Journal of Mechanical and Electrical Intelligent System (JMEIS)

International Space Station (ISS) Intelligent Human Centrifuge

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Keywords: artificial gravity, International Space Station, astronaut, centrifuge, HTV-X

Abstract. The International Space Station (ISS) astronauts need physiological countermeasures against microgravity (weightlessness on ISS). Recent abnormal findings in the eye (Space flight–Associated Neuro-ocular Syndrome, SANS) after 6-month-stay on the orbit tell us that current exercise measures are not complete. Ultimate solution should be the Artificial Gravity (AG) for astronauts. Before closure of the ISS program, which is slated for 2024, we would like to have a test bed on the JAXA HTV-X cargo ship berthed to ISS, which verifies feasibility and usefulness of AG. ISS Multilateral Medical Operations Panel is interested in ISS AG for medical operations purpose. Roscosmos, the Russian space agency, expresses intention to fly a human centrifuge on ISS. The overall design of AG by short-arm centrifuge with exercise function is not easy to come by, in terms of rotor cost savings. The authors propose to develop a human-powered centrifuge for ISS medical operations. To make AG effective and safe on manned spacecraft, incorporating advanced information processing mechanism into the AG machine should be the natural choice. Also, especially deep space exploration spacecraft which are exposed to high Linear Energy Transfer (LET) ion particle radiation, need to have onboard systems which are equipped with intelligent self-diagnosis and recovery function. Even low-earth-orbit (LEO) subsystems on ISS are known to be prone to space radiation damage.

1. Introduction

The environment in manned spacecraft orbiting in Low Earth Orbit (LEO) is different from that on the Earth. Atmospheric pressure and gas composition are different from spacecraft to spacecraft. The International Space Station (ISS) uses 1 atm absolute atmospheric pressure with 21% oxygen and 79% nitrogen, at the same pressure as at sea level, to accommodate animal and other life science experiments. Space Shuttle cabin was usually at 1 atm abs., but it was occasionally at 0.69 atm abs., to facilitate denitrogenating for spacewalk (Extra Vehicular Activity, EVA) astronaut body. Nitrogen gas bubbles are the cause of DeCompression Sickness (DCS).

Also, natural space radiation dose is higher in ISS orbit than that on the Earth. The 3-mm thick aluminum alloy wall helps somewhat against radiation. The same wall is for holding atmospheric pressure of ISS. ISS has separate bumper layer to protect crew from hits by orbital debris, which are immediate hazard to ISS.

The end of mission of ISS has been extended from 2020 to 2024. Current physiological measures against microgravity (weightlessness) work well on ISS, except for ocular problems. ISS medical problems in space includes space radiation effects, social isolation, confined space environmental control, and physiological changes due to microgravity. Possible countermeasures in the future include exercise, medicine, drink water, radiation shield, and centrifuge.

The most potent physiological factor to the astronauts is microgravity (weightlessness) in LEO. Besides enhanced mobility (3D up and down) in the cabin, no positive physiological change in the body is reported in microgravity. Fig. 1 summarizes negative clinical changes in the body, for long-duration (6 months) human stay in orbital microgravity.

In Fig. 1, the most recent and best-funded study target is Spaceflight Associated Neuro-ocular Syndrome (SANS) [1, 2, 3]. In addition, NASA started to investigate, from 2019, that if upper body venous thrombosis and retrograde blood flow in jugular vein are specific to long-duration ISS spaceflight [4].

