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Research in Microgravity in Physical and Life Sciences: An Introduction to Means and Methods

Vladimir Pletser and Thais Russomano

Abstract

Microgravity is the state encountered in a vehicle in free fall, whether on Earth, in low Earth orbit or in deep space. Microgravity research has opened up new possibilities for investigations in physical and life sciences that are necessary to enhance our knowledge of how physical systems and the human body, from cells to whole body systems, perform, react and function in microgravity, which will help prepare for the human exploration of outer space. This chapter presents an introduction of the microgravity environment, which can be obtained using different microgravity platforms, including space missions. Simulation of microgravity effects is also used for research and presented here. The chapter further considers the effects of microgravity on several aspects related to the physical sciences and on the adaptation of the human body to this altered gravity environment.

Keywords: microgravity research, microgravity platforms, microgravity simulation, microgravity effects in physical sciences, human physiology

1. Space orbital environment

Space orbital environment is characterized by several factors that affect experiments in physical sciences and influence the good functioning of all living systems, from cells to humans. The main factors are weightlessness, high-energy radiations, vacuum and temperature differences. These last two factors are generally mitigated by the vehicle yielding the necessary life support to the systems under study. The first two factors on the contrary cannot be completely compensated.

The concept of weightlessness will be developed further.

Perfect protection against high-energy radiations cannot be completely achieved, unless thick shielding walls are installed all around the spacecraft, which is presently excluded in view of launch costs per kg. Nevertheless, a vehicle in low Earth orbit (a few hundred kilometers altitude) stays relatively protected by Earth's Van Allen radiation belts (inner energetic proton belt at 1,000–6,000 km altitude and outer energetic electron belt at 13,000–60,000 km altitude).

To these orbital factors, one should add the conditions at launch and during atmospheric reentry and landing of a spacecraft, i.e. important accelerations and vibrations, that can affect the quality of physiological samples or configurations obtained in microgravity (e.g. for crystals).

2. Weightlessness and microgravity

The state of microgravity, or more correctly micro-weightiness, exists in an orbital vehicle in a state of free fall, i.e. without any force acting on it except for gravitational forces [1]. This means that the vehicle must not be propelled or submitted to any other nongravitational force. Perfect weightlessness is an ideal state practically impossible to achieve. However, microgravity of an excellent quality (typically $10^{-5}g$,

Physical sciences	Life sciences
Fundamental physics	Human research
Complex plasmas and dust particle physics	Integrated physiology
Aerosol particle motion	Cardiovascular function
Frictional interaction of dust and gas	Respiratory function
Plasma physics	Body fluid shift
Aggregation phenomena	Central venous pressure system
Materials science	Digestive system
Thermophysical properties	Muscle and bone physiology
Thermophysical properties of melts	Skeletal system
New materials, products and processes	Blood lactate studies
Morphological stability and microstructures	Body mass tests
Physical chemistry	Human locomotion
Aggregation phenomena	Posture
Granular matter	Bone models
Fluid and combustion physics	Neuroscience
Structure and dynamics of multiphase systems	Neurobiology
Pool boiling	Vestibular functions
Heat and mass transfer	Spatial orientation
Dynamics of drops and bubbles	Motion sickness
Thermophysical properties	Motor skills
Interfacial phenomena	Biology
Dynamics and stability of fluids	Plant physiology
Evaporation	Statolith movement
Complex dynamic systems	Gravitropism
Diffusion	Gravireceptors
Foams	Cell and developmental biology
Chemo-hydrodynamic pattern formation	Animal physiology
Combustion	Aging processes
Droplet and spray combustion	Electrophysiological and morphological properties of human cells
Soot concentration	Osteoblast cells
Combustion synthesis	Technology
Laminar diffusion flames	ISS experiment validation
Fuel droplet evaporation	Phase separation technologies for biological fluids
Ignition behaviour	Crew foot restraint
Technology	Crew exercise devices
ISS experiment validation	Urine monitoring system
Metal halide lamps	
Micro-acceleration measurement	

Table 1.
Non-exhaustive list of research fields in microgravity.

where g is the acceleration of weightiness, commonly and erroneously mistaken for gravity¹, with an average value of 9.81 m/s^2) can be achieved in orbit.

Gravity (weightiness) disturbs certain experiments and reduces the field of investigation of some scientific domains. Gravity (weightiness) effects hide other effects pertaining to materials or fluids under study, and that depends often on intrinsic properties of matter or of its state. Convection in fluids, so evident that it is called “natural,” is caused by gravity (weightiness) acting on local differences of density caused by differences of temperature or concentration. The resulting Archimedes or buoyancy force induces an ascending motion of fluid zones of lesser density and a descending motion of fluid zones of larger density, creating convection cells in gases, liquids and solids in fusion, yielding disruptive phenomena in separation processes.

Although physical and biological processes are often investigated in hypergravity, e.g. in centrifuge, one knows less what happens in reduced gravity. However, in most cases, one cannot extrapolate from results obtained in hypergravity to microgravity, most of the phenomena being nonlinear in function of the gravity level. One observes many more differences while passing from 1 g to 0 g than between 5 g and 4 g, for example.

