Chapter 3

HISTORY OF ARTIFICIAL GRAVITY

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This chapter reviews the past and current projects on artificial gravity during space missions. The idea of a rotating wheel-like space station providing artificial gravity goes back in the writings of Tsiolkovsky, Noordung, and Wernher von Braun. Its most famous fictional representation is in the film *2001: A Space Odyssey*, which also depicts spin-generated artificial gravity aboard a space station and a spaceship bound for Jupiter. The O'Neill-type space colony provides another classic illustration of this technique. A more realistic approach to rotating the space station is to provide astronauts with a smaller centrifuge contained within a spacecraft. The astronauts would go into it for a workout, and get their gravity therapeutic dose for a certain period of time, daily or a few times a week. This simpler concept is current being tested during ground-based studies in several laboratories around the world.

Figure 3-01. A short-radius human centrifuge. "Artificial gravity is an idea whose time has come around, ...and around, ...and around, ..."-- Laurence Young, Man-Vehicle Laboratory, Massachusetts Institute of Technology.

1 CONCEPTS

1.1 History of Artificial Gravity   Space Travel and

The notion of creating a substitute for gravity through centrifugation was introduced early in the conception of human space travel. In fact, schemes for achieving artificial gravity in space preceded real manned spaceflight by many decades. Konstantin Tsiolkovsky, the influential Russian space visionary, discussed the idea in 1883. In his manuscript *Free Space*, first published in 1956, he drew the primitive design of a true spacecraft, which moved in space with the help of reactive forces, described the life and ways of motion in zero gravity, and discussed the possibility of a spinning space vehicle for creating artificial gravity (Figure 3-02).

Figure 3-02. This was the first drawing of Tsiolkovsky's of a space vehicle, from his monograph Free Space *(1883). It shows cosmonauts in weightlessness inside the vehicle, and in artificial gravity when running along the internal walls.*

Tsiolkovsky never saw his designs materialize. However, 50 years later, a younger generation of Russian engineers and scientists began to make his visionary concepts reality. Among these was Sergey

Korolev, who would become the "Chief Designer" of the Soviet space program, and who launched humanity into space with Laika on Sputnik and Yuri Gagarin on Vostok (for a detailed chronology of the space missions involving humans and animals, see *Fundamentals of Space Biology*, in this Space Technology Library series).

As early as 1959, a team of enthusiasts led by Sergey Korolev was already working on a concept, fantastic at the time, for a manned mission to Mars. Gradually, the concept was taking on the form of a design, which became the basis for defining specifications of the advanced N1 rocket, then in its initial design phase. N1 rocket was to put into a circular orbit a spacecraft with an upper stage, which was then to be injected into a Mars fly-by trajectory. Subsequently, assisted by the Martian gravity field, it was to come back to the vicinity of the Earth, and the descent vehicle was to return to Earth. The *Heavy Interplanetary Manned Vehicle* (HIMV) had a mass of 75 tons, a length of 12 meters, and a pressurized cabin of 6 meters in diameter for a crew of three. For the total flight time of 2 or 3 years, it was envisaged as having an instrumentation compartment (doubling as a radiation shelter for the crew during solar flare activity), as well as a biological reactor to provide food for the crew. In flight, HIMV was to revolve about its long axis to create artificial gravity.

The development of the HIMV was projected for 1962-1965 (Vetrov 1998). During the following decade, however, the Soviet rocket industry concentrated its efforts mostly on matching NASA's Apollo program and toward the mass deployment of intercontinental ballistic missiles. Nevertheless, Korolev was always interested in application of artificial gravity for large space stations and interplanetary craft. He sought to test this in orbit from the early days of the Voskhod program (Harford 1973). Two modules connected by a tether were considered. Separation of the two components would first produce 0.03 g of artificial gravity. When the distance between the two modules would reach 300 m, a rotation rate of 1 rpm would achieve 0.16 g. The two modules scheme was attractive because nose-to-nose tethering meant that the living module would have the correct vertical orientation for sustained experiments. However, the flight would be limited to a maximum of three days of experiments because the batteries would run down since the solar cells could not be kept oriented to the sun during the artificial gravity experiment. After Korolev's sudden death in 1966, the project was closed and not pursued further.

In the same period, inspired by the pioneering projections of Hermann Oberth, Hermann Noordung introduced a detailed engineering proposal for a space station with artificial gravity in 1928. Noordung's proposed design consisted of a wheel-shaped structure for living quarters, a power generating station attached to one end of the central hub, and an astronomical observation station. The last two components were connected to the habitat by an umbilical. Collecting sunlight through the concave mirror in the center generated power. This power allowed the habitat wheel to rotate, thus creating artificial gravity inside the space station (Figure 3-03).

Figure 3-03. The Austrian writer Hermann Noordung's space station was a 30-m diameter rotating station called "Wohnrad" (Living Wheel) that he placed in geostationary orbit. This cover of the August 1929 number of the Science Wonder Stories *magazine by well-known science fiction illustrator Frank R. Paul illustrates Noordung's space station array.*

In his vision of space exploration in the *Collier's Weekly* space magazine, Wernher von Braun proposed an updated Noordung's rotating wheel of 76 m in diameter (von Braun 1953). Orbiting at an altitude of 1730 km[1], his inflated three-deck space station would be built of reinforced nylon fiber covered with protective plates and rotate at three revolutions per minute (rpm) to provide the occupants with 0.3 g, a suitable platform for Mars expeditions (Figure 3-04).

Figure 3-04. Von Braun's original vision for a spinning space station with its crew of fifty was to serve as a major jumping off point for exploring the Solar System. In the centre of the wheel is a "de-spun" section housing the airlock.

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[1] This orbit was later found to be within the then-unexpected Van Allen's radiation belts and therefore unusable by a manned spacecraft.

Later, Wernher von Braun worked with Walt Disney Studios on presenting to the public concepts about space travel. The spinning station in the Disney television series *Man in Space* (1955-1957) was an update of the *Collier's* station that von Braun had designed a few years earlier, the main difference being that instead of being solar powered the station included nuclear reactor on its axis (Figure 3-05).

Figure 3-05. Wernher Von Braun spinning station in the Disney television series Man in Space aired on ABC in 1955.

1.2   Science Fiction

The popularization of artificial gravity, however, is attributable to the science fiction community. The large rotating space station image in the second episode (TMA-1) of the movie *2001: A Space Odyssey*, directed by Stanley Kubrick in 1968 (Figure 3-06) is also based on Wernher Von Braun's concept. The movie script was based on Arthur C. Clarke's short story *The Sentinel*, written two decades earlier (Clarke 1948). Clarke returned the favor to Stanley Kubrick by writing a novel version of the film that was published concurrently with its release (Clarke 1968). The Earth-orbiting space station in the second episode of the movie was 300 m in diameter and was home to an international contingent of scientists, passengers, and bureaucrats. It rotated around its center to provide artificial gravity to its inhabitants.