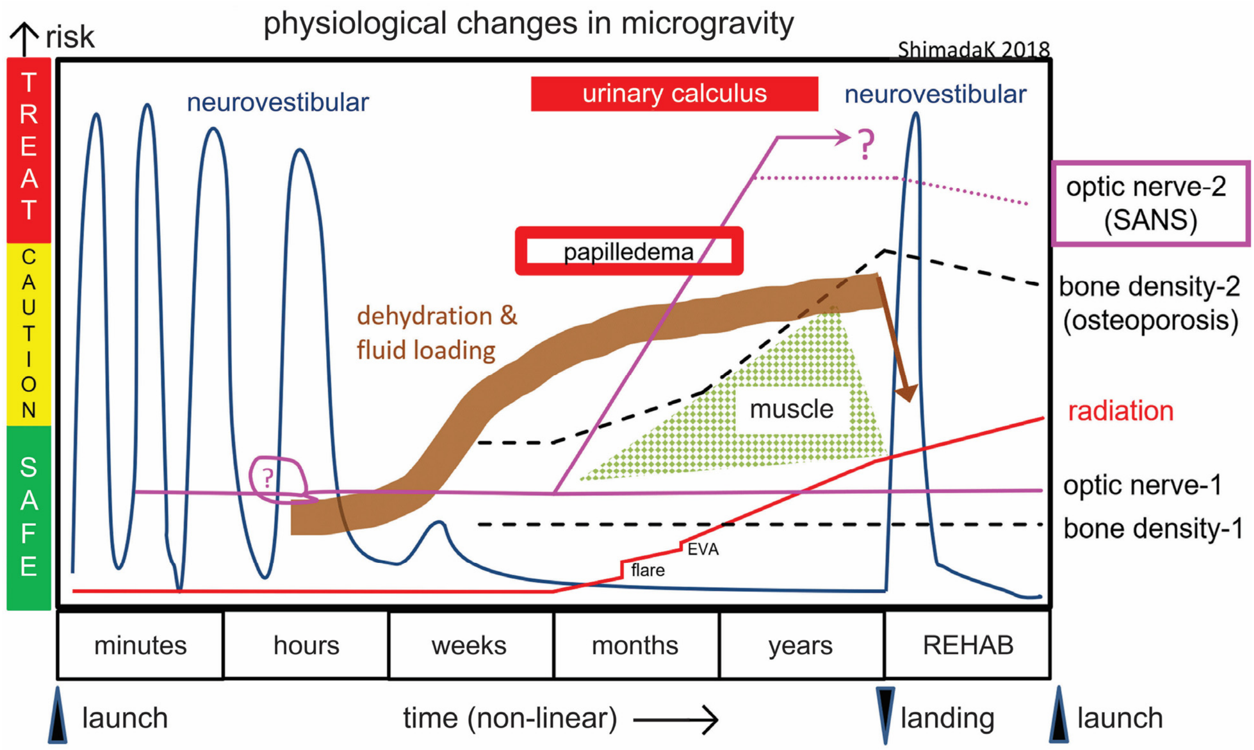


Fig. 1. Physiological changes in microgravity. This figure summarizes symptoms and physiological problems identified on the International Space Station (ISS). The latest in this chart is the ocular issue (SANS, Spaceflight Associated Neuro-ocular Syndrome), including ocular fundus abnormality (papilledema) and related changes. Dash one '-1' indicates no symptom group, '-2' is for affected population [5]. In 2019, NASA started investigation if upper-body thrombosis is also the result of long-duration microgravity exposure [4].

2. Spacecraft Environment

The era of space station started with Soviet Union Salyut 7 in 1971. Then NASA Skylab followed in 1973. USSR dominated in the space station domain with Almaz-Salyut in 1974 and Mir space station in 1986. NASA initially intended to boost the altitude of Skylab module to prolong its use, but the delay of Apollo program prevented the orbital reboost of the space station. In addition, its orbital decay rate seems to have been quicker than predicted.

NASA considered flying a space station early in space race history. During 1970's NASA started planning for an orbital module. Initial detailed design in 1980 is known as Space Station Freedom. Then budget reduction work was started to write up a design that achieves a more realistic transport scheme. With addition of Russia as an International Partner, revised Space Station Alpha became the International Space Station (ISS) for US, Japan, Europe, and Canada.

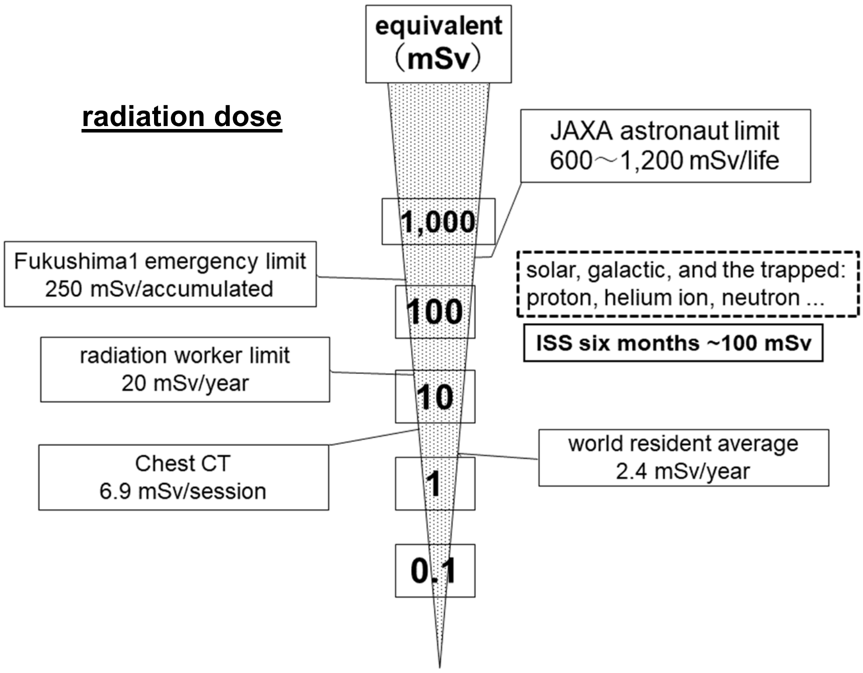


Fig. 2. ISS space radiation dose compared to ground exposures. Long-duration mission on ISS for 6 months gives a crewmember 60-100 mSv equivalent dose of space radiation, which comes from the Sun, distant galaxies, and protons trapped close to the earth. Lifetime dose limit of radiation is regulated by each ISS International Partner (U.S., Russia, Japan, Europe, and Canada).

2.1 ISS Communication

Holding humans aboard spacecraft for a longer period poses new challenges to space operators. For a low-earth orbit station, communication with a control center needs to be secured to cope with a vehicle emergency that necessitates an early return to base. A set of geosynchronous communication satellites or a number of ground stations are necessary. For Space Station Mir, Soviet Union placed a half a dozen ground station to cover communication period over its territory. This is a similar approach NASA took to support Apollo flights. For ISS, NASA uses Tracking and Data Relay Satellite System (TDRSS). Currently, three third-generation TDRS's are active; older ones are kept for backup. Still, time coverage is shy of 24 hours. Its 24-hour coverage is preplanned when there is an important task schedule, e.g., an ExtraVehicular Activity (EVA, spacewalk). Filling a gap (Zone of Exclusion, ZOE) with a backup TDRS is always doable, but it is not budget-friendly. Frequency bands are S (2-4 GHz), Ku (12-18 GHz), and Ka (27-40 GHz). Practically S band audio communication between ISS and Control Center-Houston is 24 hours coverage throughout the year. As TDRSS transponder time is shared by US Air Force and deep space science satellites, Ku band use, which allows ISS video downlink, is pre-coordinated. Later in ISS program, NASA offered the Russians TDRS time to make ElectroCardioGraphy (ECG or EKG) schedule flexible. With TDRS, Russians do not have to synchronize EKG recording schedule with the period when ISS is flying over Russian ground stations.

JAXA operated its single DRTS geosynchronous satellite for S and Ka band communication including ISS Japanese Experimental Module data relay from 2002 to 2017.

ISS communication is between ISS and ground Mission Control Centers at Houston, Tsukuba, Moscow/TsUP, and Munich. The communication environment on ISS allows immediate voice comm with ground control, but video downlink has to be pre-coordinated.