Many scientific fields profit from the peculiarities of weightlessness to enlarge their field of investigations. Material sciences, fluid physics and life sciences (biology and physiology) were the first to use microgravity, followed later by many other disciplines (combustion physico-chemistry, crystallography, fundamental physics, critical point phenomena, etc.) in view of varying a new experimental parameter: gravity. Microgravity allows to deepen scientific knowledge in domains that are hardly accessible on Earth.

Table 1 shows some of the scientific fields in which experiments were conducted in microgravity.

3. Physical sciences research in microgravity

Microgravity research allows to study the gravity effects on these different phenomena and the effects of other forces normally masked by gravity on Earth. Weightlessness became an experimental research tool that allows to transpose in microgravity the investigation of phenomena known on Earth but sometimes insufficiently understood, in order to investigate the fundamental processes and to understand their functioning without gravity.

Modifications appear when one studies matter behaviour in weightlessness. One observes on the one hand the disappearance of “natural” phenomena caused by gravity and, on the other hand, the preponderance in microgravity of phenomena that can hardly be observed in normal conditions of gravity. These modifications are particularly important for certain physical, chemical and metallurgical processes having at least one fluid phase: crystal growth, alloy solidification, separation of biological substances, etc.

The main differences that are observed for fluid phases in weightlessness are as follows.

¹ The term “gravity” usually designates the force associated with the phenomenon of gravitation. One should therefore in all correctness use here the term “weight”, which is the force associated with the phenomenon of weightiness, and the resulting force of gravity and inertia forces existing in the reference frame in which the measure of the weight is done. However, the common (although incorrect) usage of the term “gravity” and its derivatives (microgravity, hypergravity, etc.) instead of “weight” and its derivatives will prevail throughout this introductory chapter.

3.1 Disappearance of separation phenomena

Separation phenomena observed on Earth in multiphase systems that include a fluid phase disappear in microgravity. Sedimentation (precipitation of dissolved or suspended matter) and Archimedean buoyant force (or buoyancy, i.e. the force due to a liquid pressure on a body-immersed volume) disappear. The advantage of the absence of separation in weightlessness is the possibility of obtaining mixtures that are unstable on Earth and material alloys impossible to obtain on Earth or with great difficulty. A disadvantage of the absence of separation in weightlessness is the difficulty of eliminating the gaseous inclusions while, on Earth, degassing is done “naturally” (gaseous zones in liquid matrices go up to the free surface).

3.2 Disappearance of “natural” convection

“Natural” convection disappears in fluids in microgravity. There is no more natural upward displacement of hot zones and downward displacement of cold zones. In fact, there is no up and no down. Other forces become dominant for movements in liquids in microgravity. These forces are linked to superficial or interfacial tension between two liquids. Indeed, such an interface behaves as an elastic “membrane” whose tension is a thermodynamic function of temperature (or concentration for solutions), as shown in **Figure 1**.

For an interface subjected to a temperature difference, superficial tension for most liquids is generally smaller for the hot side than for the cold side. The interface, i.e. the common layer formed by molecules of both fluids, physically moves parallelly to itself from the hot side to the cold side; this membrane deforms itself and slides from the hot side to the cold side. The liquid layers on both sides of the interface are dragged along by viscosity, and a new convection appears,

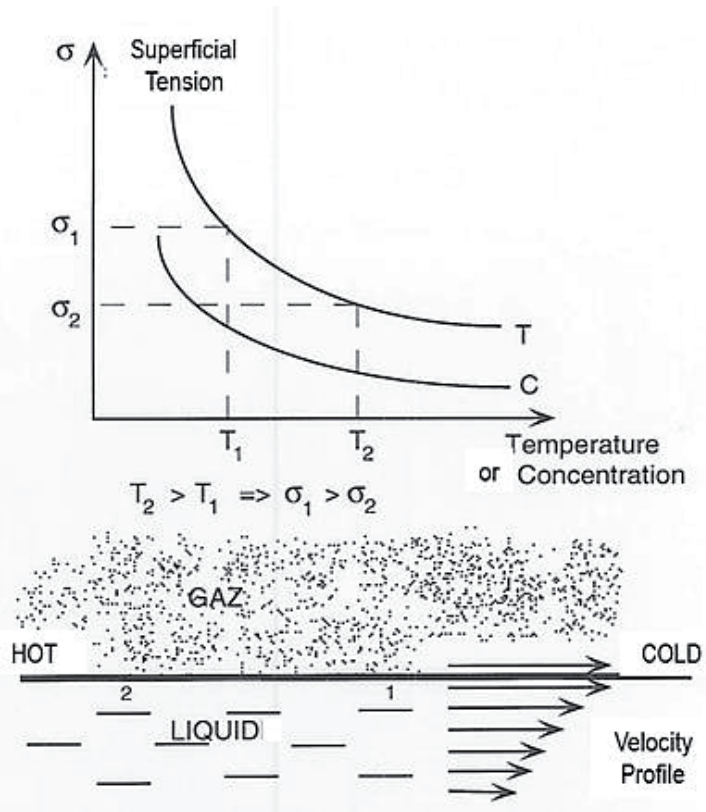


Figure 1. Liquid/gas interface submitted to a superficial tension gradient, yielding a Marangoni convection cell caused by the physical displacement of the interface membrane from the hot side (point 2) to the cold side (point 1) [1].

called Marangoni convection, after the name of the Italian physicist who studied this phenomenon at the end of the nineteenth century. This phenomenon exists obviously also on Earth, but as its effect is much smaller than those caused by gravity, it is in general negligible and much more difficult to observe. Its study in microgravity allows thus to better understand the fundamental characteristics of liquid behaviour.

