Shuttle. (Credit Ansari-X Prize).

the curved Earth below. On October 4, 2004, *SpaceShipOne,* designed by Burt Rutan of Scaled Composites, won the $10,000,000 Ansari-X Prize, which was awarded to the first private company that could fly a vehicle at an altitude of 100 km twice within 2 weeks. The 100-km altitude is beyond the Kármán Line, the arbitrarily defined boundary of space. Virgin Galactic, one of the leading space tourism groups, is planning to begin passenger service aboard the *VSS Enterprise*, a Scaled Composites *SpaceShipTwo* spacecraft. The initial seat price will be $200,000, but that price is expected to eventually fall to $20,000. To date, over 80,000 people have made down payments on bookings. No doubt about it, space tourism is a reality, and it's a good and necessary development for the future of human space exploration.

1.2.2. Surviving the Odyssey

Early predictions of the response of humans to spaceflight assumed that space adaptation would be analogous to human disease processes rather than to normal physiology. The predictions made by scientists about the ability of humans to endure spaceflight were indeed dire. Despite ground-based studies proving the contrary, there was true concern that the g forces of launch and re-entry (6–8 g for the earliest spacecraft) would render human passengers unconscious, severely impaired, or even dead. The mystique of this alien environment was so great that many feared a psychotic breakdown when humans would find themselves disconnected from and looking down on mother Earth.[6] Some physicians voiced concerns that bodily functions in weightlessness might suffer from a long list of calamities: swallowing, urination, and defecation would be impaired or impossible in the absence of gravity (although anyone who has ever swallowed while standing on their head hanging upside down could have proven otherwise); the bowels would not work without gravity; the heart might cavitate like a pump or beat so irregularly as to cause problems; sleep would be impaired; and muscles, including the heart, would become so weakened as to prohibit return to Earth [Churchill, 1999].

The first space missions showed, however, that with the proper protection, humans could survive a journey into space. Biomedical changes have been observed during spaceflight, due to the effects of microgravity, but also to other phenomenon, such as high launch and re-entry gravitational forces, radiation exposure, and psychological stress.

To illustrate of what we do know at this point, colleague and friend Susanne Churchill, in one of her lectures at the International Space University, used to describe the space journey of an hypothetical space traveler who experiences all of the known problems. We will use the same approach below.

So, let us take a journey with our hypothetical astronaut. She is in excellent health and fully trained for the rigors of her 3-month increment on board the ISS. Launch occurs as anticipated: a couple of hours before launch she had joined the others lying down in the seats of the space shuttle, strapped in, feet above head, as in the early Mercury, Gemini, or Apollo launches. But there, the similarity ends. For during shuttle lift-off she does not undergo the unpleasant gravity load, which went as high as 8 g on earlier flights. Instead, she experiences 3 g only twice. The first time comes and goes quickly near the 2-min mark, just before the two solid rocket boosters burn out and drop by parachute into the Atlantic Ocean. The final 3-g load comes 5 min later and lasts for a minute. Less than 10 min from lift-off, she finds herself floating in the weightlessness of space.

Without warning, however, she suddenly vomits and is overwhelmed with intense symptoms of motion sickness: nausea, a sense of dizziness, and disorientation. Her symptoms become worst when she moves about in the cabin or sees one of her fellow crewmembers floating upside-down. She is unable to keep food down and rejects even

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[6] This was one reason why the earliest spacecraft were totally automatic, with no controls for a disoriented or "crazed" pilot to use independently.

water to drink, so she quickly dehydrates. She is concerned that she could not help the rest of her crew with the rendezvous procedures of the shuttle with the ISS, because looking out of the windows triggers more symptoms. She takes some pills and is getting ready for sleep. However, when looking in the mirror above the washbasin, she realizes that her eyes seem smaller, her face is round and puffy (Figure 1.15), and her neck veins are bulging. The good news is that her wrinkles have disappeared and she looks younger. When undressing, she notices that her legs look like sticks. She tries to sleep but has a persistent backache, a definite feeling of sinus congestion, and keeps waking to discover that her arms are floating above her head. So disconcerting!

When she wakes up and dresses, she finds her clothes too short. Because of the absence of perceived gravity, her vertebrate disks are less compressed, making her height increase by 5–6 cm (Figure 1.16) and causing continuing back pain. Also, as a result of the fluid shift (which is also responsible for her puffy face and "chicken" legs) her waistline has shrunk about 4 cm, and she must tighten the bands of her pants. Her shoes have also become too loose.

Within a couple of days, the motion sickness symptoms begin to subside, though her face and legs remain changed. Her posture, too, is different, but not for the better. Joints go to their midpoint in zero gravity, so that the hips and knees are bent into a slight crouch. Her arms tend to float in front of her unless she consciously holds them down. When she sits at a workbench, she has to strap herself in place. Even so, her seated posture is to lean back. Nevertheless, she learns to move around in weightlessness by gently pushing and pulling her body with her fingertips.

Rendezvous and transfer to the ISS occur without incident, and she starts to settle for a 3-month stay on board with her two fellow crewmates. Personal hygiene is limited to "sponge" bathing; food becomes bland tasting, and she must add spices for interest.

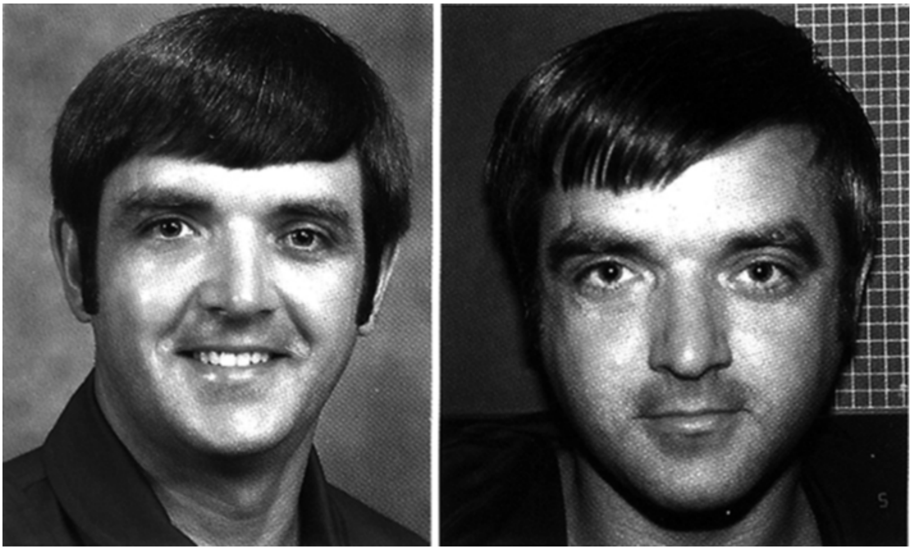

Figure 1.15. An Example of "Puffy Face." The Normal Face of an Astronaut on Earth (*Left*) Is Contrasted with His Swollen-Looking Face in Space (*Right*). (Credit NASA).