Figure 3-06. The gigantic space station in Earth orbit in the movie 2001: A Space Odyssey *produced and directed by Stanley Kubrick (1968). The station is shaped like a pair of four-spoked wheels on a common axis, about which it rotates to provide artificial gravity. It had not yet been completed: one of the wheels consisted primarily of a bare "wire" frame, with "skin" only at the points of intersection with the spokes.*

In the third episode of Kubrick's *2001: A Space Odyssey* (Jupiter mission), the *Discovery One* spacecraft used for interplanetary travel included another means for providing artificial gravity. *Discovery One* consisted of a large sphere as its fore end, then a long segmented spine with a communications dish, and a matrix of hexagonal exhaust nozzles (Figure 3-07a). The equatorial region of the sphere comprised a slowly rotating carousel, 11 m in diameter (Figure 3-07b). By rotating at slightly above 5 rpm this internal centrifuge produced an artificial gravity equal to that of the Moon. According to Clarke and Kubrick, this was enough to prevent the physical atrophy that would result from weightlessness, and it also allowed the routine functions of living to be carried out under nearly normal conditions (Figure 3-08).

Figure 3-07. A. External view of the interplanetary spaceship in the movie 2001: A Space Odyssey. *B. Cross-section of the* Discovery One *spacecraft showing the location of the internal centrifuge.*

The internal centrifuge in the spacecraft *Discovery One* presented an idealized version of life in space, free of health problems and the negative effects usually associated with transiting from the rotating to the stationary parts of the station. The carousel contained the kitchen, dining, washing, and toilet facilities. Around the rim of the carousel were five tiny cubicles, fitted out by each astronaut according to taste and containing his personal belongings. The spin of the carousel could be stopped if necessary, when this happened, its angular momentum had to be stored in a flywheel, and switched back again when rotation was restarted. But normally it was left running at constant speed, for it was easy enough to enter the big, slowly turning drum by going hand-over-hand along a pole through the 0-g region at its center. According to Clarke's story "transferring to the moving section was as easy and automatic, after a little experience, as stepping onto a moving escalator"[2] (Figure 3-09).

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[2] In reality, adaptation to the changes in gravity level and to Coriolis forces when crewmembers were passing from artificial gravity to weightlessness and back might take much more than just "a little experience", as suggested by the ground-based studies in slow rotating rooms (see this Chapter, Section 3)!

For making the scene involving the astronauts walking and jogging inside the spinning carousel, Kubrick had an 11-m diameter circular set (built at the cost of $750,000, a considerable part of the film's budget), which could spun on its axis at a rotation rate of less than 1 rpm (corresponding to a speed of 0.5 km/h at the rim). The actors were always at the bottom. As they walked, the set would be turned to keep the actors at the bottom and prevent them from falling over, like the hamsters in an exercise wheel. The camera and the operator were installed on a wheeled dolly allowing it to also sit at the bottom. From the camera's point of view, and the audience's, the astronauts appeared to be walking around the walls while the set stood rock steady. Earlier shots in the mocvie, of a stewardess climbing around the walls in the *Aries* kitchen module, were achieved in a similar way (Bizony 2000). A similar technique was first used in the movie *Royal Wedding* (Director Stanley Donen, 1951, MGM) where Fred Astaire in one of his best-known solos dances on the walls and ceilings of his hotel room (Figure 3-10). The number was filmed by mounting the camera and operator in a cage that rotated with the room, while Fred Astaire was dancing in a normal orientation relative to gravity.

Science and the popular press, however, continued to concentrate on Von Braun and Kubrick's "space wheels". In 1971, Henry Gray proposed expanding the hub of such a station into a cylindrical habitat, which he called a *Vivarium* and patented under that name. Earlier, in 1956, Darrell Romick had advanced a yet more ambitious proposal for a rotating cylinder one km long and 300 m in diameter that would be home to 20,000 people. In 1964 Dandridge Cole and Donald Cox suggested hollowing out an ellipsoidal asteroid about 30-km long, rotating it about its major axis to generate artificial gravity, reflecting sunlight inside with mirrors, and creating on the inner shell a pastoral setting as a permanent habitat for a colony.

In his novel *Rendez-Vous With Rama* (1973) Arthur Clarke took Romick's kilometer-long cylindrical habitat and increased its size by an order of magnitude, combining it with the concept of the "generation ship" as a vehicle for interstellar travel at an achievable velocity. The vehicle called *Rama* was a dome-ended cylinder 50-km long and 16 km in diameter, rotating at one 0.25 rpm to produce a near-terrestrial acceleration on the interior of its hull. Huge banks of lights in three vast trenches running the length the cylinder, 120 degrees apart, lighted that interior. A ten-km-wide "Cylindrical Sea" at its equator divided it into two sections.

Another futurist thinker who has considered space stations with artificial gravity is Gerard K. O'Neill, an American physicist at the Institute for Advanced Studies, Princeton. In 1969, O'Neill began to work out a strategy for the future expansion of the human race into space. He championed the idea of orbital settlements in several papers (O'Neill 1974) and his book *The High Frontier* (1972). O'Neill first envisaged the construction of a space colony within a self-sufficient sphere, some 500 m in diameter. His

Island One space sphere, rotating at 2 rpm would generate an Earth-normal artificial gravity at its equator. An advantage of the sphere is that it has the smallest surface area for a given internal volume, so minimizing the amount of radiation shielding required.

O'Neill later built plans to orbit permanent colonies at the L4 and L5 Lagrange points in near-Earth space, culminating in a structure 32-km long and 3.2 km in radius, and capable of permanently supporting hundreds of thousands (*Island Two*) or even millions of inhabitants (*Island Three*). Normal Earth gravity would be achieved by rotating the colony at a rate of 0.53 rpm. The interior of the cylinder would have three inhabited "valleys" each containing lakes, forests, towns, and so forth (Figure 3-11). Three large mirrors, capable of being opened and closed on a regular day/night basis, would shine sunlight into the valleys, and a large parabolic collector at one end of the cylinder would focus solar energy onto steam-driven generators to provide the colony's electricity needs. His large orbiting space colony consisted of an immense rotating aluminum cylinder, the structure of which would be built of material mined from the Moon or asteroids.

Figure 3-11. Dr. Gerard O'Neill's vision of a space colony with artificial gravity. The cylinder sits with one hub pointed so that a maximum shielding affect is gained in the direction of maximum solar storm flux. Visiting spaceships dock at the center of the hub. There is zero gravity at the axis, so this area could be used for human powered flight, 0-g sports or microgravity research. Artificial gravity is generated on the inner rim of the cylinder.

1.3   Formal Studies

Clarke and O'Neill's "space arks" sparked fire with both the science-fiction readership and the scientific community. Suddenly, mere space stations like the NASA Skylab were no longer enough. Once-conservative scientists began setting their sights higher and their goals loftier. Artificial worlds were now the order of the day.

The first formal studies into the feasibility of man-made worlds were conducted in 1975 with a 10-week program in systems engineering design conducted by NASA and the American Society for Engineering Education. This resulted in a 185-page report called *Space Settlements: A Design Study* (Johnson and Holbrow 1977). It proposed several types of space habitats: an updated version of the O'Neill *Island One* sphere, a domed cylindrical design inspired by Clarke's *Rama* and a ring-shaped design that expanded Von Braun's space wheel into a self-sufficient "space island."