It is also because of the absence of “natural” convection that the shape of a combustion flame is different in weightlessness. On Earth, gases produced by the chemical reaction of combustion (e.g. of a candle wick), much hotter, rise, and fresh air oxygen migrate to the combustion centre to feed the combustion process. In microgravity, hot gases have no reason to rise anymore, and the flame is surrounded by a hemispherical ball formed by combustion gases (**Figure 2**), limiting the amount of fresh oxygen transfer.

3.3 Disappearance of hydrostatic pressure

In microgravity, hydrostatic pressure disappears. On Earth, it is responsible for the tendency of fluids to deform under the effect of their own weight, a liquid zone supporting the weight of zones on top. The same phenomenon exists for solids. Structures can be built that would collapse under their own weight on Earth, e.g. crystalline networks (**Figure 3**).

Liquids in weightlessness, abandoned to themselves without any contact with a solid surface, form spherical drops (**Figure 4**), which is the minimal surface enclosing a given volume when subjected to the only forces of superficial tension.

3.4 Possibility of natural levitation

On Earth, crucibles are used to melt alloys, which may contaminate the melt liquid phase. In weightlessness, the liquid phase can be maintained in a contactless levitation, without touching any solid walls, using an electrostatic, magnetic or acoustic confining (**Figure 5**). Many parameters of materials at high temperatures are still unknown and cannot be measured on Earth due to difficulties and limitations caused by crucible contamination and gravity effects.

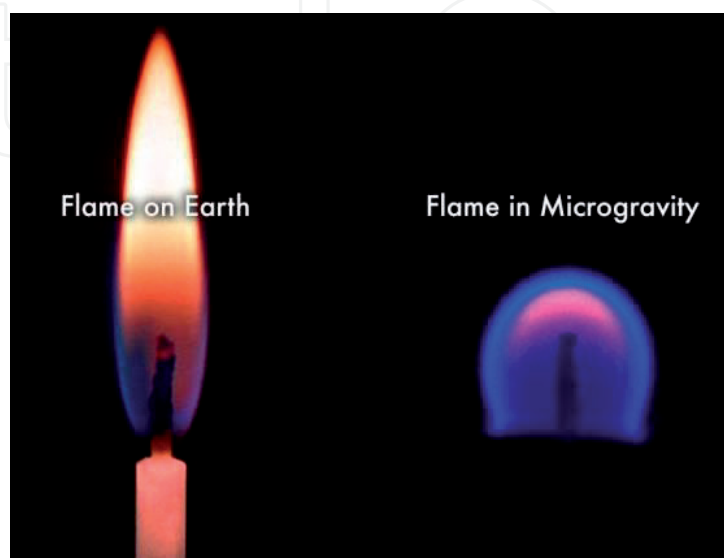


Figure 2. Flames on ground in 1 g (left) and in microgravity in near 0 g (right). Notice the near-hemispherical shape of the flame in microgravity with the reddish-purple part on top due to some convection caused by small perturbations in the microgravity environment (photo credit: NASA).

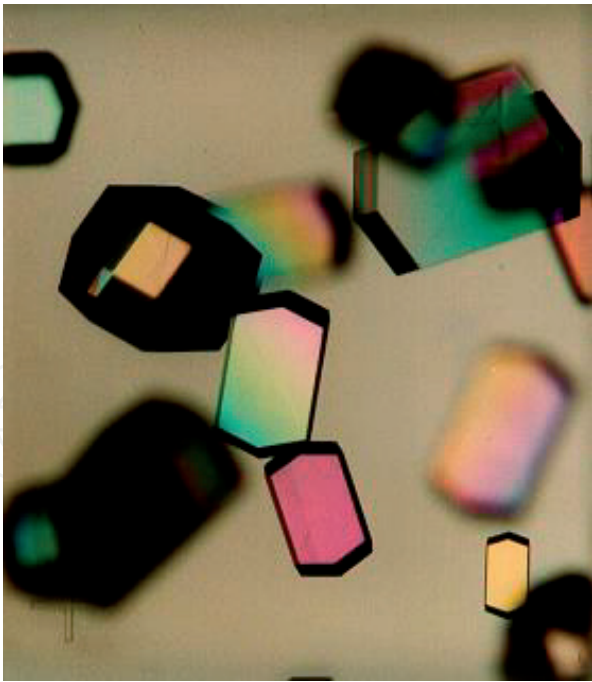


Figure 3.
Protein crystals obtained with ESA's Advanced Protein Crystallization Facility during the Life and Microgravity Spacelab mission on NASA Space Shuttle STS-98 in May 1995 (credit: Prof. Martial, University of Liege, Belgium).