As there is no Ku band uplink to ISS, use of S band with low-resolution digital two-way video/voice is the current practice. Digital video system is required to privatize medical communication between an ISS crewmember and a Flight Surgeon on the ground. These mean that if a quick medical consultation is wanted, it starts with private voice, then use of digital two-way video, or digital still camera data downlink. Data file downlink is not immediate, it happens a couple of times a day in a bulk, usually during crew sleep. Thus, for an immediate care, onboard physician is the key. Physician crewmember manifest is not mandatory by rules. If there is no physician, one of two dedicated Crew Medical Officer will be at work. Official emergency return to ground time is 72 hours for ISS, but there is much risk in spacecraft operations if early return is forced to happen. The consensus is that for many medical conditions, ‘stay and fight’ would be less risky than to conduct an emergency return whose landing place could be far to a definitive treatment facility.

Beyond lunar orbit, including Martian surface, communication delay mandates autonomy of the crew in medical emergency resolution. Delayed communication has been simulated as ISS operational experiments. During the trial, ground controllers did not respond immediately; they gave ISS crew more autonomy than usual.

All systems onboard deep space exploration vehicle, including our intelligent human centrifuge, needs to be autonomic.

2.2 ISS Life Support

Next factor for a manned space station is a set of life support systems. It starts with atmosphere supply and air conditioning. As spacecraft air seal is good (ISS has an excellent, i.e. very low, leak rate), supply of nitrogen is enough with a series of pressurized gas tanks. Russian spacecraft always use 21% oxygen and 79% nitrogen atmosphere with 1 atm abs. pressure, which are the same for that on the ground. United States spacecraft applied different atmospheric composition. To make spacecraft lighter, a lower atmospheric pressure is preferred. Space station Skylab used 74% oxygen and 26% nitrogen at 5 psi (0.34 atm abs). At 0.34 atm abs, physiologically sea-level-equivalent oxygen percentage is 62%. Thus, Skylab atmosphere had more oxygen than on the ground, which means we must start to be careful about oxygen toxicity to the lung.

Apollo capsule initially used pure oxygen, then after Apollo 1 fire which happened ground oxygen pressure of 16 psi (1.1 atm abs), NASA converted it to two-gas oxygen/nitrogen system that made the hardware and protocol complex, with some adverse effects [6]. As humans use oxygen and carbon dioxide is exhaled, the essential function of atmospheric system is to remove carbon dioxide and supply the amount of oxygen used by crew. When humans are kept in a confined space without life support system, they die from high concentration carbon dioxide poisoning before hypoxia starts a serious condition. Principle carbon dioxide removal on ISS is by two zeolite beds. When one bed is absorbing carbon dioxide from ISS cabin, the other zeolite bed is exposed to vacuum, then absorbed carbon dioxide will diffuse out to outer space.

Apparently, air temperature control is mandatory. It is attained by heaters in the wall, chiefly for prevention of water condensation, and an air conditioner with foul odor remover. Usually considerable amount of heat is dissipated by avionics, life support mechanism, and experimental apparatus, heat removing function is activated on spacecraft. ISS removes cabin heat via water loop, heat exchanger, ammonium loop, to external radiator.

There are two ways to supply oxygen and water in manned spacecraft. One is the fuel cell system used by Gemini, Apollo, and Space Shuttle. They were not stable, intimate care was given. When fuel cell system is selected, capsule carries pressurized oxygen and hydrogen tank. Solar panels are not needed. Electricity is generated by fuel cell. Water for system and crew is a biproduct of chemical combination reaction. Amount of water exceeded daily requirement, thus jettisoning of excess water was conducted.

Water regeneration by ISS Water Reclamation System (WRS), from urine and wall condensate is not simple. It starts with accommodating high calcium urine, which made early Space Shuttle toilets with a lot of calcium compound accumulation. Purifying urine to yield potable water is working on ISS with many troubles. Water regeneration is currently by high pressure and high temperature. In 2010, Sabatier chemical reaction system was activated, to catch cabin air carbon dioxide and generate water. It consists of a furnace, a multistage compressor, and a condenser/phase-separation system [7].

2.3 Space Radiation

At the orbital altitude of 400 km, ISS is exposed to space radiation. But ISS is also partially shielded by earth magnetosphere and atmosphere from the radiation. There are 3 sources of space radiation: galactic, solar, and earth-trapped particles (proton and electron) [6]. Nominally total dose from these does not affect crew significantly [Fig.2]. However, there is always a chance of a large solar flare gives a large dose to ISS crew. It has not happened yet, in the history of ISS, largely due to the smaller volume angle steradian of the earth area. Not all direction s around the sun are affected equally by a solar flare. ISS crew had to stay in the center of ISS, where the shield from module walls, for a day due to solar flares. This shield procedure has been exercised twice so far. Wall thickness of ISS modules is equivalent to about 3 mm-aluminum.

There has been no case of acute radiation sickness in space operations. Each ISS International Partner regulates their astronaut's acute and lifetime dose limits.

In the case of Mars mission, not only proton but heavy ion from galaxies are to be considered. For example, iron ion radiation effect to Central Nervous System (CNS) is in discussion [8].

ISS electronical equipment has shown many incidents due to space radiation. Not only crew, but also equipment onboard deep space exploration spacecraft needs to be either high-LET radiation tolerant, or more realistically, to be with self-diagnosis and recovery intelligence. This applies to our intelligent human centrifuge, too.

2.4 Psychological Considerations

Often media reports on confinement and social isolation effects on ISS astronauts. On ISS, atmospheric confinement is a big issue at the time of fire or air leak. But there has been no prominent case of psychological problem case on ISS. Since around 2010, NASA augmented Internet Protocol Phone (IP Phone) and internet browsing on ISS. At leisure time crew can call out anybody on the phone (receiving call is regulated by mission control center), and browsing speed is at a practical level.