NASA selected the new space wheel or "toroidal habitat" design, submitted by Stanford University students and later dubbed the *Stanford torus* to recognize their contribution, as the most feasible of the proposed designs, making it the focus of the study. Deemed both ambitious and achievable, the *Stanford torus* was a cylindrical tube 130 m in diameter and 5.6-km long, bent into a circle and joined end-to-end to form a wheel 1.8 km across. The shape and design of the *Stanford torus* is perfect for creating artificial gravity. Spinning the torus like a giant centrifuge at exactly 1 rpm generates centripetal acceleration toward the exterior that feels just like Earth gravity to the inhabitants of the colony. The *Stanford torus* would accommodate 80,000 people in a near-Terrestrial environment complete with suburban villages, parks, and woodlands with free-running streams (Figure 3-12).

Figure 3-12. Artist conception of the inside of a Stanford torus, with a radius of 1.8 km and spinning at 1 rpm to produce a 1 g artificial gravity environment. Photo courtesy of NASA.

Following these pioneering ideas, the majority of early space station concepts created artificial gravity one way or another (see Figures 2-12, 2-13, and 2-14) in order to simulate a more natural environment for the astronauts. During the Mercury and Gemini program, the astronauts had no trouble doing activities as long as they were inside the spacecraft, but they experienced difficulty when carrying out extravehicular activities (spacewalk or EVA). Only later, it was discovered that training for EVA could be reasonably achieved on Earth in simulations, such as neutral buoyancy in a water tank. At the time, artificial gravity in an orbital station was seen as a situation "where we [NASA] do not have to train

the people, where we would be able to accommodate a greater variety of experimenters and not to have to end up training for every task prior to flight" (Faget and Olling 1968).

However, the concept of a rotating spacecraft or two spacecrafts connected by a tether presents serious design, financial, and operational challenges for a maneuvering space station. In more recent studies, emphasis has been placed on reducing the artificial gravity level, reducing the radius, and increasing the rotation rate (Loret 1963, Shea 1992). However, all these trends introduce new problems. First, the surest artificial gravity solution is clearly one that produces a gravito-inertial environment close to that on Earth. It remains to be determined whether a lesser gravity level will suffice. And second, reducing the radius and increasing the rotation rate introduce potential problems associated with gravity gradient and Coriolis forces (see Chapter 2, section 3), such as disorientation, and impaired movement and locomotion. These problems might in turn compromise the conditions of living and working in a rotating environment.

An alternative to a rotating spacecraft is in-flight exposure to artificial gravity within a small internal centrifuge. A 2-m-radius centrifuge permits subjects to stand upright and even walk within its limited confines. Of course, the head is then close to the center of rotation and a significant gravity gradient appears in the head-to-foot direction. As the radius shrinks even further to less than 1.5 m, the taller subjects can no longer stand erect but must assume a squatting or crouching posture. In order to generate 1 g at the subject's feet, such a short-radius device would also have to spin much faster than a large continuous system, and would produce significant Coriolis forces and motion sickness stimuli if the head is moved, at least until adaptation occurs.

However, just for other physical stimuli, there must certainly be some dose-response relationship between the amplitude and duration of the gravity level and the physiological body functions, which remains to be determined (Young 1999). Although our current knowledge is limited, it is very likely that humans do not need a continuous exposure to 1 g to remain healthy. As part of our normal circadian rhythm, the very gravity dependent processes that result in body fluid loss and bone deconditioning are probably turned off during normal sleeping hours (Diamandis 1997, Vernikos 2004). Furthermore, with the use of a centrifuge for short periods, there is no reason to be restricted to 1 g: the exposure might be as high as 2 or 3 g in periods of perhaps 1 hour daily or several times per week, just enough to deliver adequate stresses on the bone, muscle, cardiovascular, and sensory-motor systems. An on-board human periodic or intermittent small centrifuge therefore presents a realistic near-term opportunity for providing artificial gravity during planetary missions. Note that the physiological responses to continuous Mars gravity (0.38 g) exposure, such as anything other than 1 g, are unknown. If it turns out that substantial physiological deconditioning occurs at Mars gravity, then intermittent artificial gravity may be required to protect crews during long stays on the surface of Mars as well.

The potential use of 1.5 to 2-m-radius centrifuges for intermittent artificial exposure to astronauts has been validated in numerous ground-based studies as an effective way to overcome the deconditioning of bed rest. The main results of these studies are reviewed in the flowing section.

2   EXPERIENCE WITH ARTIFICIAL GRAVITY

Despite the long-standing interest in artificial gravity, experimental evidence from space is very limited. A few space missions early in the space program were devoted to animal studies. Rats were centrifuged continuously at 1 g for several days and showed no deconditioning. Hopefully, the planned 2.5-m-radius centrifuge on the ISS will afford the opportunity to examine the adequacy of various levels of artificial gravity in protecting rodents during spaceflight. Human experiments with artificial gravity are even more limited. They include anecdotal reports of the crew on the lunar surface, during space missions with tethered and spinning vehicles, during orbital maneuvering systems burn, or when riding eccentric rotating chairs and sleds used by scientists for investigations of the vestibular system in orbit.

2.1   Flight Animal Experiments

The Soviet space research community expressed an early and intense interest in artificial gravity and, in 1961, began testing rats and mice in the 25-s weightless periods of parabolic flight. Animals showed normal appearing posture and locomotion during brief periods at 0.3 g, thus setting this as a minimum g requirement for locomotion (Yuganov *et al.* 1962, 1964).

The first animals to be centrifuged in space were flown on the 20-day Cosmos-782 mission in 1975, when fish and turtles housed in containers were centrifuged at 1 g. The center of the containers was placed at 37.5 cm from the center of a platform rotating at 52 rpm. After the flight, the centrifuged animals were found indistinguishable from their 1-g ground and 0-g flight controls. Furthermore, turtles centrifuged at levels as low as 0.3 g showed none of the muscle wasting typical of weightlessness (Ilyin and Parfenov 1979).

A much more extensive investigation was carried out on rats centrifuged during the 19-day mission of Cosmos-936 in 1977. Rats were kept in individual cages and were not restrained. Cages were placed in a small-radius (32 cm), high-speed (53.5 rpm) 1-g centrifuge (Figure 3-13). Results showed that in-flight centrifugation had a protective effect on the myocardium and the musculo-skeletal system, as compared to the microgravity-exposed animals. On the other hand, some adverse influences of in-flight centrifugation were noted on the visual, vestibular and motor coordination, such as equilibrium, righting reflex and orientation disorders. These deficits may have been the result of the high rotation rate of the centrifuge and the high gravity gradient (Adamovich *et al.* 1980).

Figure 3-13. Centrifuge for housing rats on board the Cosmos missions. Adapted from Adamovich et al. (1980).