Figure 4.
Water drop in free float on ISS (credit: NASA).

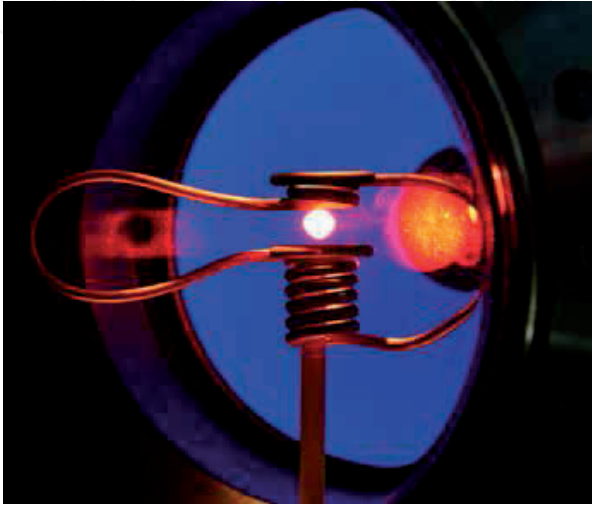


Figure 5.
Core element of an electromagnetic levitator (photo credit: DLR).

The list of the advantages and applications of microgravity to scientific research could be continued at length but is outside of the aim of this publication. The interested reader will find other examples and more details in Refs. [2–5].

4. Physiology research in microgravity

Initially developed in the 1950s and 1960s to support US and USSR space programs, space microgravity medical research quickly evolved. Manned spaceflights very quickly showed physiological changes in astronauts and cosmonauts. The duration of spaceflights has increased throughout the years, from a few hours at the beginning of the 1960s to several months (or even more than a year) today on board the International Space Station (ISS, **Figure 13**). The ISS allows to conduct and to repeat experiments during several years.

New phenomena have been observed on astronauts, some of these effects appearing only after several weeks or months in space. Despite the large number of hours spent in orbit around the Earth by astronauts and cosmonauts from all countries involved in space research and exploration, some problems are still far from being fully understood, and the necessary solutions have not yet been found.

Although physiological systems of human organism function interdependently, one can classify physiological effects of microgravity in four categories:

- Perturbations of sensorial systems related to balance, orientation and the vestibular system
- Modifications of bodily fluid distribution and their impact on the cardiovascular system
- Effects on metabolism and bodily functions
- The adaptive processes of muscular and skeletal systems and their pathological consequences

Relevant knowledge and research on human physiology are presented below, and more details can also be found in Refs. [6–11].

4.1 Balance, orientation and vestibular

On Earth, in a normal gravity environment, the human body has three means to obtain the information of the reference vertical direction and of the top-bottom orientation, characteristic of the gravitational environment on our planet.

The main system is the vestibular system, which is double, located in the inner ear. In one of these organs, small crystals of calcium carbonate called otoliths weigh on a membrane with nervous endings. The semicircular canals form another sensor. Formed by the three canals in planes approximatively orthogonal to each other, a physiological liquid moves by inertia in these canals during a head movement, stimulating nervous endings in the canals. The combination of the information coming from the otoliths and semicircular canals allows the brain to interpret the movement and the position of the head.

The second source of information is the visual system. The visual information allows the brain to recognize the body position with respect to external references (floor, ceiling, walls).

The third information source is the proprioceptive system, constituted of the whole of skin tactile perceptions, articulations and muscle tension. The neck proprioceptive system is the most developed and informs the brain on the position of the head with respect to the rest of the body.

In weightlessness and in absence of accelerated motion, there is no stimulation of the vestibular system. Otoliths are no longer attracted downward by gravity, and the semicircular canals are no longer stimulated. However, the visual and proprioceptive systems continue to function normally. Information sent by these different systems to the brain are incoherent for an organism used to normal gravity and create confusion in the brain zone that normally treats the information on position and orientation. This confusion often yields dizzy spells and nausea and sometime triggers the reflex of emptying the stomach. In short, the subject is sick. This sickness, called space adaptation syndrome, affects most astronauts. On average, one out of two astronauts suffers from nausea during the first few days of spaceflight. After a day or two, the human organism adapts to the new environment, and astronauts can continue to function and work “normally.” After the flight, the balance and orientation systems readapt quickly to the Earth’s environment.

4.2 Body fluids and cardiovascular system

4.2.1 Loss of body fluids

On Earth, while standing in normal gravity, arterial blood pressure is normally distributed such that, if intracardiac pressure is taken as unity, it is approximately double in feet arteries and two third at head level. While lying down, the distribution of blood pressure is more uniform. Passing from the lying to the standing position yields a blood flow toward the lower part of the body, and blood pressure diminishes in the head. Known as orthostatic postural intolerance, the change of blood pressure is detected by baroreceptors in the vascular system and close to the heart. These receptors send signals that yield, firstly, an increase of cardiac rhythm to compensate the blood volume decrease in head arteries and, secondly, a contraction of arteries in the lower body to diminish the blood flow toward the legs.