Generally, crewmembers are happier on orbit than in training on the ground. Psychological cases are occasionally seen on the ground.

Volume of ISS is larger than a regular house. Its volume exceeds the internal volume of Boeing 747. As they can move in 3D, and each crewmember can occupy almost one module per person, 'restricted' personal space is not an issue. Sometimes they do not see each other after a morning briefing until dinner.

For smaller spacecraft, psychological issue is of higher importance. NASA Orion space capsule is larger than Apollo capsule, but not much. For this regard NASA and Roscosmos have a good amount of experience in the past. The key is to pick crewmembers who knows each other well. To do so, training as a group on the ground for sufficient length is the practical solution.

2.5 Physiological Countermeasures against Microgravity

Apollo lunar missions were only one week long, but exercise machine (Exer-Genie Exerciser) was already made available, which was first tried in Gemini program (bungee on Gemini IV and isometric exercise on Gemini VII) [9, 10]. Skylab crew used cyclergometer in medical experiment M171:

Metabolic activity [11]. They also had Dr. William E. Thornton's makeshift treadmill that the third crew brought with them to the station. The treadmill device consisted of a Teflon-coated aluminum plate bolted to the floor of the workshop [12].

During Space Shuttle program, the Skylab cyclergometer was kept in use. It was launched folded, and was extended on mid-deck floor while they were flying. For ExtraVehicular Activity (EVA) preparation, grip exerciser was used by EVA crewmembers. For research, Lower Body Negative Pressure (LBNP) device was extensively tested. The consensus on LBNP then was that it is good for cardiovascular assessment, but it never became operational in NASA program, while it was required operationally in Russian program [13].

On ISS, crew physical exercise is the primary physiological countermeasure against microgravity. Other countermeasures implemented for ISS crew are pharmacological (Vitamin D), and LBNP (for Russian cosmonauts). Food nutrition follows WHO recommendation.

2.6 New Medical Issues

ISS medical operations have not seen new physiological issues for almost 10 years after permanent human habitation was started. However, new health issues were identified recently [Fig.1] [14].

A surprise came around 2009, when they found an index case of papilledema, which was not resolved after landing [1]. Most prominent feature of these cases was the flattering of posterior side of the ocular globe.

Then in 2017, MRI study revealed brain shift after ISS flights [15]. This may explain the mechanism of ocular globe flattering and papilledema [2, 3].

In 2019, NASA started looking into upper torso venous thrombosis. It is a candidate of long-duration spaceflight adverse effect [4].

As we do not know what kind of new health issue would be found, we need to seek for a holistic approach to ill effects from long duration spaceflight.

3. Artificial Gravity as a holistic countermeasure

The differences in environment, between space and that on the ground, to crew onboard spacecraft, are;

1) Microgravity
2) Space Radiation
3) Atmospheric Confinement
4) Social Confinement.

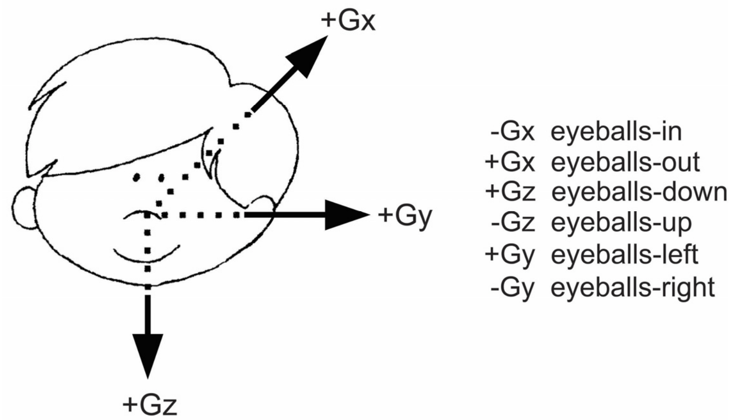
In this paper, above we discussed microgravity and space radiation. Below we continue to discuss microgravity effect on crew.

As microgravity onboard spacecraft is the reason for most of health problems for crew, applying gravity artificially should rectify adverse physiological effects. However, we do not know how much or how long acceleration (gravity) should be loaded to human body to prevent health problems onboard spacecraft. Some hints, e.g., for ocular issues, are acquired by animal study [16]. A considerable amount of research has been done on the ground with centrifuge [17]. An international life science society research proposal 'AGREE' [18, 19] was submitted for an ISS short arm human centrifuge/cycloergometer, but the proposal was rejected in 2012 by ISS Program [14].

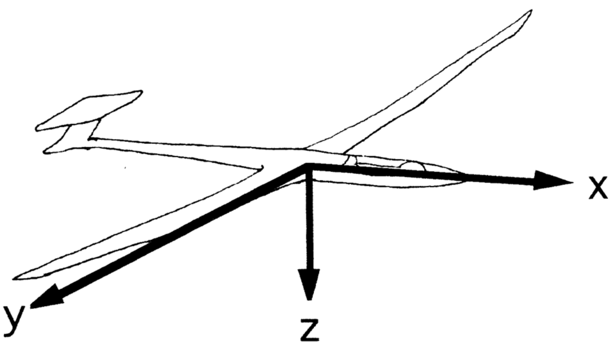
For animal experiment, a large animal centrifuge for ISS was proposed before the first element launch of ISS in 1998, but it was cancelled [14]. Japanese space agency, JAXA, is running a mouse centrifuge onboard ISS [14, 20]. Its 'partial gravity' run was initiated in 2019, starting with 1/6 G.

As animal response to microgravity has been studied since Sputnik 2 with dog 'Laika', more is known by now (for lunar orbit Apollo 17 flew 5 mice for radiation monitoring [21]), but no 'partial gravity', i.e., 0 – 1.0 G, spacecraft experiment has been conducted [22]. For human spaceflight, lunar surface (1/6) and Martian surface gravity (1/3) are of most interest at present. If there is a threshold either lower than 1/6 G or 1/3 G, sustainable human presence on the moon or Mars could be without extensive physiological countermeasures.