In another series of experiments, four rats were rotated on suborbital rockets during a 5-min period of free fall. A special motor rotated the rocket at 45 rpm about its longitudinal axis, creating a variable artificial gravity field of 0.3 to 1.5 g along the boxes that housed the rats. The rats' movements recorded on film showed than one rat stayed where the artificial gravity was about 0.4 g, whereas the other three settled down where the artificial gravity was 1 g (Lange *et al.* 1975).

Small radius centrifuges (with high rotation rate) have also flown in the Spacelab of the Space Shuttle or in the Skylab, Salyut, and Mir space stations, to conducted experiments on bacteria, cells, and other biological specimens. Results showed that microgravity effects, especially at the cellular level, may be eliminated by artificial gravity (see Clément and Slenzka 2006 for review).

The current plans for the ISS include a module for a 2.5-m-radius centrifuge to carry up to eight modules for rodents, fish, and eggs (Figure 3-14). This variable gravity animal centrifuge not only serves as a 1-g control for the 0-g experiments, but also allows exploring the entire range from 0.01 g to 1 g for a variety of species. Such device would afford the opportunity to examine the adequacy of various levels of artificial gravity in protecting rodents during spaceflight. It would be very unfortunate if this centrifuge, which is the heart of the gravitational biology flight program, were to be eliminated from the ISS program. Not only is it essential for basic research, but it also forms the basis for understanding the physiological effects of short radius artificial gravity in a manner needed for effective human artificial gravity prescription.

Finally, it is worth to mention the efforts of the students from the Massachusetts Institute of Technology (MIT), and the Georgia Institute of Technology who propose to study the effects of Mars gravity on mice on board an unmanned biosatellite. Their project of *Mars Gravity Biosatellite* is a 400-kg biosatellite carrying 15 mice housed in individual life support systems that will rotate about its central axis, providing 0.38 g outwards against a curved floor. After 5 weeks in low Earth orbit, the re-entry capsule will separate from the primary spacecraft to return the mice safely to a landing zone in the Australian desert. The biosatellite provides autonomous life support capabilities and data telemetry or storage from on-board experiments. The comparison between the deconditioning of the mice in the Mars Gravity Biosatellite and in previous microgravity space missions should provide valuable data about the effects of partial gravity on physiological functions.

2.2   Human Space Experience

No formal human artificial experiments were performed in space during the first 40 years of the space age. During the earliest years of human spaceflight, the major physiological disturbance involved space motion sickness and this was of concern only for the first few days in orbit. After the Apollo missions, the NASA flight surgeon position was the following: "The magnitude of the motion-sickness problem experienced by astronauts to date does not appear to suggest clearly the need for design and incorporation of artificial gravity system in near-future space vehicles" (Berry 1973). The debilitating effects of weightlessness on the bone, muscle, and cardiovascular system were demonstrated on the longer Skylab missions in the early 1970s and later on the long-duration Salyut and Mir flights. However, it was believed that in-flight exercise, augmented by resistance training and fluid loading, would solve the problem. As time passed, the opportunities for human centrifuges or rotating spacecraft in orbit disappeared.

The Gemini-11 mission in 1966 offered the first chance to turn artificial gravity science fiction into fact. Half the Gemini program had passed, however, before NASA got around to planning tethered vehicle flights. When NASA planners listed tethered flight as a mission objective, they first thought of it as a way of evaluating the tether as an aid to station keeping, but it might also be a means of inducing some degree of artificial gravity. The minimum rotation rate depended on whether the tethered activity was intended primarily for formation flying or for achieving gravity. NASA decided to try for both, although it would settle for "an economical and feasible method of long-term, unattended station keeping", and chose a 36-meter Dacron line (Wade 2005).

An astronaut tethered an orbiting Agena rocket casing to the Gemini-11 spacecraft during a spacewalk and the two vehicles were put into a slow spin (see Figure 2-03). The rotation rate was about 0.15 rpm. At a distance of about 19 m from the center of rotation, the Gemini cabin and its crew (astronauts Gordon and Conrad) experienced 0.0005 g of artificial gravity. When the astronauts put a camera against the instrument panel and then let it go, it moved in a straight line to the rear of the cockpit and parallel to the direction of the tether. However, the crew, themselves, did not sense any physiological effect of gravity. After they had been rotated for 2½ orbits around the Earth (about four hours), the pilots ended the exercise by jettisoning the spacecraft's docking bar. All in all, they reported it had been "an interesting and puzzling experience" (Wade 2005).

It is now known that Sergey Korolev also had a project for an artificial gravity experiment in 1965-1966 (Harford 1973). As mentioned above, his plan was to deploy a tether between a Voskhod vehicle and the spent last stage of its booster, and rotate both vehicles, thus providing artificial gravity in the crew compartment. The flight was planned to last for 20 days to definitively upstage the Americans. The crew would have included a pilot and a physician (Volynov and Katys), and artificial gravity experiments would have been conducted for 3-4 days of the flight. However, after the unexpected death of Korolev in January 19966, the Soviet space program was in crisis. This mission was postponed to February 1966, with the deletion of the artificial gravity experiment, before being definitely cancelled (Wade 2005).

No further spacecraft artificial gravity tests have been conducted. Since then, the only opportunities for artificial gravity human experiments in weightlessness have come from anecdotal reports by the crew, and from neurovestibular system investigations utilizing controlled, although short-lasting, linear accelerations.

For example, during the Skylab missions, the crew took advantage of the large open compartment to run around the curved circumference, imitating the jogger in Stanley Kubrick's film. The astronauts produced a self-generated artificial gravity by running (see the video at the following URL site:

http://www.artificial-gravity.com/Skylab-clip2.mpg). They reported no difficulty with either locomotion or motion sickness during this exercise (Conrad and Klausner 2005).

In late 1960s, tests were also conducted in parabolic flights to define artificial gravity requirements for a space station, and to assure that the crew could perform well in reduced gravity. Parabolas were flown at 0.1, 0.2, 0.3, and 0.5 g during about one-half minute each. The tests subjects, who had previously flown several hundreds of parabolas in reduced gravity, carried certain predefined tasks. These tasks included walking while carrying small and large containers, tightening bolts, connecting and disconnecting electrical equipment, and pouring water back and forth between two containers. These tests, although preliminary in nature, indicated that 0.2 g provided a much better environment for such tasks than did 0.1 g. At gravity levels greater than 0.2 g, very little gain in performance was indicated. Furthermore, the test subjects reported that at 0.5 g they felt as sure of themselves and as comfortable as they did at 1 g (Faget and Olling 1968).

In a *European Space Agency* (ESA) linear acceleration experiment on board the Spacelab D-1 mission in 1985 subjects were oscillated in a sinusoidal fashion on a linear sled at frequencies between 0.18 Hz and 0.8 Hz generating a peak linear acceleration of 0.2 g (Figure 3-15). The acceleration could be in either the interaural (Gy) or the longitudinal (Gz) direction, with ±Gy directed to the right or left shoulder, respectively, and the ±Gz directed head-to-foot or foot-to-head, respectively (for the definition of axis and direction, see Figure 2-02). The fundamental result was that the test subjects in microgravity did not perceive linear Gz accelerations of less than 0.2 g in magnitude as artificial gravity (Arrott *et al.* 1990).