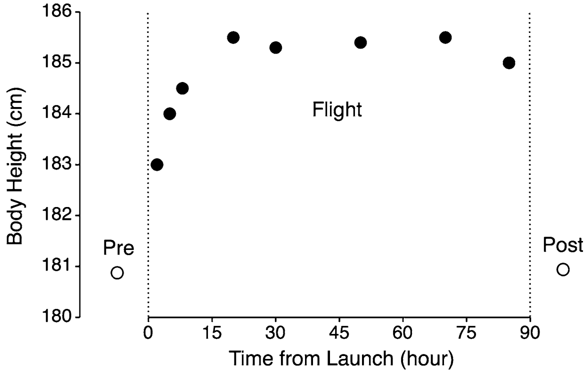

Figure 1.16. Diagram Showing the Increase in the Height of an Astronaut During the First Hours of a Space-Flight. (Adapted from Thornton and Moore [1987]).

There are experiments to monitor and several hours of exercise daily on the treadmill or cycle ergometer. After a few weeks, however, the routine becomes boring and it gets harder and harder to keep up with the exercise. The more she looks out of the window, the more she longs for the sounds of rain and wind, and the smell of flowers. The objects outside the station look “unreal in clarity.” However, when she closes her eyes, she experiences light flashes, especially when the ISS flies over the South Atlantic Anomaly. The crew starts to argue about the smallest things. One planned space walk has to be canceled because of a persistent irregular heartbeat in one crewmember. Since that incident, this crewmember seems to be withdrawing from the others. The weekly videoconferences with family and friends are eagerly anticipated, but she wonders why there has been no communication from her youngest child for several weeks. Has something happened? Anxiety arises, and she has a persistent pain in her lower abdomen, which, if it continues, might prompt an emergency evacuation to Earth.

But at last the time to return approaches. An interesting mixture of excitement and anxiety pervades the crew. Visions of favorite foods and what to do first are the main topics of conversation. Yet, the group has become so firmly a part of each other that the thoughts of reintegrating into Earth’s society are intimidating. But at last the crew is on its way home. When donning her re-entry space suit, she realizes it is too tight because she has grown a few centimeters. During the re-entry into Earth’s atmosphere our traveler experiences disorientation again when she tilts or rolls her head. After landing, she reports an unbelievable sense of “heaviness” and finds herself unable to stand up unassisted from her seat, much less walking down the stairs. Her heart is beating fast; she sweats and almost faints.

Even after several days of rehabilitation, balance is poor and walking uncoordinated. Muscle weakness is very evident; she quickly feels short of breath and is constantly thirsty. Weight loss that occurred in space is rapidly disappearing, but her physician tells her that she had lost much of bone density in her hips and that her immune system seems to be impaired. Now she is concerned because she remembers that the various bacterial colonies they were studying on board the ISS laboratories showed explosive growth rates! Several months later, though, all her body functions seem to have re-adapted to Earth’s gravity.

This story is not meant to discourage anyone from wanting to be an astronaut. In reality, not all people experience all of the adverse effects of spaceflight. It is rather meant to show how little we really know about the human body's response to spaceflight and how very dangerous this new environment can be. The interpretations for the observed physiological and psychological changes during spaceflight will be detailed in Chapters 3–6 of this book.

1.2.3. Life support systems

Spaceflight includes conditions such as vacuum, extreme temperatures, noise (mostly due to the life support systems), and radiation. Protecting humans from these harmful conditions requires the use of life support equipment and technologies such as space suits, pressurized and isolated living quarters, and radiation shielding.

In addition, certain basic physiological needs must be met for human beings to stay alive. On Earth, these needs are met by other life forms in conjunction with chemical processes that effectively use human waste products in conjunction with energy from the Sun to produce fresh supplies of food, oxygen, and clean water. In the artificial environment of a spacecraft, these materials must be provided, and human wastes removed, without relying on the natural resources of Earth's biosphere.

To date, space missions have used a simple "open" system, bringing along all necessary food, water, and air for the crew and venting waste products into space or collecting and storing them for return to Earth. When the point is reached where it is no longer cost effective or logistically possible to re-supply the spacecraft or habitat with water, atmosphere, and food, ways must be found to recycle all these components. This recycling of material is referred to as a "closed" system and can be achieved using physical-chemical systems, or better, using biological systems (Figure 1.17).

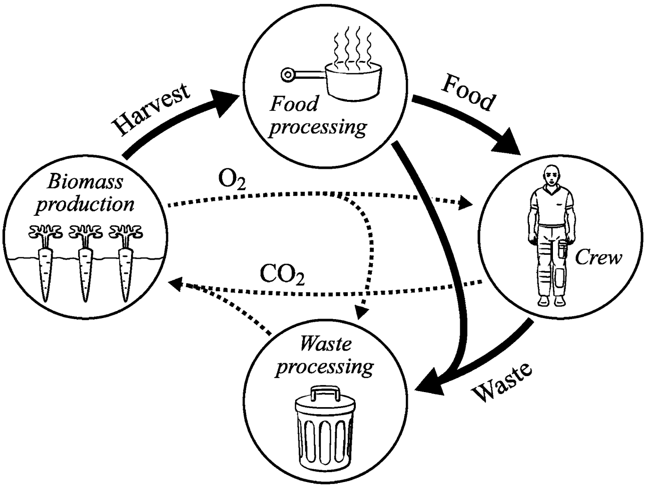

Figure 1.17. A Closed Ecological Life Support System Employs Biological Components and Uses Higher Plants. Higher Plants Are Easily Digestible and Are Customary Sources of Human Food. Besides Producing Food They Also Remove Carbon Dioxide from the Atmosphere, Produce Oxygen, and Purify Water Through the Process of Respiration. (Credit Philippe Tauzin).

Think of the human body as a sealed box with one pipe in and one pipe out. In go oxygen (O_2), water, and food; outcome solid and liquid wastes, bacteria, and carbon dioxide (CO_2). The outlet pipe is fed into a second sealed box, the closed (or controlled) ecological life support system (CELSS). The CELSS must be as "magical" as the first, for it must transform these by-products of the body into fresh supplies and pipe them back [Collins, 1990].