Today we have no idea if a long surface stay on Mars or the moon would harm the eyes or brain. That kind of research should be started before ISS comes to the end of mission, with animal and human centrifuge.



(a) Human body acceleration axis system.



(b) Aircraft acceleration axis system.

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Fig. 3. Axis nomenclature for Artificial Gravity. There are different axis systems used in aerospace field, (a) In this paper, the most popular human body axis system used in aerospace medicine is employed, Gz axis is from the head to the feet, (b) One of popular aircraft axis systems.

3.1 Artificial Gravity implementation

NASA's Artemis-Gateway plan would not be able to accommodate large modules. ISS can. Spacecraft to Mars would need to be equipped with artificial gravity device. In this paper we use the axis system used in aerospace medicine [Fig. 3].

3.1.1 Running on Skylab

It is widely known that Skylab crewmembers ran on the circular wall of the spacecraft. They had difficulty in starting the run under microgravity and continue running (from NASA Skylab video, about 2 m/s, thus at 0.14 Gz at feet) [Fig. 4].

This type of running on the wall in spacecraft, without any vehicle rotation assist, could be the final configuration for attaining G for crew body as a microgravity countermeasure. However, we do not know what limits their body movement per vestibular symptoms, or if a crewmember can run fast enough, with simple running shoes, in a smaller diameter volume (to benefit from higher rotational rate). We need to accumulate experience with a human centrifuge onboard spacecraft.

There is an anecdote that ground controllers did not like crewmember moving this way, as it used Skylab system fuel for attitude control. Rough estimation of attitude control system load can be made before launch, but how crew use their body movement during actual G load should be verified onboard.

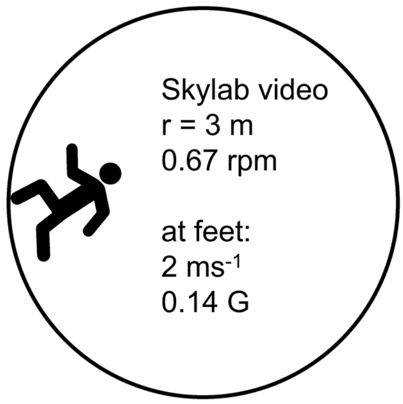


Fig. 4. Running on Skylab. By analysis of Skylab NASA Public Affairs Office motion film, the crewmember was running on the wall (3 m radius) at 9 seconds a revolution (0.67 rpm). At this rotation speed, the centrifugal acceleration at feet was ca. 0.14 Gz. Starting the run was difficult, since before they gained velocity, there was no mechanism to stabilize their body in microgravity. As the +Gz value at the heart level was very small, no cardiovascular effect was expected.

3.1.2 Artificial Gravity for Space Shuttle

Spacelab science module in Space Shuttle cargo area once accommodated a short-arm human off-axis centrifuge for 'Neurolab' life science payload mission, but subject orientation was only for vestibular study, thus no Gz (acceleration in the axis from head to toe) was loaded [23, 24]. However, their G load reached 1 Gy (sideway acceleration).

3.1.3 Artificial Gravity for ISS

In October 2016 at Tokyo meeting, ISS Multilateral Medical Operations Panel was presented with HTV-X option of ISS human short-arm centrifuge, and agreed that this possibility should be continuously monitored. Also, in 2016 Roscosmos was reported to plan a human centrifuge on ISS [25]. ISS human centrifuge is expected to fill in knowledge gaps, and HTV-X AG option fits very well in AG roadmap [17].

At present, centrifugation on ISS is only for micro-organism and mice [14, 18, 26, 27]. As stated above, a large rat centrifuge was cancelled before the launch of ISS, and international short-arm human centrifuge research plan 'AGREE' was turned down in 2012: there is no launch plan of a human centrifuge. Currently the 'Permanent Multi-purpose Module (PMM)' which AGREE planned to use for centrifuge implementation and storage is occupied with hardware. But a newer expandable module, Bigelow Expandable Activity Module (BEAM), was added later [28]. BEAM's diameter is rather small at 3.23 m, though.

The scheme for AGREE centrifuge launch/installation was that 1) European Space Agency (ESA) builds the centrifuge rotor; 2) JAXA launches the rotor; 3) NASA gives out installation volume in PMM; 4) NASA gives out crew time to assemble the rotor on ISS; 5) research time would be shared by ISS International Partners (IPs). The weakness in this scheme is that rotor integration becomes multilateral and complex, and also a long and error-prone onboard assembly of a large machine was necessary.

3.1.3.1 HTV-X human short-arm centrifuge option for ISS

We are now at a later stage of ISS Program which financially ends in 2024. A new opportunity became available after the 2012 AGREE proposal rejection. Since 2009 JAXA has been flying an ISS cargo ship 'HTV', which has the largest internal payload diameter of 4.1656 m, among ISS cargo transfer ships. JAXA is developing its new spacecraft, 'HTV-X' that will start launching in 2022. The prominent difference between HTV and HTV-X is that the latter will have longer orbital life, which is nominally 6 months (HTV orbital life is 3 months), but could be much longer if required. The advantages of HTV-X human short-arm centrifuge, compare to the AGREE scheme are:

1) HTV-X can accommodate the AG rotor like a new, empty module.

2) JAXA does not have to prepare an extra rocket launch. If it negotiates with NASA for NASA's cargo rights (maybe for NASA crewmember participating in AG trial) on HTV-X (about half of a cargo ship), a launch already on manifest can be allocated.

3) If the cargo ship stays berthed to ISS for 6 months or longer, many of the objectives of AGREE could be fulfilled.

4) The AG rotor can be assembled and firmly installed in a cargo ship. Welding, which is unable to conduct on ISS, becomes an option for assembly.