In microgravity, gravity does not attract liquids downward anymore, and a redistribution of body fluids takes place. A volume of approximately two liters of body fluids is displaced from the lower extremities to the upper part of the body, increasing the blood volume and pressure in the heart. The volume and blood flow receptors are alerted, and this new situation is interpreted as an overload of the blood system. The reaction of body liquid elimination starts and yields a complex hormonal game, which results in a natural elimination by urine of body liquids. The organism adapts to this new environment, and a new balance is established after 4–5 days.

On the other hand, liquid transfer from lower members toward the upper body has other secondary effects: face swelling due to blood rush in the head, the increase of intraocular pressure, and sinus congestion. These secondary effects disappear up to a certain point after a few days in microgravity. Back on Earth, the organism readapts to a 1 g environment.

4.2.2 Myocardial muscle atrophy and cardiac rhythm

The results of experiments performed with ultrasound echocardiography show a diminution of the left ventricle and auricle volumes during a spaceflight of several weeks. However, after the flight, the cardiac muscle comes back to a normal state.

In microgravity, a decrease of cardiac rhythm and of arterial tension is observed, the heart not needing to pump blood against gravity's downward pull (**Figure 6**).

A high tachycardia (increase of the cardiac rhythm) is observed also at launch, due to psychological stress, but also necessary to compensate the effects of accelerations, in the order of 3–4 g, with a maximum of 8 g.

4.2.3 Visual impairment and intracranial pressure

Visual impairment and intracranial pressure are another consequence of the upward body fluid shifts, the head filling with blood and other bodily fluids. The various consequences are an increase in intracranial pressure that can cause headache of varying levels of severity and an increase of the intraocular pressure that affects the visual performance and other more minor effects such as congestion of the sinuses. These effects, although observed and investigated for several years, are thought to be temporary as they tend to disappear after return to Earth.

However, intracranial pressure and visual impairment were only recently recognized as more serious as they could impair the performance of astronauts during long-duration 0 g travels in space.

4.3 Physiological functions and metabolism

In microgravity, the main physiological functions are practically unchanged. Astronauts can eat and drink without major constraints. Digestion and intestinal transit are accomplished also nearly normally, except that gravity action is no longer present.

Breathing is also made without too important problems. However, the breathing mechanism is altered: the distribution of inspired and expired gases in the lungs and oxygen exchanges in blood hemoglobin at the level of pulmonary alveoli are modified. The way to breathe is also modified: statistically, in weightlessness, the forced movement of the abdomen contributes more to the breathing mechanism.

Astronauts can also sleep in space. However, daily and sleep rhythms are disturbed. Indeed, on board the ISS in low Earth orbit at 400 km altitude, day and night alternation repeats approximately every 90 min. Astronauts see a sunrise and sunset 16 times per terrestrial 24 h a “day.” Psychological and emotional factors and travel excitement intervene also. To remedy it, one imposes a strict and well-established schedule taking into account human natural rhythms. On board the ISS, a three times 8-h schedule

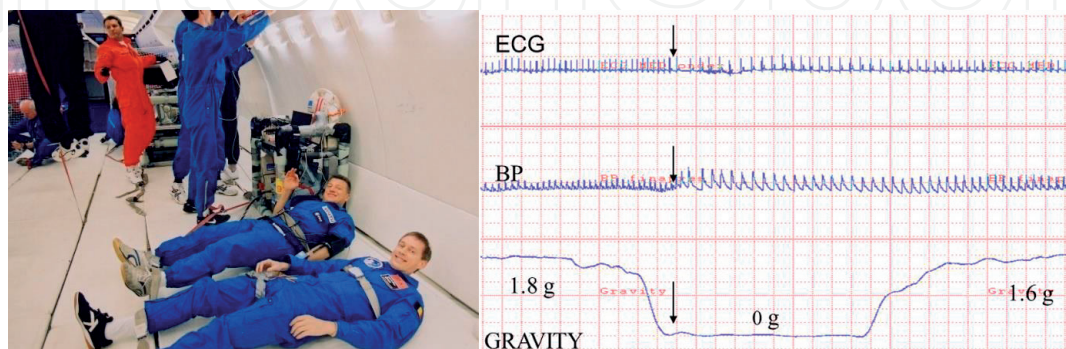


Figure 6.

Experiments during aircraft parabolic flights (left) showed (right) a decrease in heart rate, seen at the beginning of microgravity (arrows), i.e. an increase of duration between successive peaks, corresponding to increased vagal modulation of the heart rate. A sudden increase is also seen in pulse blood pressure (difference between maximum and minimum pressures), indicating an increase in stroke volume (ECG, electrocardiogram; BP, blood pressure) (credit: Left, ESA; right, Prof. A. Aubert, Katholieke Universiteit Leuven, Belgium).

is applied: 8 h for sleep, 8 h for work depending on missions and 8 h for personal time, meals, rests, etc. This schedule is purely theoretical as astronauts on board the ISS spend much more of their time to work, although for long-duration stays on ISS, schedules are loose, and longer rest periods are foreseen some days, generally used by astronauts to watch Earth through windows, mainly the cupola (**Figure 7**).