Trying to recreate the cycles of nature in a relatively small volume is a great technical challenge. Plants "breathe" CO_2 and "exhale" O_2, so in a broad sense human wastes are used by plants and vice versa. But in nature the nutrients, air, water, and energy are freely available. In a CELSS system all of these elements must be imported and carefully managed in a closed cycle. There are critical questions being addressed for CELSS during human missions. For example: How far can we reduce reliance on expendables? How well do biological and physical-chemical life support technologies work together over long periods of time? Is a "steady state" condition ever achieved with biological systems? How do various contaminants accumulate, and what are the long-term cleanliness issues? Eventually, in the case of interplanetary missions, is it possible to duplicate the functions of Earth in terms of human life support, without the benefit of Earth's large buffers – oceans, atmosphere, land mass? How small can the requisite buffers be and yet maintain extremely high reliability over long periods of time in a hostile environment? Eckart [1996] has addressed most of these questions. We will summarize them in Chapter 8.

1.3. Challenges facing humans in space

1.3.1. Astronauts' health maintenance

As it will be detailed in the following chapters, exposure to microgravity and the space environment has important medical and health implications, including bone loss (matrix and minerals), increased cancer risk from space radiation, spatial disorientation, orthostatic hypotension, and many others. One of the primary objectives of space life sciences is to ensure the health of crewmembers working on board the spacecraft and in the hostile environment outside their vehicles. Responsibilities of the operational medical program include preflight activities such as screening and selecting new astronaut candidates, health stabilization, in-flight activities such as the administration of countermeasures and medical care, and postflight procedures such as rescue after an emergency landing or rehabilitation for a prompt return of crewmembers to flight status [Nicogossian and Parker, 1982; Barratt and Pool, 2008].

1.3.1.1. Preflight

The minimal medical criteria for the selection of astronauts are different for those astronauts who actually pilot the vehicle (pilots), those who support onboard operations and perform extra-vehicular activities (mission specialists), and those passengers who just "participate" either as politicians, journalists, or tourists (see Chapter 7, Section 7.2.1).

Based on the knowledge of specific health risk factors associated with spaceflight, appropriate and proven tests are utilized in selecting the astronauts. Annual medical evaluations are then performed to identify and correct medical risks to maintain health, provide certification for flight duties, and ensure career longevity. These tests may include further clinical evaluation, e.g., using state-of-the-art imagery techniques, or fitness assessments in order to prescribe individualized exercise programs and provide one-on-one preflight and postflight conditioning activities. Both selection and periodic medical evaluations rely on the accepted ground-based standards of preventive medicine, health maintenance, and medical practice. These standards are revised on a periodic basis to ensure that they are fair and appropriate to meet the needs of human spaceflight.

During preflight training, the primary emphasis of medical support is on prevention. For example, the purpose of the Crew Health Stabilization program is to prevent flight crews from exposure to contagious illness just before launch. A preflight quarantine limits access to flight crew during 7 days just prior to launch. Even before this period, the health of an active duty crewmember family is of critical importance, and factors such as infectious disease and stress affecting a crewmember family may have serious adverse effects on the crewmember health and performance, as well as the health and performance of other crewmembers. Medical and dental care is provided to the crewmember's immediate family by an onsite flight medical clinic, as long as the crewmember is eligible for assignment to a spaceflight mission.

Crewmembers are also trained in the use of special countermeasures to offset spaceflight physical deconditioning and in medical monitoring and clinical practice procedures. Medical training for the crew, medical supervision of mission planning, schedules, payloads, exercise training, conditioning, and other health maintenance activities are all part of the preflight period.

1.3.1.2. In-flight

The primary emphasis of in-flight medical support is on health maintenance. Health monitoring and medical intervention, countermeasures to bodily function deconditioning, and environmental monitoring insure a comprehensive program tailored to crew and mission needs and for the periodic assessment of crew medical status, including the identification of potential and unexpected health risks.

Among these potential health risks are the levels of acceleration, vibration, and noise during launch, the exposure to toxic substances and pressure changes, and the risk due to radiation. With the possible exception of the immune system, bodily changes that occur after entering microgravity represent normal homeostatic responses to a new environment. The body's control systems recognize the lack of gravity and begin to adapt to this unique situation, not realizing that the ultimate plan is to return to 1 g after a transient visit to microgravity. In-flight, typical adaptive and pathophysiological changes occur in the heart and blood vessels (dysrhythmias), muscles (atrophy), bones (density loss, fractures, renal stones), nervous system (disorientation and nausea), and in the immune system (infection). Extra-vehicular activities (EVA), also called space walks, may also be responsible for strain on muscles and bones and decompression-related disorders.

Psycho-sociological issues become increasingly more important as space missions become longer, and spaceflight teams become larger and more heterogeneous. The isolated, confined, and hazardous environment of space create stress beyond that normally encountered on Earth, even when training for a space mission. Extended duration missions place an even greater stress on individual, interpersonal, and group relations for astronaut crews, between astronaut crews and ground control, and on astronaut families. Current countermeasures focus primarily on the individual, mission crew, and to some extent the families of mission crews, by providing psychological training and support through in-flight communications. Finally, for spaceflight missions, emphasis is not only on health maintenance, disease prevention, and environmental issues, but also on the provision of medical care to manage possible illnesses and injuries.

1.3.1.3. Postflight

The primary emphasis of postflight medical support is medical care. During return to Earth, piloting tasks are challenged by the presence of g forces in deconditioned individuals (Figure 1.18). After nominal landing, astronauts often exhibit difficulties in standing, a phenomenon known as postflight orthostatic intolerance (see Chapter 4, Section 4.1) and walking. These difficulties could prove dramatic in the case of a non-nominal landing where the crew may be required to suddenly egress the vehicle with no help from ground support.

Astronauts must have career longevity, normal life expectancy, with rehabilitation and recovery capabilities available upon their return from spaceflight. After landing, health monitoring and physical rehabilitation are performed to accelerate the return of crewmembers to normal Earth-based duties. An important factor to take into account is the return to flight status for pilot astronauts.