5) Rotor location can be closer to ISS berthing mechanism, than the one planned for PMM.

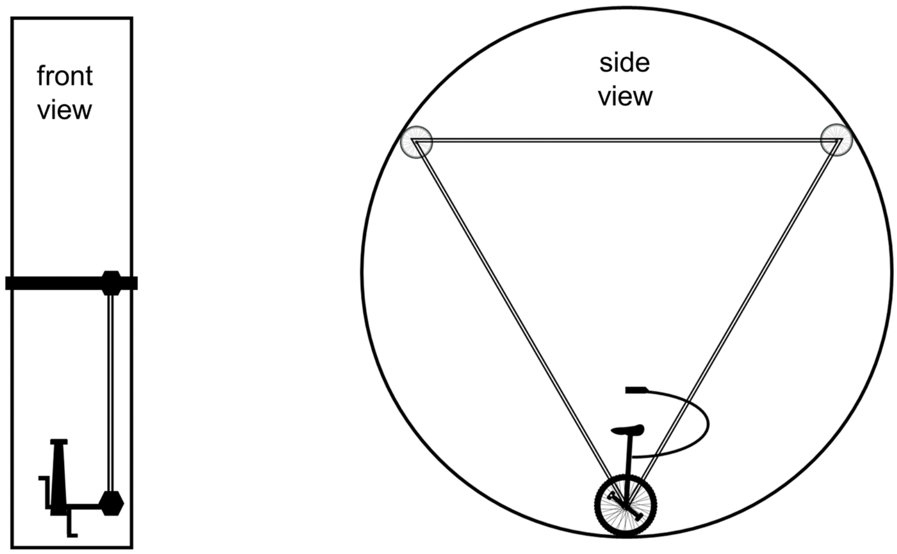
6) As HTV-X will be thrown away after unberthing, it is easy to launch an improved rotor on another HTV-X.

3.1.3.2 Human-powered rotor option for ISS AG

The real major reason, estimated, for the reason of cancelling of AGREE was that rotor cost was too expensive. As AGREE rotor feasibility study showed that the rotor would be very complex, thus additional effort to reduce hardware vibration was not materialized. The rejection letter from NASA and JAXA management to AGREE Principal Investigator (PI) said that whole ISS vibration was to exceed 'desirable' allowance. The AGREE rotor mass estimation grew from the original human-powered 60 kg machine with two subjects to 320 kg motorized model with one subject. The mass of cancelled CAM rat centrifuge rotor was 2 ton and was said to have cost 200 million US dollars. The CAM rotor was at an engineering module stage when it was cancelled, but safety review was not complete then. Its design was said to have never met the design safety requirement to tolerate sudden halt torque of the rotor.

One option to reduce cost and be safer in operation is to choose the subject as power source and control personnel. The energy to start up and brake a human-powered AG rotor on ISS is about the same as riding a bicycle on the ground. With some design, highly reliable racing bicycle component could be used.

When one of the authors held a Technical Interchange Meeting (TIM) with AG researchers at NASA Ames Research Center in 2016, attendants from Massachusetts Institute of Technology, ESA, and Johnson Space Center all agreed that the first human AG rotor abord ISS does not have to be as complex as the research centrifuge for AGREE. One comment was “Rather than keep watching AG proposal ‘rounds, rounds, rounds around realization’ for more than 4 decades, anything that accommodates a subject to see exactly how much vestibular effects the person feels is welcome.” There could be unexpected issues; e.g., we do not know if airflow is comfortable for a subject astronaut or not. We need to learn about human short-arm centrifuge on ISS before we apply AG for Mars mission physiological countermeasure.



(a) Center shaft configuration (b) Wall track configuration

Fig. 5. Design options for an ISS human short-arm centrifuge [27], (a) front view of a swing rotating around a center shaft design. Heavy members sustain the center shaft. If motorized, this may be easier to build, (b) side view of a monocycle running on a rail on the wall. Authors’ preference. Weight distribution is for the rail and the truss (triangular for this design sample). Very similar to riding a bicycle, braking is easy, inherently safe.