After long stays in weightlessness, changes are observed in blood composition that can be problematic. Firstly, the number of red blood cells and the hemoglobin level decrease. Secondly, red blood cells of unequal sizes and of abnormal shapes have been also discovered. After 6 months in microgravity in orbit, up to 2% of ovalized red blood cells have been observed in Russian cosmonauts. Thirdly, the immune defense system of astronauts diminishes in microgravity after approximately 7 days of flight. One observes a reduction of production of lymphocyte T cells (the white blood cells) that intervene in the immune responses and in antibody production. This observation did not find so far a satisfactory fundamental explanation, and this problem could be the one that would impede mankind to adapt to long-duration space travels in microgravity. Astronauts are more prone to infections in space, and they need more time to recover after an infection on ground after their return. The immune system is back to its normal preflight level after a period of 5–10 days after return to Earth.

4.4 Musculoskeletal system

4.4.1 Spine

In microgravity, the first effect that is noticed is the spine extension up to a point that astronauts can gain a few centimeters in height. This is due to the partial decompression of intervertebral discs that do not have to support the weight of the upper body anymore. Back on Earth, after the flight, this effect disappears, and height becomes normal again but with, sometime, the risk of having a nerve blocked between discs and vertebrae. Furthermore, some astronauts complained of back pains during or after a spaceflight, probably caused by this phenomenon of spine extension.



Figure 7. NASA astronaut Karen Nyberg, Expedition 37 flight engineer in 2013, enjoys the view of earth from the windows in the ESA-built cupola of the International Space Station. A blue and white part of earth is visible through some of the seven windows of the cupola (photo credit: NASA).

4.4.2 Muscular system

The muscular system atrophy is a second consequence, observed after some days in weightlessness. In particular, the most affected muscles are those that control posture and that contribute to support the body weight on Earth. In microgravity, the natural position that astronauts take is a curved position with the legs slightly bent. One floats freely and moves by pushing oneself against a wall, using the action-reaction principle. One notices thus a muscle atrophy, a loss of mass of muscles and the elimination of muscular proteins (**Figure 8**).

By practicing regularly (more than 2 h per day!) and by applying sometime treatments of muscular fiber electrostimulation, astronauts and cosmonauts have no difficulties to readapt upon return to Earth after a more than 6-month mission.



Figure 8.
British ESA astronaut Tim Peake operates the muscle atrophy research and exercise system (MARES) equipment inside the Columbus module. MARES is an ESA facility used for research on musculoskeletal, biomechanical and neuromuscular human physiology to better understand the effects of microgravity on the muscular system (photo credit: NASA/ESA).

4.4.3 Bone demineralization

Bone demineralization, and mainly decalcification, is the most important and serious physiological phenomenon observed in microgravity. Appearing only after 1–2 months in orbit, this could be the second problem that could thwart the hopes of mankind to adapt to space travels in weightlessness.

The loss of calcium is still not completely understood. One knows that decalcification is related to an atrophy of bone fibrous cells containing calcium, corresponding to the part of the bone that allows the marrow to pass. This effect seems to be irreversible once it has started. The rate of calcium loss varies from an astronaut to another and varies also from a type of bone to another. Numerous experiments yield sometime diverging results. On one side, one observes an increase of activity of osteoclastic cells, whose role is to eliminate and resorb elements of bone tissues. On the other side, some results show that bone demineralization would be due to a decrease of activity of osteoblastic cells, responsible for regenerating bone tissues.

This problem of bone decalcification resembles by certain aspects osteoporosis, an illness known on Earth affecting mainly elderly people. This sickness yields a change in the structure (demineralization) of bones, but the composition stays globally the same. The bone loses in thickness, fragilizes and fractures more easily. This shows the importance of conducting research in microgravity on astronauts to better understand this sickness and to contribute in finding a cure for it.

5. The means of microgravity generation

All the means to generate microgravity are based on the principle of free fall; any other method will not result in a real microgravity environment but in a simulated microgravity environment. Microgravity is created in a non-inertial reference frame attached to a vehicle in free fall, in which the resultant of forces other than gravity is null or negligible.

Figure 9 summarizes the different platforms used for microgravity research in an increasing order of microgravity duration.



Figure 9. Reduced gravity platforms accessible to microgravity researchers (vertical axis, duration of microgravity; horizontal axis, quality of microgravity) (credit: DLR).

Drop tubes and drop towers provide a few seconds (up to 5 s) in the vertical drop mode, where an experimental payload is literally dropped in vacuum or behind a shield to reduce the perturbing effect of air friction.

The level of microgravity obtained in the drop tube of NASA Marshall Centre of 105 m high and 25 cm diameter is in the order of $10^{-6} g$ during 4.6 s in a vacuum. In Europe, the ZARM drop tower in Bremen, Germany (**Figure 10**), is 110 m high with a diameter of 3.5 m. Experiment capsules fall during 4.7 s in vacuum, yielding microgravity levels of $10^{-5} g$. The microgravity duration can be doubled up to 9.5 s by launching the experiment capsule in a catapult mode from the bottom of the tower upward, falling freely first upward and then downward [12, 13].