There is a large catalog of reported postflight symptoms captured in the mission medical debriefs that are collected after a space mission through interviews between the astronauts and crew flight surgeon. After every space shuttle mission, a NASA

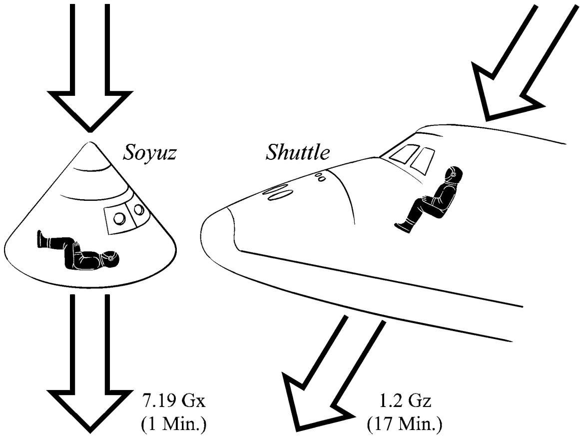

Figure 1.18. Direction of g Forces Experienced During Landing in a Soyuz Capsule (*Left*) and the Space Shuttle (*Right*). Lower g Forces Are Tolerated When Directed Along the Body Longitudinal Axis (Gz), in a Direction Parallel to the Big Blood Vessels. (Credit Philippe Tauzin).

flight surgeon holds a medical debrief with each crewmember on the day of landing and then 3 days later. Standardized debrief forms are used during these meetings, at which time the physician and crewmember discuss pre-, in-, and postflight medical issues. The crewmembers are interviewed about their experiences, using both open-ended and specific questions. Information from these debriefs is available in a database known as the Longitudinal Study of Astronaut Health (LSAH). NASA flight surgeons of the Flight Medicine Clinic at NASA Johnson Space Center provide the interface with the LSAH, which is a long-term program investigating whether the unique occupational exposures of astronauts are associated with increased health risks. Such studies are particularly relevant regarding the issue of radiation exposure.

1.3.2. Environmental health during space missions

During space missions, medical care does not only focus on health maintenance and disease prevention, but also on environmental issues. Spacecraft are closed compartments, and therefore standards for air, water, microbiology, toxicology, radiation, noise, and habitability must be established. In-flight environmental monitoring systems are available to prevent crew exposure to toxicological and microbial contamination of internal air, water, and surfaces; to radiation sources from within and external to the spacecraft; and to vibration and noise. These systems must have near real-time and archival sampling and provide a mechanism to alert crewmembers when measured values are outside acceptable limits.

Habitability of a spacecraft is vitally important to the crew's health, well being, and productivity, especially as mission duration increases. Habitability issues regarding the human presence in space includes human factor design considerations (colors, equipment layout, and hardware design), adequate and ergonomically correct work and living volume, with similarly adequate stowage volume. Areas must be designed that allow for restful sleep and personal space, with adequate lighting and exterior views. Schedules must produce interesting work, with sufficient rest and recreation periods to avoid chronic fatigue. Ideally, each crewmember should have private time and physical space for fitness and recreation, in order to keep his/her motivation.

Time and resources are set aside for personal hygiene and sanitation (see Chapter 8, Section 8.3.4). In addition, a healthy, palatable variety of food and beverage must be provided (Table 1.3). The daily food supply totals a high 3,000 cal, plus snacks. The meals also attempt to compensate for the body's tendency to lose essential minerals in microgravity, such as potassium, calcium, and nitrogen.

At the same time, the meals must be attractive, not like the early missions when astronauts had to suck their meals out of "tooth-paste" tubes or plastic bags without being able to see or smell the food. Nowadays, attention is given to individual crewmember preference with regard to palatability and nutritional adequacy of food items during missions.

Medical and psychological personnel have also an opportunity to review all design considerations early in the design process to ensure that spacecraft design and support systems meet medical and psychological requirements.

Table 1.3. The Space Shuttle Menu Currently Features More Than 70 Food Items and 20 Beverages. Shuttle Crewmembers Have a Varied Menu Every Day for 6 Days. Each Day, Three Meals Are Allowed, with a Repeat of Menus After 6 Days. The Pantry Also Provides Plenty of Foods for Snacks and in Between Meal Beverages and for Individual Menu Change.

Thermostabilized

- Heat processed foods (“off-the-shelf” items) in aluminum or bimetallic tins and retort pouches

Irradiated

- Foods preserved by exposure to ionizing radiation
- Packed in flexible foil laminated pouches

Intermediate Moisture

- Dried foods with low moisture content such as dried apricots
- Packed in flexible pouches

Freeze Dried

- Foods prepared to the ready-to-eat stage, frozen and then dried in a freeze dryer that removes the water by sublimation
- Freeze-dried foods such as fruits may be eaten as is while others require the addition of hot or cold water before consumption

Re-hydratable

- Dried foods and cereals re-hydrated with water produced by the shuttle orbiter’s fuel cell system
- Packed in semi-rigid plastic container with septum for water injection

Natural Form

- Foods such as nuts, crunch bars, and cookies
- Packed in flexible plastic pouches

Beverages

- Dry beverage powder mixes
- Packed in re-hydratable containers

1.3.3. Human Mars mission

The eventual decision to go to Mars will be strongly influenced by non-scientific reasons. Science, though a factor, will not be the driver. Thus, the real issue here is, if humans are to go to any planetary body, what science and related activities can be performed to take maximum advantage of the presence of humans on these missions?

For many, the major science objective of sending humans to Mars is to search for evidence of past or current life on another planet, investigate the Martian climate, study Martian geology and geophysics, and prepare for future missions and sustained habitation. A human Mars mission can also be regarded as an important cultural task for humankind with the objective to globalize the view of our home planet Earth, thereby contributing to the solution of local conflicts. In any case, a human Mars mission would meet the natural human need to explore and expand to new regions.

Using the current rocket technology, traveling between Earth and Mars will require lots of fuel and good timing. The most fuel-efficient trajectory occurs when Earth is at a 6 o'clock position at launch and Mars is at about 4 o'clock – a juxtaposition that occurs just once every 26 months. The first leg will take about 6 months. Astronauts must wait on Mars for their launch toward home until Earth is in alignment. After their surface stay of approximately 500 days, the astronauts will ascend to orbit, rendezvous with the transit habitat, and return to Earth. Total mission duration will be about 30 months (Figure 1.19).

In 2004, NASA embarked on the new Vision for Space Exploration. This was an ambitious plan to send human missions to the Moon, Mars, and beyond as part of the Constellation program. Early in 2010, following the recommendations provided by the Augustine Commission [Augustine et al., 2009], U.S. President Barrack Obama announced the cancelation of this program. Instead, he called for a shift in focus, directing NASA's attention towards sending humans directly to Mars using international cooperation, as well as innovative and cost-effective new technologies.

The design decisions and plans outlined within the NASA Design Reference Architecture 5.0 [NASA DRA 2009] are likely to represent a relevant baseline for any future Mars mission. This reference mission is assumed to begin with cargo launches in the 2039 launch window and the crew launching in the 2041 window. Precursor missions to Martian orbit, as pledged by U.S. President Obama in an April 2010 speech at the NASA Kennedy Space Center, should occur by 2035.