3.1.3.3 Requirements for the rotor

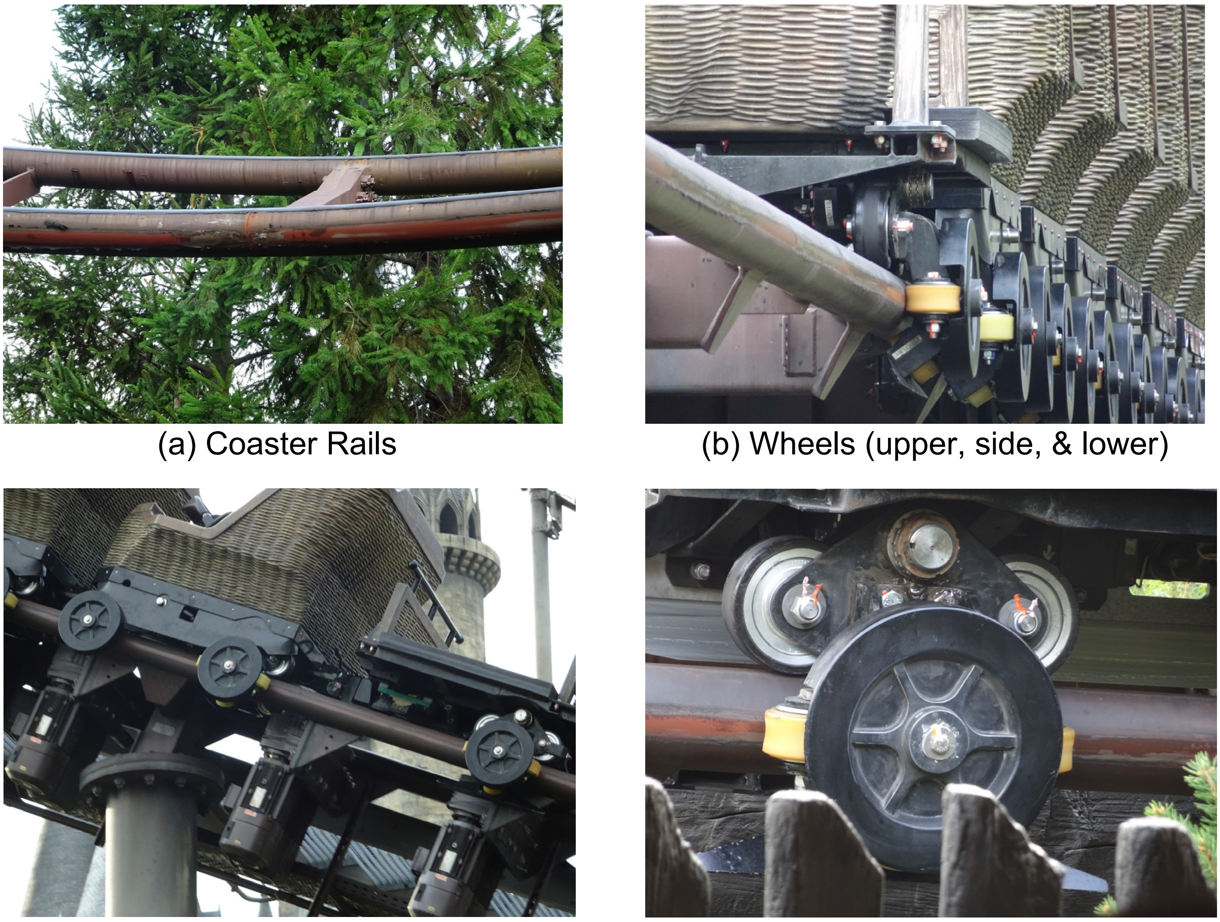
Basic requirements for the first-ever ISS human short-arm operational centrifuge are:

1) Able to be safely halted by a subject.
2) Safe when a foreign body suddenly stops the rotation.
3) Inner ear position can be adjected to be as close to the center of rotation.
4) Highly reliable, durable mechanics.
5) Able to monitor and adjust rotation rate (that equals to Gz value).
6) Able to adjust distance, as large as possible, between inner ear and center of rotation.
7) Cyclergometer variable loading. Max oxygen uptake load is desirable; at least 200 W range.
8) Can be operated by a subject, no need for a safety monitor person.

3.1.3.4 Design sample – rail or center shaft

Most of ground short-arm centrifuges are laid horizontally, and have a rotation shaft in the center [Fig.5 (a)]. However, in microgravity, other configurations could be optimal, like use of module wall or rails to run on with a wheel or two [Fig.5 (b)]. In the latter case, holding a wheel on the wall needs some restraint mechanism. At least, to start the rotation, something to hold a wheel in place is necessary. The same restraint member could be used for correcting riding track and for safety. When a subject is vigilant, rails may not be necessary after rotation has started. But for a safe sideway tracking, some restraint member is desirable.

Authors prefer [Fig.5 (b)] wall track/rail approach for our human-powered rotor. One of the tightest and robust designs for wheel-rail, popular on the ground, is found in roller coasters [Fig.6] [29]. This mechanism allows cars to sustain G's from all directions. Many of roller coasters are with a pair of rails, but monorail system and vibration damping systems are materialized [30, 31]. For this paper we take a model from roller coaster design. Vibration isolation system for exercise machines on ISS is important, but it should be discussed later when more details are defined for rotor design.



(a) Coaster Rails (b) Wheels (upper, side, & lower)

(c) Fake Wheels (black) (d) Dual Upper Wheels

Fig. 6. An example of roller coaster rail/wheel system. Those large, wheel-like pieces are fake wheels. Each bench is held with 4 groups of upper two wheels, two outer side wheels, and one under wheel that contact to one of two rails. Each wheel group consists of 5 wheels on one side.

3.1.3.5 Design sample – ergometer installation

ISS human short-arm rotor should be both for AG load and leg exercise. As the rotor arm length is short, steep Gz gradient is inevitable. The Gz value to the heart is hard to reach 1 G. Vice versa, Gz on feet becomes larger than 1 G. Without lower extremity exercise, venous blood pooling would result; leg exercise is anyway necessary.

There are efforts to shorten the time necessary for ISS countermeasure exercise, which is 2 hours in time block and exercise time about 1.5 hours besides preparation and clean up, by menu selection [32], but High-intensity Interval Aerobic Training (HIAT) is not yet well accepted for ISS implementation.

Exposure duration to AG per day was researched on the ground, from 0.5 to 4 hours per day [33]. The cardiovascular and musculoskeletal effect of AG depends not only the loading duration but also on its combination with load G value. As short as 0.5 hour per day with multiple sessions (e.g. 5 min each) is reported to have had a significant result. Countermeasure time slot length shortening is well expected.

A mechanical cyclergometer was used in Skylab and Space Shuttle program. Workload heat was dissipated to air via metal enclosure. ISS cyclergometer, 'Cyclergometer with Vibration Isolation System (CEVIS)' is electronically controlled [34].

There are other loading devices used for bicycle. One good example is a compact device for indoor bicycling with permanent magnet [Fig.7].