Figure 3-15. The ESA linear sled on board the Spacelab D-1 mission could generate linear accelerations ranging from 0.2 g to 1 g. Due to the limited track length (2.5 m), sustained constant exposure was only possible for very low (<0.05 g) acceleration levels. Perception studies involved sinusoidal profiles with the subjects behind accelerated back and forth in either the interaural (sideways) or longitudinal (forward-backward) directions. Photo courtesy of ESA.

Another experiment conducted during the Spacelab International Microgravity Laboratory (IML-1) mission flown on STS-42 in 1992, four subjects were spun on a rotator in pitch and in roll (Figure 3-16). The head of the subjects was 0.5 m off-center experiencing an acceleration of 0.22 g (–Gz), while the feet were on the other side of the rotation axis, experiencing an acceleration of 0.36 g (+Gz). No unusual inversion phenomena were reported, indicating that the artificial gravity stimulus of –0.22 g at the head did not provide a vertical reference in any of the test subjects (Benson *et al.* 1997).

Figure 3-16. The Microgravity Vestibular Investigations *rotator flown on STS-42. With the subjects being spun in pitch (as seen here) or in roll, because the axis of rotation was at about the center of mass, the centrifugal force (0.22 g) exerted at the head was directed foot-to-head (-Gz), whereas the centripetal acceleration exerted at the feet was directed head-to-foot. Photo courtesy of NASA.*

During the Neurolab mission frown on STS-90 in 1998, a systematic evaluation of the effects of artificial gravity in humans was conducted using the ESA off-axis rotator, a short-radius centrifuge with a variable radius of 0.5 to 0.65 m that was capable of generating artificial gravity levels of 0.5 and 1 g. The artificial gravity forces were applied through the subject's ±Gy or –Gz axis for seven minutes at a time (Figure 3-17). Eye movements and perception recorded during the artificial gravity events provided both objective and subjective data. The experiment indicated that the test subjects perceived sustained levels of 0.5 g and 1 g as artificial gravity (Clément *et al.* 2001).

Figure 3-17. The off-axis rotator (also known as the "Visual and Vestibular Investigation System" or VVIS) developed by ESA for the Neurolab mission (STS-90). In this orientation, the axis of rotation was at hip level. During centrifugation on Earth, the subjects had the sensation of a head-down tilt of 27 deg (at 0.5 g) or 45 deg (at 1 g). In microgravity, the centripetal acceleration was the only acceleration stimulus and the subjects had the illusion of standing on their head. Photo courtesy of NASA.

Although the threshold for perception of linear acceleration in humans is on the order of 0.007 g (Benson *et al.* 1986) the threshold for perception of artificial gravity by astronauts in space is, based on

the data we have so far, somewhere[3] between 0.22 and 0.5 g. Perhaps it is not necessary to *perceive* artificial gravity at the cognitive level for it to be effective as a countermeasure. However, for purposes of defining the comfort zone of astronauts in an artificial gravity environment (whether it's a rotating spacecraft or on-board centrifuge), it would be extremely useful to determine the threshold value of perceived artificial gravity. Unfortunately, there are no plans to put a human centrifuge on board the ISS, at least in the near term.

In fact, the astronauts who visited the lunar surface were exposed to a reduced gravity on the Moon (0.16 g) for several hours or days during their 12-day space missions. They reported having "difficulty in determining just what straight up and down was". During Apollo-11, the lunar module floor on the Moon surface was tilted 4.5 deg from the horizontal, but the crew did not perceive this tilt. During their spacewalks on the Moon, the astronauts lost their balance several times, in most cases because they could not evaluate the slope of the terrain. They also reported this problem "caused our cameras and scientific experiments sometimes not maintaining a level attitude we expected". (Godwin 1999).

Interestingly, less decrease in heart size and less increase in heart rate were found postflight in the Apollo astronauts compared with Skylab and Shuttle astronauts (Johnston *et al.* 1975, Johnston and Dietlein 1977, Nicogossian *et al.* 1994). Unfortunately, there was no comparison between the results obtained on those astronauts staying on the Moon and those who stayed in orbit around the Moon. So, it cannot be firmly concluded that the exposure to lunar gravity during the course of their exploration missions was helpful in reducing cardiovascular deconditioning. All of these astronauts were highly trained fighter jet pilots in exemplary physical condition. Their long hours flying high-g maneuvers in jet aircraft may have increased their orthostatic tolerance and promoted the development of adaptive protection in these individuals, as compared to other Skylab and Space Shuttle astronauts (Clément and Pavy-LeTraon 2004).

Interestingly, the four subjects tested intermittently in the on-board centrifuge during the Neurolab Spacelab mission mentioned above, seemed to have achieved some measure of resistance to postflight orthostatic instability and did not show the usual decrease in vestibular sensitivity to tilt. The other three crewmembers on that mission had orthostatic intolerance. Based on the result that about 64% of astronauts experience profound postflight orthostatic intolerance (Buckey *et al.* 1996), the probability that four crewmembers on the same flight do not exhibit orthostatic intolerance by chance is approximately 1 in 60 (0.364) (Moore *et al.* 2000). During the flight, the centrifuge runs cumulated at about 10 minutes at 0.5 g or 1 g every other day, for a total duration ranging from 45-60 minutes during the 16-day mission. Obviously, more experiments are needed to validate these results.

3   GROUND-BASED CENTRIFUGE EXPERIMENTS

Despite the absence of flight-test opportunities, several laboratories worldwide have continued ground-based studies of the efficacy and acceptability of large scale rotating artificial gravity environment. Of course, all of these investigations are hampered by the presence of the steady gravitational pull. On Earth, gravity adds to the centrifugal force vectorially and produces a net specific *gravito-inertial force* (GIF) that is tilted relative to the horizontal. In weightlessness, the artificial gravity level is equivalent to the centrifugal force (Figure 3-18).

Ground simulations have shown that humans are extremely sensitive to rotation. Although few adverse effects are present when rotation rate is less than 1 rpm, higher rates produce motion sickness (similar to that occurring during the acute period of adaptation to weightlessness) as a result of the unusual pattern of vestibular stimulation under these conditions. As a neurovestibular countermeasure could likely be used to pre-adapt the posture, locomotion, sensory-motor coordination, and motion perception of crewmembers for return to planetary gravity. However, the Coriolis effects on inner ear endolymph flow and on moving limbs create disorientation, nausea, vomiting, and loss of coordination.

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[3] It is interesting to note that the human factor design envelope derived from rotating studies also suggests a lower limit of 0.3 g (see Chapter 2, Section 3.4).

Unless the head motion are restrained or a dual-adaptation to both microgravity and artificial gravity environment occurs, motion sickness can be a serious problem.