Aircraft parabolic flights provide a reduced gravity environment of approximately 20 s, with the major advantage of having human operators and subjects on board. The level of microgravity is typically in $10^{-2} g$ when attached to the floor structure that can be improved down to $10^{-3} g$ for a few seconds when left free-floating (**Figure 11**). This important microgravity platform is addressed in the next chapter.

Sounding rocket flights, for which microgravity levels are in the order of 10^{-4} – $10^{-5} g$, are used for automated or remotely operated experiments with relatively reduced volumes. Depending on the size of the rocket and the engine used, the duration of microgravity during the ballistic phase of the flights varies between 3 and 14 min [14].

In the near future, suborbital flights will provide microgravity duration in the order of 3–4 min for paying customers but also for microgravity experiments. There are typically two US companies that are working on suborbital vehicles (**Figure 12**): Blue Origin with the New Shepard capsule and a reusable rocket and Virgin Galactic and the SpaceShipTwo spaceplane carried by the WhiteKnightTwo airplane carrier. These two systems would carry passengers and experiments up to an altitude of 100 km or more in a propelled mode and continue in a ballistic mode for approximately 3–4 min after propulsion has stopped.

Manned orbital platforms provide microgravity periods of several years for the International Space Station (ISS, **Figure 13**) [15–17], and the future Chinese Space Station is foreseen to be assembled in orbit in 2022 (**Figure 14**). Residual accelerations are in the order of 10^{-2} – $10^{-4} g$, depending on internal perturbations (e.g. crew movements) and external ones.



Figure 10.
The ZARM drop tower in Bremen, Germany. The 146 m high building protects the free fall facility from atmospheric perturbation and wind (photo credit: ZARM).



Figure 11.
During a parabolic flight on board the Airbus A300 ZERO-G during an ESA campaign, several experimental racks are visible to the left and the back, while one of the authors floats freely “upside down.” There is no “up” and “down” in weightlessness (photo credit: ESA).



Figure 12.
Two suborbital facilities in development: (left) the New Shepard capsule with a reusable rocket (credit: Blue origin) and (right) the WhiteKnightTwo airplane carrying the SpaceShipTwo spaceplane (photo credit: Virgin galactic).



Figure 13.
The International Space Station (ISS) is the first major international project that includes 14 countries in its realization: The USA, Russia, Canada, Japan and 10 European countries (France, Germany, Italy, Belgium, the Netherlands, Spain, Sweden, Switzerland, Denmark and Norway). With a total mass of 440 tons (but weighing 0 kg ...), the ISS is in low earth orbit between 400 and 450 km altitude at 51.6° inclination. Since November 2000, the station is inhabited by permanent international crews (photo: NASA).

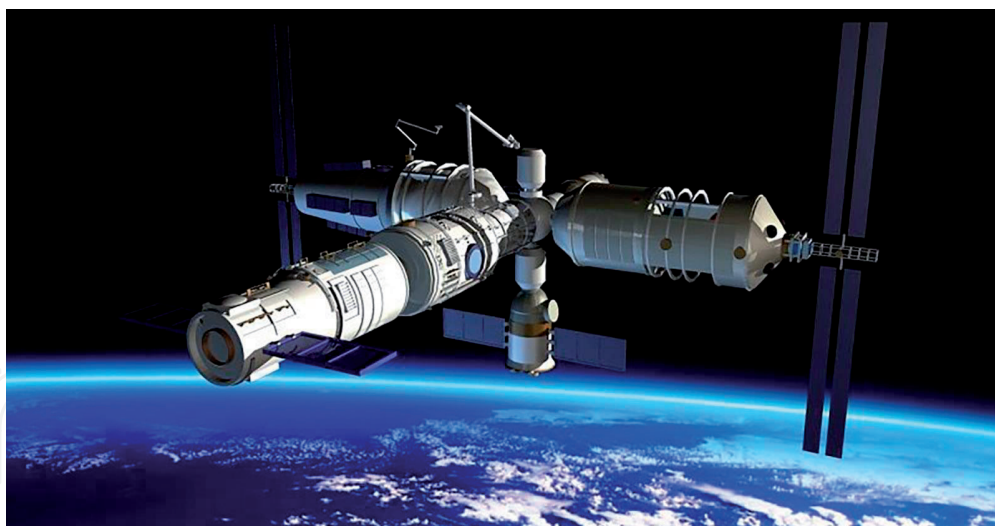


Figure 14.

The Chinese Space Station foreseen to be launched and assembled in the coming years with an assembly completed for 2022. From left, the Tianzhou (meaning “heavenly vessel” in Chinese Mandarin) cargo freighter docked to the Tianhe (“harmony of the heavens”) core module in the Centre; a piloted Shenzhou (“divine vessel”) vehicle is connected to a node in front of Tianhe, which are connected to two scientific modules: Wentian (“quest for the heavens,” at right) and Mengtian (“dreaming of the heavens,” left) (credit: CMSA).