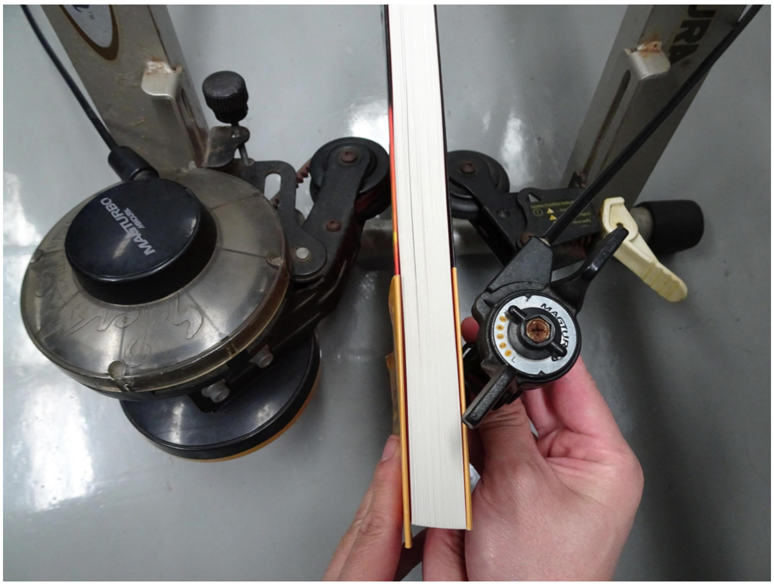


Fig. 7. An example of permanent magnet bicycle rim loader [V]. Level of load is adjustable with the dial in hand. These items are sold commercially for serious athlete riders. Its durability is excellent. The location of bicycle aluminum wheel rim is shown by a book. Rubber rollers are replaced regularly.

3.1.3.6 Design sample – ISS human-powered intelligent rotor

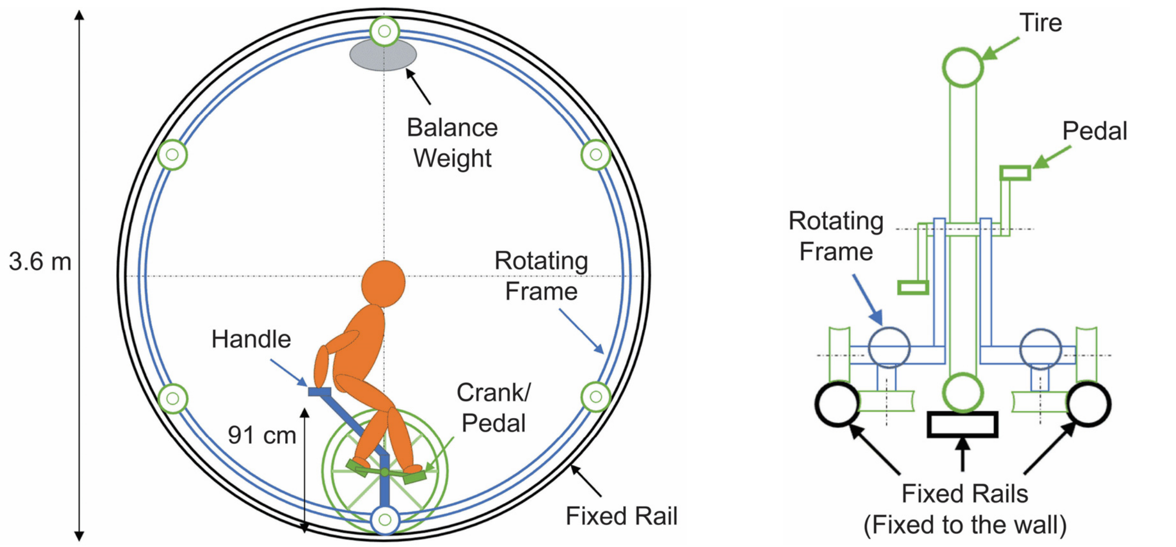
With design options described above, Fig.8 shows the initial draft of our ISS short-arm centrifuge for astronaut physiological countermeasure. It combines AG load with cyclergometer exercise. The design has two rails with firm wheel grips, modeled from roller coaster standard design. Compared with a simpler delta truss design in Fig.5, this rail/wheel could be excessively tough and heavy, but should be a good, safe starting point. We may leave only one fixed rail and one rotating frame, to reduce mass. After we gain experience with the first rotor, we may depend on subject self-control for correct path tracking.

Braking power necessary for this rotor is about the same for sport bicycle. Same components could be applied. To free subject hands and make it simpler, foot coast brake may be chosen.

Height of subject above the monocycle wheel, or distance between subject inner ears and the center of rotation, should be adjustable. To accommodate subject of different size, either variable size pedals/cranks, or alteration of subject posture is needed.

The shape of truss member, or rotating frame, prefers circular shape for ease of operation, and spacing to avoid inadvertent crew contact with the frame when anomaly happens.

This version follows the rotor dimension of AGREE rotor (3.2 m diameter), and assumes up to 30 rpm rotation rate. The larger the diameter, adjustment for subject height becomes somewhat easier, but attaining higher Gz may become more difficult, as inertia of the cycle becomes larger.



(a) Centrifuge Concept (b) Frontal section view of monocycle

Fig. 8. An initial draft design of ISS short-arm centrifuge [26]. This is a robust, safe design to start with. The diameter of 3.6 m follows the AGREE rotor dimension, assuming rotation up to 30 rpm. To reduce mass, one rail and one rotating frame could be removed. To adjust the distance between inner ears and center of rotation, and receive different height crewmembers, subject position may have to be altered. Average height male subject needs a large monocycle wheel. Tire can be air-filled or flat-free type. The former would have advantage in mitigating high frequency vibration. Counter balance weight could be fixed or dynamically located with intelligent control. Foot coaster brake may be employed, which free hands. The brake may supplement friction loading components that can be located at each rotating frame wheel. Distributed workload device has advantage in heat dissipation. Overall intelligent anomaly detection system should be in place for safety.

4. Conclusion

This paper first reviewed requirements for an ISS human short-arm centrifuge, then examined each component of centrifuge rotor. Our initial design of the AG rotor chose a human-powered monocycle configuration with fixed rails and rotating circular frame. Detailed design work should reduce mass of the rails and wheels.

To reduce mass of safety components and detect anomaly earlier, realization of the function for real-time intelligent analysis and recovery is desired.

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