The reference mission consists of two cargo spacecraft. The first will place the ascent stage and cargo on the surface of Mars. The second will place the surface habitat in Martian orbit. The ascent stage will land with an In Situ Resource Utilization (ISRU) unit that will produce oxygen from the Martian atmosphere along with methane brought from Earth to fuel the ascent stage. A crew of six will be launched 2 years later.

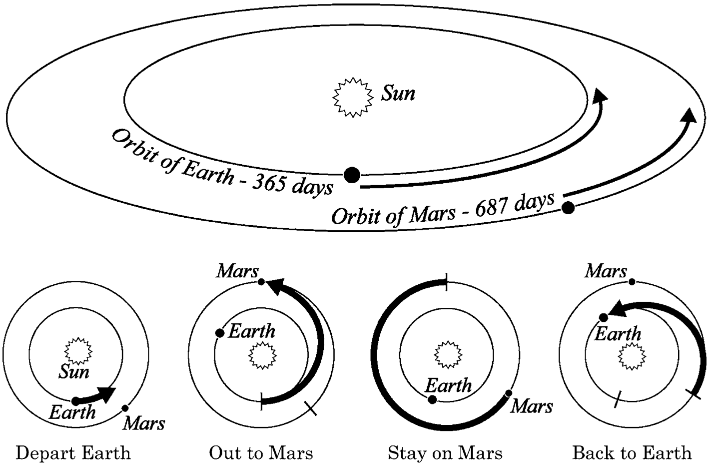

Figure 1.19. *Top*: Schematic of the Orbits of Earth and Mars Showing Their Position for a More Fuel-Efficient Trajectory During Launch. *Bottom*: The Respective Positions of Earth and Mars Determine the Duration of Travel and Stay on the Martian Surface.

The crew will be mixed gender and international with their roles being pilot, physician, geologist, biologist, and mechanical and electrical engineers. Upon arrival they will rendezvous in orbit with the habitat and use it to land on Mars. The transit module will remain in orbit for the duration of the surface mission.

Upon landing, the astronauts will take several weeks to adapt, during which they can somewhat recover from their microgravity transit and conduct only essential activities. After this period, they can engage in scientific research. A variety of robotic, pressurized, and unpressurized rovers, as well as scientific equipment and drills delivered by the landers, will be waiting for the crew. It is assumed that the landing will take place in an area believed to be relatively safe, but which will presumably not be of substantial scientific interest. From there the astronauts will use rovers to travel distances of up to hundreds of kilometers, to rougher, more interesting sites. The robotic rovers are intended for use in areas deemed to be particularly likely to contain life or evidence of past life. These areas must be protected from contamination at all costs to maintain the integrity of astrobiological investigations. The rovers will be teleoperated to investigate these sensitive areas without compromising planetary protection protocols.

Developing the technical capability to reach Mars is only one aspect of the necessary preparations; it is equally important to consider the human factors that would affect such a mission. How will the human body and mind react to extreme circumstances such as microgravity, radiation, and isolation? How does an astronaut perform his or her work if direct communication to Earth is not possible? How can a life support system keep the astronauts alive and healthy during a multi-year mission without possibility of re-supply? More studies and experiments must be performed to gain knowledge on these and numerous other topics to adequately prepare for a human mission to Mars [Smet et al., 2010].

Luckily, the Mars gravity of 0.38 g might act as a countermeasure to the physiological deconditioning that will take place in microgravity during the trip from Earth to Mars. However, landing maneuvers on Mars and Earth are characterized by maximum g-loads of up to 6 g due to atmospheric drag. If the interplanetary cruise is carried out at zero gravity level (i.e., if no artificial gravity is provided within the spacecraft), such high g levels in deconditioned astronauts appear critical for the health of the crew.

Any trip beyond low Earth orbit will involve radiation threats not faced by residents of the ISS, which sits inside the planet's magnetic field. A 30-month trip to Mars, including 6–9 months of travel time each way, would expose an astronaut to nearly the lifetime limit of radiation allowed under NASA guidelines. There are two primary forms of hazardous space radiation particles: high-energy particles emitted by the Sun during intense flares and more energetic cosmic rays from undetermined galactic sources. Solar and galactic radiation can cause severe cellular damage or even cancer (see Chapter 8, Section 8.3.5). The Martian atmosphere, about 1% as dense as Earth's, manages to stop just about all of the solar particles, but it lets most of the cosmic rays through. However, the crew needs to be protected against the occasional solar flare with a "storm shelter," e.g., with food racks and water tanks packed around the walls to absorb the radiation.

Cosmic rays are a different story. They are constantly present, coming from all directions. The radiation consists of heavy, slow-moving atomic nuclei that can do far more damage to more cells than the alpha and beta particles of solar flares. This radiation requires several meters of shielding for complete blockage, and since the nuclei come from all directions at all times, unlike the brief solar flares that last only a few hours or days, a storm shelter would be insufficient to protect the crew. The planet itself offers natural protection against cosmic rays by blocking half the sky. In addition, the habitats of the Mars base can be covered with thick layers of soil to provide full-time radiation protection, so nearly all the crew's radiation exposure would occur during the period of interplanetary travel. Even if such shielding methods prove difficult to engineers, some scientists believe that the cosmic ray doses can simply be endured. Exposure to a thin, continuous stream of radiation does far less damage than an equal magnitude of radiation delivered in 1 day. There is still the possibility of cancer, but this probability is rather low.

The combined solar and cosmic ray particle exposure is measured in Sieverts (1 Sv = 100 rem). An astronaut on a 6- to 9-month journey to Mars would be exposed to about 0.3 Sv, or 0.6 Sv on a round-trip. Another 15–18 months on the surface would bring another 0.4 Sv, for a total exposure of 1 Sv. Limits set by NASA vary with age and gender but range from 1 to 3 Sv. This dose would lead to a 3% increase in the probability of contracting a fatal cancer later in life, compared to an already existing 20% cancer risk for non-smokers on Earth, and would probably be acceptable to the volunteers for this mission. However, since the biological effects of cosmic radiation are poorly understood, the resulting cancer risk may conceivably be off by as much as a factor of 10, and thus jump to 30%, or drop to 0.3%.