There is not a clear consensus in the definition of short- and long- radius centrifuges in the literature. Distinction can be made on radius length, gravity gradient, or subject mobility. The latter parameter will be used in this book. By *long-radius centrifuge*, we mean a device in which a subject is completely free to move about, whereas a *short-radius centrifuge* is one where the subject is immobile, i.e., either strapped in or otherwise constrained.

Figure 3-18. Drawing illustrating the difference between the physical effects of centrifugation on Earth (A) and in space (B). On Earth, the gravito-inertial force (GIF), i.e., the resultant of gravitational and centrifugal forces, 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 this design and subject posture, the AG level is 1 g at the feet and 0.38 g at the head for a rotation rate of 20.8 rpm.

3.1   Long-Radius Centrifugation

The earliest of the extensive tests of sustained rotation were conducted in the Naval Medical Research Laboratory in Pensacola, beginning in 1958. The *Slow Rotating Room* (SRR) had a 5-m-radius with complete living facilities, in which subjects could live for periods ranging from 1 day to 3 weeks. Rotation rates ranged from 1 to 10 rpm, with the floor of the SRR staying horizontal. Initially, most subjects developed motion sickness symptoms when they made head movements at room rotation rates in excess of 3 rpm and, through that experience, learned to restrict them. Incremental increase in the speed of the room was employed. After several days, most subjects were able to make head movements without nausea at rotation rate up to 6 rpm. Only some of the subjects could go further to move comfortably at 10 rpm.

Research was also performed to examine the problem of adapting the postural system to a 3-rpm run. Like for motion sickness, their balance control was initially disrupted on entering the SRR, but it recovered within 3-4 days. Then, most subjects were able to walk on thin rails about as well as Earth-normal, throw darts, and pour coffee without having to think about motor control. They also performed watch-keeping tasks within normal limits (Guedry *et al.* 1964).

When the SRR was stopped after 12 days, subjects felt an after-effect and an erroneous motion sensation during head movements. Their balance control was again disrupted for 3-4 days. These effects were stronger after runs at 10 rpm than after runs at 3 rpm (Graybiel *et al.* 1965).

The investigators concluded from these studies that humans can adapt to rotation rate of 3 rpm, and that a 14-day period of rotation at this velocity causes no significant changes in general condition or performance. In contrast, no adaptation took place when subjects were rotated at 10 rpm for 12 days, implying that a 10-rpm rotation rate is close to the upper threshold of endurance.

As a next step, ways of adapting humans to rotation at 10 rpm were investigated through incremental increases in rotation speed over time. Symptoms of motion sickness at 10 rpm, as well as impaired balance, were prevented by increasing rotation rate in nine approximately 2-day stages over the course of 16 days (Graybiel *et al.* 1969). Results also indicated that the time needed to adapt can be shortened greatly by making many specific head movements. The higher rotation rate, the more difficult the adaptation, but adaptation to 10 rpm was possible as long as rate-increase increments were held to 1-2 rpm with a period of 12-24 hour at each increment (Faget and Olling 1968). The time needed for this adaptation might therefore prove to be too long for practical use during spaceflight. However, anti-motion sickness drugs could then be used to attenue motion sickness while the terminal velocity is more rapidly achieved (Lackner and DiZio 2000b).

Interestingly enough, during the long-duration SRR runs periodic 10-15 minutes stops were required for re-provisioning. Over time, the on-board experimenters who helped in this activity made transitions between the stationary and SRR rotation without experiencing motion sickness or disruptions of movement control. They showed perfect *dual-adaptation* (Cohn *et al.* 2000, Lackner and Graybiel

1982), thus indicating that is is possible to be simultaneously adapted to rotating and non-rotating environments. Also, in all the subjects, there was retention of the adaptation to the SRR for several days, which implies that transitions from weightlessness to rotation should be acceptable under certain conditions (Graybiel and Knepton 1972).

Beginning in the 1960s a major ground research program on artificial gravity was conducted at the Institute for Biomedical Problems in Moscow. Their earliest tests in the *MVK-1* small rotating chamber at speeds up to 6.6 rpm allowed rotating one or two subjects for up to a week. It was followed by the roomier 10-m radius *Orbita* centrifuge, capable of rotating two to three people for several weeks at speeds up to 12 rpm. The longest tests were for 25 days at 6 rpm.

The initial exposures produced the expected disturbance of dizziness, equilibrium, and coordination. Within an hour, the usual pattern of motion sickness symptoms occurred, including vomiting in some cases. In 4-5 hours, subjects also complained of drowsiness and headache. Three periods of vestibular adaptation were distinguished for these long-duration exposures. The first 1-2 days were characterized by severe motion sickness. This was followed by a week during which the nausea and related acute symptoms disappeared, but drowsiness and headache remained. Finally, after the first 7-10 days, subjects showed immunity to motion sickness, even when additional vestibular stimulation was provided.

As found in Graybiel's SSR studies in Pensacola, the severity of motion sickness symptoms and the time to adapt to prolonged rotation on the Russian small rotating room *MVK-1* were related mostly to rotation rate. There was an absence of any motion sickness symptoms at 1 rpm, moderate symptoms at 1.8 rpm, and marked symptoms at 3.5 rpm. On the larger *Orbita* centrifuge, however, symptoms appeared only above 1.8 rpm. Head movements brought on discomfort in all cases (Kotovskaya *et al.* 1981).

The authors also report the following: "cardiovascular function remained within normal limits, […] no significant sleep disturbances were noted in the long-rotation environment, […] all assignments were completed even in the presence of pronounced illness, and no decline was noted in short-term verbal memory" (Shipov 1977).

These experiments with long-radius centrifugation suggest that all of the unexpected sensations are proportional to the rotation rate. Almost all subjects can adapt quickly to work in a 3-rpm rotating environment. With higher rotation rate, however, the subjects will experience symptoms of motion sickness and disturbances in postural equilibrium, the extent of which are a function of the rotation rate. Nevertheless, adaptation can be achieved under these conditions in 6 to 8 days, and the remained of the stay in a rotating environment is characterized by normal health and performance.

These studies in the 1960s were actually quite preliminary and involved a limited number of subjects (a total of only 30 subjects for the SRR in Pensacola). At the time, there was no attempt to identify optimum exposure and training strategies for adapting people to rotating environments. Also, subjects in the SRR tended to avoid moving, especially at higher rates of rotation. Recent experiments have demonstrated that complete adaptation to rotation rates as high as 10 rpm can be achieved within minutes if repeated voluntary movements are made, so that the central nervous system can anticipate the forthcoming Coriolis forces (see Lackner and DiZio 2000b for a review). The subjects in the SRR in the 1960s did not make movements that would have provided experience with Coriolis forces. Consequently, it is not surprising that these subjects failed to fully adapt at high rotation rates. In fact, Lackner and DiZio (2000b) conclude their review by expressing a need for a reevaluation of these ealier SRR studies. In particular they state: "Concerns that it would be difficult if not impossible to adapt to Coriolis forces generated by movements made in a vehicle rotating at more than 3 or 4 rpm have turned out to be unfounded. Everyday reaching and walking movements typically involve simultaneous body turning and generate higher levels of Coriolis forces than would be elicited by body movements in an artificial gravity environment rotating at 10 rpm".