Space missions of orbital platforms and of sounding rockets require a long preparation, typically of several years, and should be considered for experiments that need a long exposition duration to microgravity. The relatively short preparation time for the use of drop tubes and towers and of aircraft parabolic flights (typically of few days to few months) renders them particularly attractive for short-duration experiments of a few seconds. The utilization of these experimental platforms of earthbound microgravity must be considered as preparatory and complementary to space missions.

Let us insist on the fact that the platforms described in this section do not simulate microgravity but that they really create microgravity, even if it is not always perfect, as all these means are in free fall.

6. The means of microgravity simulation

To the contrary of the means creating microgravity, simulation methods do not allow to really create microgravity. The simulation means allow to obtain experimental configurations in which certain aspects of phenomena can be studied in a way similar to what could be observed in microgravity but without being in weightlessness.

Therefore, these methods have important limitations that reduce their scientific interest to the investigations of some very specific cases. The results obtained by these simulation methods generally complete those obtained in real microgravity. In none of the three following configurations, microgravity is really created as there is no free fall.

The first simulation method was used at the end of the nineteenth century by a Belgian physicist, Joseph Plateau, who gave his name to this method. The principle is simple: it consists in immersing a liquid in another immiscible liquid matrix having the same volumetric mass. By Archimedes principle, the buoyancy exerted by the liquid matrix of volumetric mass ρ_1 on a volume V of a liquid of volumetric mass ρ_2 is directed along the gravity acceleration vector and reads

$$\vec{F}_f = V \cdot (\rho_1 - \rho_2) \cdot \vec{g} \quad (1)$$

This force becomes null for $\rho_1 = \rho_2$, yielding results similar to what could be obtained in weightlessness when $g = 0$. In the Plateau configuration, the gravity force is not balanced by inertia forces but by a buoyancy force.

Only static configurations are truly well simulated with this method, e.g. configurations of static equilibrium of liquid zones.

The second simulation method is less known. It consists in balancing locally the force of gravity acting on a body by a magnetic or electrostatic force acting in the other direction. The effects of two fields, the gravitational field and a magnetic or electrostatic field, have to be locally balanced. One sees immediately the limitation of this configuration that would work only for bodies sensitive to magnetic induction or electrically charged. Furthermore, the power needed to maintain these fields is quite important and limits the size of observed configurations. Nevertheless, this method is used sometime to investigate magnetohydrodynamic problems in the absence of gravity effects.

The third simulation method is what is called the dimensionless reduction. This method mainly applies to fluid research for which scientists use a series of dimensionless numbers describing the ratios of different forces acting on fluids. Reducing physical dimensions of an experimental liquid zone greatly diminishes effects caused by gravity in comparison to other forces acting on fluids, e.g. superficial tension force or capillarity forces. One manages to build floating liquid zone of a few millimeters size that allow to study certain phenomena. The main limitations of this method are linked to reduced sizes: firstly, they make it difficult to install precise means of observation and measurement; secondly, they reduce the field of investigation to limited ranges of values of other effects specific to fluids.

Space medical and physiological research does not limit itself to conducting medical experiments in orbit or during parabolic flights but relies also on results obtained by earthbound means. For research on adaptation of the human body to weightlessness, scientists use two simulation techniques that allow within certain limits to recreate the effects of microgravity on the human body. It consists firstly



Figure 15. Head-down bed rest simulates microgravity effects on human physiology. Subjects stay in slightly tilted head-down (typically 6°) beds for weeks or months at a time (photo credit: CNES/ESA).

of immobilization (or hypokinesia, **Figure 15**) in a horizontal position or slightly inclined (head-down) that simulates the shift of body fluids, mainly blood, toward the upper part of the body like in weightlessness.

The second technique is water immersion. As the human body is mainly made of water, buoyancy induces conditions partially similar to microgravity acting on the human body, somewhat akin to Plateau's configuration. A variant of water immersion, called dry immersion, is also used sometime where the subject is placed in an elastic or plastic sheet in a liquid matrix, such that the subject is immersed in the liquid but without direct contact with the liquid.

7. Conclusion

A better understanding of the effects of microgravity on physics and the human body, from cells to body systems, is essential if the human exploration of outer space is to continue. The capacity to conduct research in the microgravity environment provided by spaceflight is fundamental, especially given current plans to expand long-term missions in low Earth orbit and to establish the commercial use of space, together with the ultimate goals of creating a human colony on the Moon and sending a first crewed mission to Mars. Nonetheless, there are many limiting factors that restrict the performance of experiments in space, such as the high costs involved in sending resources and equipment up into space, the safety requirements to which experimental devices must adhere and the small number of astronauts per flight. These constraining factors have motivated the establishment of ground-based research facilities and parabolic flights. The latter presents some limitations in terms of the short period of time of exposure to microgravity given and the hypergravity condition that precedes and succeeds each parabola. However, it is the only provider of microgravity, in which experiments in physics, biology, physiology and medicine can be conducted by human operators and volunteers. Parabolic flights are not a perfect analogue of spaceflight, but they remain a valuable research tool that enables research and testing to take place and a better understanding of the effects of microgravity, assisting academia, the private sector and governments to better design future plans for the human exploration of outer space.

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