Not much research can be done safely on Earth to investigate these radiation effects, as cosmic rays are difficult to generate, and no one would consent to being exposed to a theoretically fatal dosage. The ISS could provide a good testing ground because large numbers of astronauts will be exposed to modest amounts of radiation in their 6-month tours of duty, but a full investigation might require waiting decades until these astronauts retire and die either of natural causes or of cancer. Obviously Mars mission advocates have no intention of waiting that long. It actually makes the most sense to accept the radiation risk on the Mars mission. After all, this is a journey into the unknown, and the risk of radiation is mild compared to the dangers that explorers on Earth have faced, and overcome, in the past [Reifsnyder, 2001].

1.3.4. Countermeasures

We will see in the following chapters that the changes in human physiology during spaceflight are appropriate adaptations to the space environment. They are not life threatening for at least 14 months, which is the longest continuous period that humans have spent in space. That's the good news. The bad news is that adaptation to space creates problems upon returning to Earth. Difficulty in standing, dizziness, and muscle weakness pose problems after landing. Therefore, appropriate countermeasures must be developed that balance health risk against mission constraints, and particularly the limited resources regarding medical care possibilities.

Countermeasures refer to the application of procedures or therapeutic (physical, chemical, biological, or psychological) means to maintain health, reduce risk, and improve the safety of human spaceflight. The countermeasures typically aim at:

(a) Eliminating or preventing adverse and harmful effects on crew health. Examples include the provision of a substitute gravitational effect in orbit (artificial gravity), thus preventing microgravity from degrading the health of the astronauts.

(b) Mitigating the effect of adverse or harmful agents or enhancing the astronaut's ability to ward off the effects of these agents. Examples include preflight and in-flight exercise to counteract the effects of microgravity, in-flight administration of medications to prevent space motion sickness, and spacecraft design changes to minimize radiation exposure.

(c) Minimizing the effect of adverse or harmful agents on the crew once mal-adaptation, disease, or injury has been identified. Examples include fluid loading to minimize postflight orthostatic intolerance (Figure 1.20), or a postflight rehabilitation program to reverse space mission-induced musculo-skeletal or cardio-vascular deconditioning.

Preflight countermeasures include activities to support appropriate crew selection and psychological training, fitness and exercise, physiological adaptive training, a health stabilization program, and circadian shifting.

In-flight countermeasures include those activities necessary to maintain physiologic balance and health, mental and behavioral health, nutritional health, and physical fitness and mission performance. Typical physical exercise includes cycling, running on a treadmill, or rowing.

Postflight countermeasures include those activities necessary to assist the crewmembers in a return to preflight physical, physiological, and behavioral health baselines. Examples of countermeasures include, but are not limited to, circadian rhythm shifting, hormone replacement, and physical exercise.

Figure 1.20. A Shuttle Crewmember Prepares Containers of Drinking Water and Salt Tablets To Be Consumed by His Crewmates Prior to Re-entry. Fluid Loading Is a Standard Procedure on All Shuttle Flights, as an Effective Countermeasure to Orthostatic Intolerance upon Return to Earth's Gravity. (Credit NASA).

Figure 1.21. French Cosmonaut Jean-Pierre Hai-gneré Is Hand Carried by Bround Personnel After Returning from a 6-Month Stay on Board the Russian Space Station Mir. (Credit CNES).

For long-duration missions, the *Mir* and ISS experience indicates that current in-flight countermeasures are not optimal, to say the least. Evidence for this is provided by the images of the cosmonauts unable to stand immediately after returning to Earth after a long-duration stay on board *Mir*. They are helped from the spacecraft and "ceremoniously hauled around like nabobs in sedan chairs" (Figure 1.21). The situation with the ISS has not changed much. Astronauts on board the ISS exercise on a cycle-ergometer, a treadmill, or a resistive exercise device for up to 2 h/day. Yet, considerable muscle and bone loss is observed after landing (see Chapter 5, Section 5.1). Consequently, it is largely admitted that using the current countermeasure methods, humans would not be operational after landing on Mars.

1.3.5. Artificial gravity

One possible countermeasure to the effects of weightlessness is the use of artificially produced gravity on board the spacecraft. Artificial gravity could be accomplished either through rotation of the entire vehicle or by the inclusion of an onboard centrifuge. For a more complete description of the rationale for artificial gravity, the possible spacecraft design options, and its potential effect on a space crew, the reader is referred to the book *Artificial Gravity* by Clément and Bukley [2007, Springer].

The rationale for using centrifugation is that during rotation about an eccentric axis the resulting centrifugal force provides an apparent gravity vector. The centrifugal force produced by rotation is dependent upon two parameters of the rotating structure,

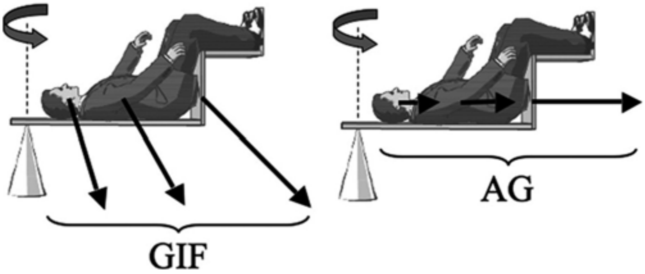

Figure 1.22. These Drawings Illustrate the Difference Between the Physical Effects of Centrifugation on Earth (*Left*) and in Space (*Right*). On Earth, the Gravito-Inertial Force (GIF) Is Tilted Relative to the Plane of Rotation. In Space, Artificial Gravity (AG) Is Aligned with the Plane of Rotation. Also Shown Is the Gravity Gradient in Both Conditions. For Example, in the Right Figure, the AG Level Is 1 g at the Feet and 0.38 g at the Head for a Rotation Rate of 20.8 rpm. (Adapted from Clément and Bukley [2007]).

the square of its angular rate (ω^2) and its radius r. On Earth the centrifugal force combines with the gravitational force, and the resulting vector, the so-called gravito-inertial force, is both larger in magnitude than the centrifugal force itself and tilted with respect to gravity. In microgravity, the subject will only be exposed to a centrifugal force, referred to as artificial gravity (Figure 1.22).

Because the centrifugal force depends on both rotational rate and radius, a specific increase in the artificial gravity level can be achieved either by increasing the radius or by increasing angular rate. This translates to a trade-off between cost and complexity, which depends mostly on the radius of the structure versus the physiological and psychological concerns, both of which depend mostly on its angular rate [Diamandis, 1997].