3.2   Short-Radius Centrifugation

More recent investigations have assessed the ability of subjects to avoid motion sickness during head movements while rotating at the high velocities associated with short-radius centrifugation. Antonutto *et al.* (1993) in Udine found that subjects who were pedaling on a bicycle-powered short-arm centrifuge were able to make head movements without acute motion sickness while rotating at 19-21 rpm. Young, Hecht, and colleagues used the 2-m radius centrifuge at MIT (see Figure 3-01) to show that most subjects could adapt both their eye movements and motion sickness symptoms by rotating at 23 rpm (Young *et al.* 2001). Both the Udine and the MIT studies were conducted at rotation rate sufficient to produce 1 g of horizontal centrifugal force or a net GIF of 1.4 g. In the Udine centrifuge, the GIF was aligned with the subject's, head-to-foot (Gz) axis, whereas in the more provocative MIT studies, the subject remained horizontal.

The Coriolis forces associated with limb movements, head movements, and walking in a rotating environment are initially both surprising and disturbing. However, in almost all cases, appropriate new motor control strategies are developed, so that subjects can adapt to the new environment and no longer are even aware of the unusual forces. Extensive experiments in the Brandeis University rotating room demonstrated the remarkable ability to adapt to unusual environments (Lackner and DiZio 2000a). A measure of dual adaptation apparently exists, so that subjects can switch from the rotating to the non-rotating environment with minimal relearning (see Chapter 4, section 5.2).

The adequacy of artificial gravity in stimulating the cardiovascular system has been investigated in ground studies. In most studies, the detrimental effects of weightlessness are simulated by sustained bed rest, often at 6 deg of head-down tilt and occasionally by partial submersion in water to approximate the fluid shift better that occurs in space. In a pioneering study in 1966, White and his colleagues at Douglas (Figure 3-19) showed that intermittent exposure to 1 g or 4 g on a 1.8-m-radius centrifuge was effective in alleviating the usual decrease in tolerance to standing (orthostatic intolerance). Exercise produced little additional benefit (White *et al.* 1965).

Figure 3-19. Short arm centrifuge utilized during the Douglas Aircraft Co.'s studies. Two subjects were tested at the same time. The subjects' head was very slightly off-center and they were lying on their side. Measurements are in inches (White et al. 1965). Photo courtesy of NASA.

The principal cardiovascular reactions of interest for centrifugation are the venous tone, especially in the legs, and the baroreflex regulation of blood pressure. For a short-radius centrifuge small enough to accommodate a subject only in a squatting position, the centrifugation does little to encourage venous return by stimulating the muscles. However, the IBMP ground centrifuge tests (Shulzhenko *et al.* 1979) demonstrated that subjects who were deconditioned by 2 weeks of water immersion could increase their post-immersion tolerance to 3 g (+Gz) by intermittent exposure to acceleration on a 7-m-radius centrifuge.

For some time, it was debated whether the intermittent centrifugation conditioned only the passive motor tone or whether the body's active baroreflex to counter the effects of gravity on blood pressure was also affected. Burton and Meeker (1992), using a 1.5-m-radius centrifuge intermittently, showed that the baroreceptors are adequately stimulated by the centrifugal force. Their slow compensation for the hydrostatic pressure drop during rotation permits the tolerance to gradual onset acceleration to exceed that to rapid onset acceleration.

Beyond even the benefit of intermittent acceleration on cardiovascular responses is the effect on blood volume. Normally, weightlessness or head-down bed rest produces a fluid shift toward the head that in turn leads to fluid loss, including plasma, and a resulting increase in hematocrit. However, Yajima and his colleagues from Nihon University School of Medicine in Tokyo (Yajima *et al.* 2000) showed that 1 hour per day of 2 g (+Gz) exposures of their subjects, using a 1.8-m-radius centrifuge, was sufficient to prevent hematocrit from increasing during a 4-day bed rest period. In other studies, they confirmed the effectiveness of intermittent centrifugation on maintaining baroreflex and parasympathetic activity

More ground-based studies evaluating the efficacy and acceptability of human horizontal centrifugation on long-duration cardiovascular deconditioning are detailed in the following chapter. There is, however, a lack of studies on the cardiovascular implications of gravity gradient.

3.3   Human Powered Centrifuge

Only recently have several research groups begun to explore the potential benefits of artificial gravity generated by a human powered centrifuge. With respect to skeletal muscle, data suggest that muscles must be mechanically loaded to maintain or increase muscle mass. Similarly, mechanical loading (e.g., microstrain) of bone is essential for maintaining or increasing bone density (see Clément 2005 for review). Given these perspectives, several authors suggest that passive centrifugation on a short-radius centrifuge will not be effective in maintaining skeletal muscle mass and bone density during long exposures to microgravity. Hence, as a complement for passive centrifugation, they have pursued the development of active centrifugation, where the subjects exercise while being centrifuged, as potential multipurpose countermeasures to microgravity. This system has the capacity for studying the effects of centrifugation on muscle mass, bone density, and orthostatic tolerance.

Currently, two general types of ground-based designs have been described in the literature. The first of these has been referred to as a *human powered centrifuge*. Both the NASA-Ames Research Center and the University of California Irvine groups have been actively pursuing research on this concept. The second approach has been described as a *Twin Bike System*, and was proposed by di Prampero and his colleagues at the University of Udine, Italy (see Chapter 5).

The *Human Powered Centrifuge* developed by Greenleaf *et al.* (1996) at the NASA Ames Research Center is a 1.9-m-radius centrifuge fitted with two recumbent rider seats, and can carry one or two on-board subjects placed in the seated supine position with their heads near the centrifuge hub. The configuration allows for one active on-board subject to power the centrifuge using a modified cycle mechanism (Figure 3-20). The cycling activity of the rider is coupled to the rotation of the platform and, hence, the development of various gravity levels along the Gz axis. An additional passive on-board rider can be carried on the centrifuge at the same time. Alternatively, an off-board operator can power the centrifuge by using an upright off-centrifuge bicycle. Centrifugal force up to 5 g at the subject's feet (Gz) is obtained during rotation at 50 rpm.

Figure 3-20. In the Human Powered Centrifuge*, the motion of the platform can be powered by the two supine subjects on the centrifuge using a cycle mechanism or by an off-board operator using an upright off-centrifuge bicycle. Adapted from Greenleaf et al. (1996).*

Similarly, in the *Space Cycle* concept, developed by the Irvine Medical Center at the University of California, subjects ride opposite one another: one on a bike and one on a platform (Caiozzo *et al.* 2004). However, both the bike and the platform are free to tilt. As one individual pedals, the cycle moves in a circular motion around a centralized pole. The motion generates a gravito-inertial force aligned with the riders along their long body axis. The rider on the platform can perform various types of resistance-training exercises, such as running on a treadmill or performing squats (Figure 3-21). Instruments on the device report the separate work rates of both subjects.

