Cardiovascular Responses to Artificial Gravity Combined with Exercise

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Abstract—**Astronauts experience important physiological adaptation to weightless environment, including bone loss, muscle atrophy, cardiovascular deconditioning, and vestibular disorientation. Physiological deconditioning will be even more challenging in future long-duration space missions, for example to Mars, in which astronauts will be exposed to microgravity for six to eight months before landing without external help to support egress. Artificial gravity (AG) is a comprehensive countermeasure that could prevent physiological deconditioning during extended exposure to microgravity, particularly if it is combined with exercise. Here, we are investigating the effect of short-radius centrifugation combined with ergometer exercise on human physiology, particularly on the cardiovascular system.**

One subject is tested under three different levels of AG: 0g (no centrifugation), 1g, and 1.4 g (g levels measured at the feet). At each AG level, the subject completes a 25 min bicycle ergometry exercise protocol with three different exercise intensities: warm-up (25W), moderate (50W), and vigorous (100W). Continuous cardiovascular variables (heart rate, blood pressure, pulse pressure, stroke volume, cardiac output, and vascular resistance) are measured at heart level using a ccNexfin system (Edward Lifescience). Preliminary results show that the extent to which the cardiovascular system responds to artificial gravity depends on the gravity level being applied, suggesting that artificial gravity combined with exercise may be effective as a countermeasure against cardiovascular deconditioning in space.

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1. INTRODUCTION

Human deconditioning in weightlessness has been considered from the very beginning of the human spaceflight era in the early 1960s. Since then, medical scientists have been involved in maintaining human health and performance in space under a new discipline called "Space Medicine" [1]. Over more than 50 years, an extensive research effort has been realized to identify, study, and resolve the medical problems that astronauts face in the 0g environment. Some of the physiological issues due to the weightlessness environment include bone loss, muscle atrophy, changes in body weight, fluid shift, cardiovascular deconditioning, and neurovestibular effects [1], [2].

Investigations in space physiology through the years led to a set of countermeasures to mitigate the effects of microgravity on the human body. For example, astronauts follow an intense exercise protocol using anaerobic (or resistive) and aerobic exercise devices, such as the Advanced Resistive Exercise Device (ARED) or the Cycle Ergometer with Vibration Isolation System (CEVIS), respectively. In addition, astronauts use nutrition supplements such as calcium and vitamin D, and wear special devices such as the lower body negative pressure (LBNP) vacuum chamber or the elastic "penguin" suit to stress the cardiovascular system in a similar way to standing [2]. However, the current countermeasures have proven to be only partially effective, and each one of them intends to mitigate one aspect of physiological deconditioning suffered in space [3].

Artificial Gravity (AG) has been introduced as an integrated countermeasure capable of mitigating most of the physiological deconditioning due to long duration exposure to weightlessness conditions. The inertial forces generated by centrifugation have the potential to affect multiple physiological systems at the same time, including musculoskeletal, cardiovascular, and the sensory-motor system [3]. Two different concepts are considered in order to generate inertial forces using centrifugation in space. The first one consists of the use of small-radius centrifuge located inside a specific module of a space station. This option involves high rates of rotation during intermittent sessions of artificial gravity. The second option considers the permanent rotation of the entire space station, involving smaller rates of rotation but much higher system complexity [3].

Artificial gravity is not a new concept in human spaceflight. It was proposed by Konstatin Tsiolkovsky in his manuscript

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"Free Space," written in 1883 [3]. Since then, many designs have been envisioned, including the famous rotating wheel-like space station concept in the film "*2001: A Space Odyssey*" by Stanley Kubrick in 1968, based on Arthur C. Clarke's story "*The Sentinel*" from 1948. However, after all these years, many fundamental questions remain unanswered. It is believed that exercise during centrifugation is one of the best combinations to maintain physiological functions in microgravity conditions [4], but the aerospace community has not agreed on a standardized protocol that will be effective. Many parameters still need to be defined, such as centrifuge design, artificial gravity exposure duration, rotation rates or exercise type, intensity and duration.

The objective of this research effort is to deepen the understanding of the physiological effects of artificial gravity generated by a short-radius centrifuge. In particular, the cardiovascular effects of exercise under different levels of artificial gravity through experimentation is explored using the MIT short-radius centrifuge.

2. CARDIOVASCULAR SYSTEM IN SPACE

The cardiovascular system experiences important changes during spaceflight in order to adapt to a weightlessness environment. In general, this adaptation process is successful. Some cardiac rhythm disturbances have been documented in the past on crew members, although it is very difficult to associate them with weightlessness instead of other factors such as stress, exercise or electrolyte imbalance [2]. However, the readaptation process when crew members return to a gravity environment is more problematic. Their cardiovascular system is not adapted to normal gravity conditions, and orthostatic intolerance occurs [2], [5].