One significant drawback of a rotating environment is the Coriolis force that is generated every time a linear motion is attempted in any plane not parallel to the axis of rotation. The Coriolis force has a magnitude of $2\omega V$; where ω is the rotation rate for the rotating environment and V is the linear velocity of the moving object. When attempting any linear movement out of the plane of rotation, the Coriolis force combines with the centrifugal force to produce a different apparent gravity vector in magnitude alone or in both magnitude and direction. To a human in a rotating environment, this vector may be manifest in two ways. First, it adds to the apparent weight of a body moving in the direction of rotation and subtracts from the apparent weight when moving against the direction of motion. Second, when a body moves toward the center of rotation, the Coriolis force is exerted in the direction of rotation at right angles to the body's motion; when moving away from the center of rotation the force is opposite to the direction of rotation. By contrast, a motion parallel to the axis of rotation will generate no Coriolis force [Stone, 1973].

The Coriolis forces affect not only whole-body movements but also the vestibular system (see Chapter 3, Section 3.2.1). Rotation of the head out of the plane of rotation generates cross-coupled angular accelerations that induce stimulation of all three semicircular canals. Such head movements in a stationary environment do not normally stimulate some of the canals, and this results in illusory sensations of bodily or environmental motion. Nausea and vomiting may result after a few head movements, particularly if the angular velocity of the centrifuge is high. Based on ground-based studies performed in the 1970s using slow rotating rooms, it was postulated that the lightest acceptable system for providing "comfortable" artificial gravity using a rotating spacecraft would be one having a radius of rotation not lower than 12 m, rotating at 6 rpm, and providing a gravity level ranging from 0.3 to 1 g [Thompson, 1965; Hall, 2009]. More recent studies showed that the subjects in a rotating environment could tolerate a rotation rate up to 10 rpm, provided that the exposure is progressive [Lackner and DiZio, 2000], or even up to 23 rpm after habituation of the motion sickness symptoms [Young et al., 2001].

The "prescription" of how much acceleration/gravity over what period of time and in what direction is required for maintaining normal health is currently unknown and logistically very difficult to determine. A rotating spacecraft that provides a constant 1-g acceleration would be ideal. However, a maneuvering station presents serious design, financial, and operational challenges. Also, head movements and resultant Coriolis and cross-coupled accelerations on a rotating spacecraft may limit the usefulness of centrifugation for other than brief periods of intermittent stimulation. From a practical perspective, it is very likely that humans do not need gravity (or fraction of it) 24 h a day to remain healthy. If intermittent gravity is sufficient, we won't need a permanently rotating spacecraft to produce a constant gravity force. An onboard device such as a human rated short-radius centrifuge, presents a realistic near-term opportunity for providing this artificial gravity.

Several designs for an onboard short-radius centrifuge have been proposed. I was the Principal Investigator of an experiment using a human-rated centrifuge generating 0.5 or 1 g along the longitudinal body axis, which flew aboard the *Neurolab* mission of the space shuttle (STS-90) in 1998 (Figure 1.23). This experiment was (and remains) the first in-flight evaluation of artificial gravity on astronauts. The results of this experiment, described in more detail in Chapter 3, suggested that centrifugal force of 0.5 g was well tolerated by the crew, and that cardio-vascular deconditioning was reduced in those astronauts who rode the centrifuge 20 min every other day during a 16-day space mission [Clément and Reschke, 2008].

An interesting new approach is a human-powered centrifuge that couples exercise with artificial gravity [Greenleaf et al., 1977]. Exercise as a countermeasure was introduced in the days of the Gemini program. It has taken on various ingenious forms of elastic, pneumatic, mechanical, hydraulic, and electrical devices. These devices apply a force (not an acceleration), and they only partially protect crewmembers. For example, crewmembers wear a harness attached to an exercise bike or treadmill and are held "down" during exercise. Elastic devices can effectively create force, but not sustained acceleration. Doing such activities during centrifugation would be much more effective.

Various designs have been proposed, such as the "Twin Bike" of the University of Udine, the "Space Cycle" of the University of California at Irvine (Figure 1.24), and NASA Ames Research Center's human-powered centrifuge [Clément and Bukley, 2007]. It is believed that exercising under these increased inertial forces will decrease the amount of time required to exercise for maintaining health and fitness in space. If the results prove positive and the amount of exercise is reduced by centrifugation,

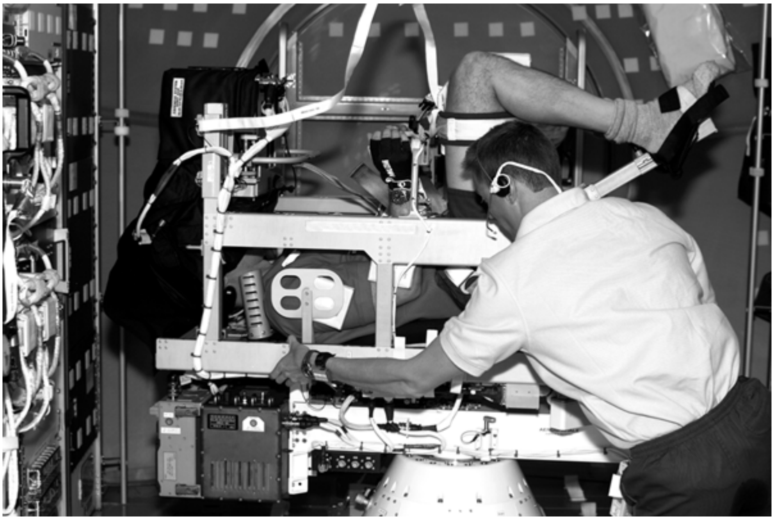

Figure 1.23. This 0.65-m Radius Human-Rated Centrifuge Developed by ESA Flew on Board the Neurolab Mission (STS-90). This Experiment Investigated the Adaptation of the Vestibular System in Astronauts by Detecting Changes in Perceived Motion and Orientation in Microgravity. (Credit NASA).

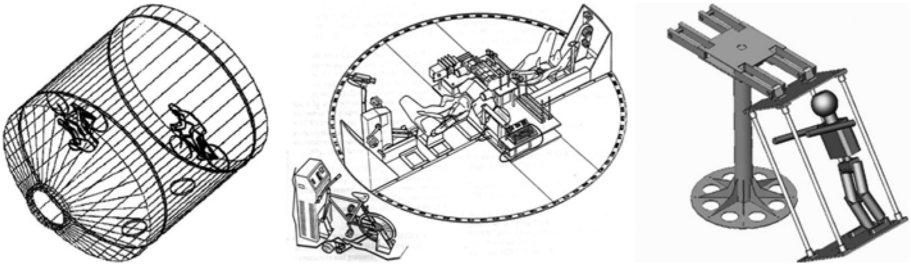

Figure 1.24. From Left to Right Are Depicted the Twin Bike, the NASA Human-Powered Centrifuge, and the Gondola of the Space Cycle (the Cycle Itself Is Not Shown). All These Devices Combine Physical Exercises and Sustained Inertial Forces Generated by Centrifugation. For More Details on These Devices, Readers Are Referred to the Book *Artificial Gravity* by Clément and Bukley [2007].

then such devices could be a good candidate countermeasure for the ISS, the spacecraft en route to Mars, or the Martian habitat.