Figure 3-21. The Space Cycle *at UC Irvine generates levels of artificial gravity ranging from 1 to 5 g on both the rider who powers the cycle and the rider who performs the squats. Here, the riders are experiencing approximately 3 g. Photo courtesy of NASA.*

The *Twin Bike System* proposed by Antonutto and di Prampero (1994, 2000) envisions two bicycles mechanically coupled to one another in a counter-rotating fashion. Astronauts would ride the bicycles along the inner wall of a cylindrically shaped space module (see Figure 5-06). The angular velocity of cycling would then determine the amplitude of the centrifugal vector along the main body axis of the rider. Like the human powered centrifuge designs developed by Greenleaf and Caiozzo, the *Twin Bike System* approach also has the potential for overcoming the deconditioning effects of microgravity on the musculoskeletal and cardiovascular systems.

In the past few years, following the impetus given by the new Vision for Space Exploration program, dedicated centrifuges for investigating the effects on centrifugation on physiological deconditioning during bed rest studies have been developed at NASA (Figure 3-22) and ESA (Figure 3-23). The objective of these studies is to place test subjects in a 6-deg head-down bed-rest position for duration lasting up to 60 days, which simulates the long-term effects of weightlessness on the cardiovascular, muscle, and bone function. Typically, one group of test subjects is placed in the supine position on these 3-m-radius centrifuges and subjected to various g levels and duration along their longitudinal axis throughout the bed rest to periodically simulate a +Gz gravitational environment. Another group of subjects is not exposed to centrifugation. After the bed rest, comparison between the deconditioning of both subject groups allows to determine the effectiveness of centrifugation as a countermeasure. These studies help to develop appropriate prescriptions for using a centrifuge to protect crews and to understand the side effects of artificial gravity.

Figure 3-22. The NASA/Wyle Laboratories bed rest centrifuge at the University of Texas Medical Branch in Galveston, Texas, USA. During the on-going initial study, 32 test subjects are placed in a six-degree, head-down, bed-rest position for 21 days to simulate the effects of microgravity on the body. Half that group spins once a day on the centrifuge to determine how much protection it provides from the bed-rest deconditioning. Subjects are oriented radially in the supine position so that the centrifugal force is aligned with their long body axis, and while spinning, they "stand" on a force plate, supporting the centrifugal loading (2.5 g at the feet, 1.0 g at the heart). The subject station allows free translation over approximately 10 cm to ensure full loading of the lower extremities and to allow for anti-orthostatic muscle contractions. Control subjects are positioned on the centrifuge but do not spin. Photo courtesy of NASA.

Figure 3-23. The ESA bed rest centrifuge. The centrifuge has two arms with a radius of 2.9 m each. The centrifuge can accommodate one subject on each arm. The arms can be equipped with supine beds or recumbent seats. The seats allow placing the subjects in a semi-flexed position, a less cumbersome and a more natural position in weightlessness. Photo courtesy of ESA.

Similar centrifuge designs are being used in Russia and Japan (Table 3-01). Other types of human-rated centrifuges, albeit with larger radius, are also utilized worldwide in aeronautics or clinical environments for aircrew training or for physiological and medical research

Name	Location	Radius	Max g	Axes
Unilateral Centrifuge	Antwerp U, B	0.4 m	0.2 g	±Gy
Unilateral Centrifuge	Charite Campus, Berlin, D	0.4 m	0.2 g	±Gy
NASA JSC centrifuge	NASA, Houston, USA	0.5 m	1.0 g	–Gz
ESA Neurolab Off-Axis Rotator	MEDES, Toulouse, F	1.0 m	1.0 g	±Gy, –Gz
Short-Radius Centrifuge	Mt Sinai School of Med, New York, USA	1.0 m	1.0 g	±Gx, ±Gy
Human Centrifuge	Brandeis U, Waltham, USA	1.2 m	3.0 g	±Gy
Short-Arm Human Centrifuge	Nihon U, Nishi-Funabashi, Japan	1.8 m	3.0 g	+Gz
Artificial Gravity Sleeper	MIT Cambridge, USA	2.0 m	1.8 g	+Gz
Short-Radius Human Centrifuge	Nagoya U, Japan	2.0 m	2.0 g	+Gz
Short-Radius Centrifuge	IBMP, Moscow, Russia	2.0 m	2.0 g	+Gz

NASA Ames Human Powered Centrifuge	Moffets Field, USA	2.0 m	5.0 g	+Gz
Space Cycle	UC Davis, USA	2.0 m	3.0 g	+Gz
ESA Short-Arm Centrifuge	MEDES, Toulouse F	2.9 m	3.5 g	+Gz
Twin-Bike System	University Udine, I	3.0 m	1.0 g	+Gz
NASA Short-Arm Centrifuge	UTMB, Galveston, USA	3.0 m	3.5 g	+Gz
TNO Desdemona	Soesterberg, NL	4.0 m	3.0 g	±Gx, ±Gy, ±Gz
Slow Rotation Room	Brandeis U, Waltham, USA	6.7 m	4.0 g	±Gx, ±Gy, ±Gz
Slow Rotation Room	NAMRL, Pensacola, USA	7.0 m	3.0 g	±Gx, ±Gy, ±Gz

Table 3-01. Short-radius centrifuge facilities utilized worldwide in research projects on artificial gravity, with their radius, the maximum gravity level (usually at the suject's feet) and the direction in which this level is exerted. This list is not exhaustive.

4   SUMMARY

While many studies have suggested the production of artificial gravity through rotation to counteract the detrimental effects of weightlessness, knowledge of the ability for humans to live and work in a large scale rotating artificial gravity environment is limited. The few observations conducted on humans in space suggest that the sustained application of a centrifugal force above 0.3 g is perceived as artificial gravity by the crewmembers. However, in these instances, the artificial gravity exposure was limited to a few minutes and subjects were restrained from moving their head or body.

Research conducted in slow rotating rooms on Earth has concluded that humans can adapt and live for extended periods of time (up to 25 days) to rotation rate as high as 10 rpm. Adaptation to continuous rotation has also been achieved with shorter exposure duration and higher rotation rates (up to 23 rpm) by using short-radius centrifugation in which subjects are supine and only able to perform head movements.

Several human centrifuges, with either long- or short-radii and either passive or human powered capabilities, are currently being used to assess the sensory-motor, cardiovascular, and musculo-skeletal responses under hypergravity conditions. One practical objective of these studies is to determine the limits for centrifugation as an effective countermeasure. It is important to stress, however, that ground-based tests are made with the deficiencies associated with Earth-bound environment. In particular, there are notable differences between a centrifuge on Earth and in space. Both conditions generate a centrifugal force in the plane of rotation, but gravity is always present and perpendicular to the plane of rotation in the centrifuge on Earth, while the artificial gravity vector is in the plane of rotation in the centrifuge in space (see Figure 3-18). Head and body motion will yield a different pattern of stimulation on Earth and in space. Given these differences, it is clear that the *final* assessment of artificial gravity prescription by centrifugation can only be carried out in space.

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