1.3.6. A new science is born

Space life sciences is a young science, having come into existence with the first studies carried out on animals during the first suborbital flight less than 60 years ago. Since then, people have visited the Moon and have lived in space for about the period planned for a mission to Mars. Still, our understanding of how spaceflight affects living organisms remains rudimentary.

The ISS, now fully operational with a permanent crew of six, should prove an ideal platform for studying fundamental biological processes in microgravity. This will undoubtedly lead to the growth and development of a new science: gravitational physiology.

Gravity affects some materials and fluid dynamics. It is required for convective mixing and other weight-driven processes, such as draining of water through soil, and assuring that what goes up comes down. One might predict that plants would grow taller without gravity, yet the lack of gravity might facilitate increased levels of growth-inhibitory or aging environmental factors around the plants, thereby causing them to dwarf. Gravity also has a role to play in development of load-bearing structures. The scaling effect of gravity is well known: the percentage of body mass contributing to structural support is proportional to the size of a land animal (e.g., 20 g mouse = ~5%, 70 kg human = ~14%, and 7,000 kg elephant = ~27%). This scaling effect in land animals would likely change in space and could result in a static scale comparable to marine mammals on Earth (~15% of mass as supporting tissues over a wide range of weights). Legs are bothersome in space and not only get in the way but also are involved in the fluid shifts that occur early in-flight. Whether legs would disappear over time without gravity (perhaps similar to the extra-terrestrial ET) or become more like grasping talons is unknown. Form follows function, and as function changes, so will form. How much change and what form organisms will assume over time in space is unknown [Morey-Holton, 1999].

Data to date suggest that certain biological structures have evolved to sense and oppose biomechanical loads, and those structures occur at the cellular level as well as at the organism level. There is evidence that the musculo-skeletal system of vertebrates change following acute exposure to space (see Chapter 5, Section 5.1). What will happen over multiple generations is speculative. The “functional hypothesis” theory suggests that what is not used is lost. If this theory holds over multiple generations in space, then gravity-dependent structures may ultimately disappear or assume a very different appearance in space. The next chapter reveals that we only have short snapshots of how small living organisms actually change in the space environment.

Another example is plants. Plants are the first organisms to be raised to the point of producing seeds in space, from seeds that were themselves raised in microgravity (see Chapter 2, Section 2.4). We now know that plants can grow in space, but the *Mir* and ISS studies have indicated that air and water require special management in microgravity. Further studies in this area are of paramount importance if one wants to move from the current physical-chemical to ecological closed life support systems.

Carrying out research in space often comes at a considerable cost (sometimes human, as demonstrated by the *Columbia* tragic event). The most striking difficulties are the small subject pool available, the lack of adequate controls, and the fact that science is, by necessity, secondary to mission safety when conducting experiments in such a hostile environment. Nevertheless, the success of the manned space program is dependent on the concomitant success of life sciences research in microgravity to solve the considerable dangers still faced by crewmembers on long-duration missions.

In this respect, the human Mars mission represents another fascinating challenge for space medicine. Such a mission, when it is undertaken, will probably be the longest period of exposure of any person to a reduced gravitational environment, and probably the longest period away from Earth, too. A recent report also suggested that radiation on Mars might be at much higher levels than previously believed. So high in fact, that it would make living there almost impossible. All together, these conditions make a human Mars mission a challenge from both the physiological and psychological points of view.

The historical record offers a rich set of examples of exploration – Christopher Columbus in his discovery of the New World, Vasco de Gama sailing directly from Portugal to India, and Lewis & Clark in the first overland expedition undertaken by the United States to the Pacific Coast, for example. These expeditions to unknown territories and back rank as some of the greatest voyages of discovery in human history. Because of the scientific and geographical discoveries that were made at the time, they stand in significance along the planned human exploration of Mars. They are many parallels between these jumps into *terra incognita* – unexplored land. All these historical expeditions took the necessary equipment, collective skill set, and vision to go into an unknown world in search of many things. The expeditions redefined, literally, a quest for scientific understanding about Earth and set the foundation for colonization. The small number of vessels and time frame are quite similar for the Mars mission and for the Vasco de Gama and Lewis & Clark's expeditions. However, the crew size was much larger and many lives were lost in the historical expeditions (Figure 1.25).

The public is presumably not ready for paying such a price in human lives for the Mars mission. Hence, more advances in research and technology are needed before the human exploration of Mars can be achieved with minimal risk. There is no doubt, however, that like the historical expeditions, the exploration of Mars will be extremely influential in terms of our knowledge of the world and satisfy the desire of humanity to explore and expand.

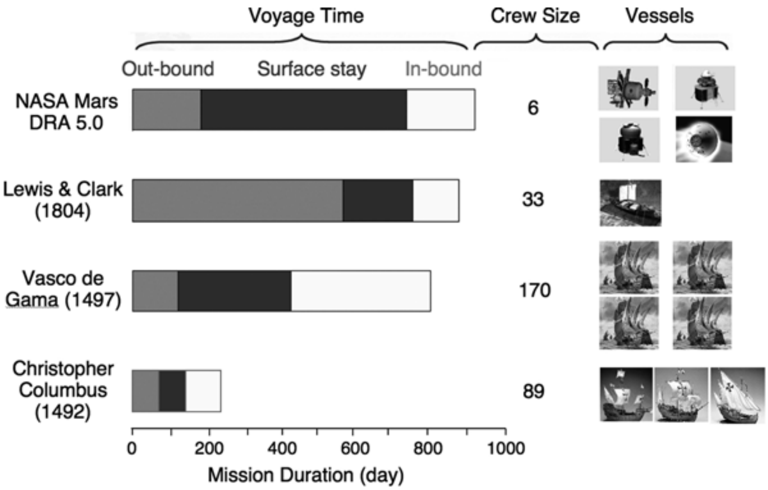

Figure 1.25. Historical Perspective for Human Exploration Missions. Comparison Between the NASA Mars Mission, Lewis and Clark's Expedition Across the Louisiana Territory, Vasco de Gama's First Direct Sailing from Europe to India, and Christopher Columbus's Discovery of America in Terms of Mission Duration, Number of Crew, and Vessels.

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