One of the main cardiovascular effects that astronauts experience during spaceflight is the central fluid shift phenomenon. Blood pressure and volume distribution are directly affected by gravity. In standing position on Earth, the blood is pulled to the lower extremities. Similarly, the venous return process is hindered by the presence of the gravity force. Nevertheless, the human body has learned how to deal with gravity effects. For example, leg muscles are used as secondary pumps to facilitate venous return to the heart [5]. In space, part of the blood that is usually located in the lower part of the body is shifted upwards to the upper body, the upper trunk, and the head. Consequently, there is a significant increase in central blood volume (volume in the heart cavities, lungs and central arterial tree). The cardiopulmonary receptors, situated in the atria and pulmonary arteries, sense this pressure change and start acting upon the "excess" body fluid (plasma and red cell mass), increasing the output of urine, and making the astronauts less thirsty, among other resulting processes [2], [5]. As a consequence, the overall quantity of fluids and electrolytes decreases, leading to a reduction in total circulation blood volume of up to 11% [2], and stabilization in a new "cardiovascular state" associated with weightlessness conditions.

The cardiovascular system also experiences other changes in space. During the first stages of weightlessness, the heart enlarges in order to handle the fluid shift and the increase in central blood volume. In later stages, when the fluid adjustments occur and the total circulating blood decreases, the heart does not need to work as hard. Moreover, the heart does not need to work against gravity either. These changes, and the reduction of the overall level of activity, lead to a decrease in heart size (both chamber size and wall thickness) causing cardiac atrophy [2], [5]. Other effects of microgravity include an increase in venous compliance resulting in blood pooling to the lower extremities and a reduction in the baroreflex sensitivity [3]. In addition, the initial increase in fluid volume in the head can cause facial edema, headaches, nasal congestion, and venous engorgement [6].

When astronauts return to Earth, their cardiovascular system may not be adapted to deal with the gravity force. This may be due to a combination of different factors, such as reduced blood volume, cardiac atrophy, reduced vasoconstriction, increased venous compliance, reduced stroke volume and cardiac output, or decrease in the baroreceptor reflex. Aerobic capacity is also reduced up to 22% after short duration spaceflight (9-14 days) [7]. As a consequence, crewmembers suffer what is known as postflight orthostatic intolerance. Back on Earth, gravity pulls the blood to the lower extremities again. The arterial pressure decreases and the heart rate increases as a result of the baroreflex response, but the body may not be able to generate the necessary pressure to force the blood back up to the head. In some cases, this postflight orthostatic stress is strong enough to make it impossible for astronauts to stand up without losing consciousness. After short-duration spaceflight, up to 63% of crew members presented signs of orthostatic intolerance [2].

Current Countermeasures

Several countermeasures are currently in place to keep astronauts healthy and mitigate as much as possible the negative effect of weightlessness on the human body. In general, these countermeasures are system-specific, focusing on one particular aspect of human deconditioning in space.

Exercise is the principal countermeasure used in space, and it is part of the daily activities of crew members. Astronauts exercise around 2.5 hours a day, 6 days a week, using different devices including treadmills, ergometers, a resistance exercise device, as well as bungees and expanders. Together, these devices provide a comprehensive exercise plan that includes aerobic, and resistive training to alleviate skeletal, muscular and cardiovascular deconditioning [2]. The exercise devices on the ISS are the Treadmill with Vibration Isolation System (TVIS), the T2 Treadmill or Combined Operational Load Bearing External Resistance Treadmill (COLBERT), the Cycle Ergometer with Vibration Isolation System (CEVIS), the VELO Ergometer, and the Advanced Resistive Exercise Device (ARED) [8]. These exercises devices are shown in Figure 1.

Figure 1: Exercise devices in the ISS (top left to bottom right): T2/COLBERT, TVIS, ARED, CEVIS, VELO Ergometer, VELO Ergometer with cable (NASA) [8]

The T2/COLBERT treadmill was added to the existing TVIS treadmill to cover the larger crew of 6 astronauts on the ISS. Both treadmills can be operated in either active mode (externally powered) or passive mode (powered by the astronauts), and they have bungee cords to pull the users against the treadmill and create some compressive loading [9]. The Russian VELO ergometer is used in the recumbent position and provides workload levels between 50-250 W at 40-120 rpm. The CEVIS ergometer is operated in the United States Laboratory Module (US LAB) and is able to provide workload levels between 25-350 W at 50-120 rpm. This ergometer provides a very accurate workload independent of the pedaling of the crew member [10]. The ARED device was sent to the ISS in November 2008 to replace the Interim Resistive Exercise Device (iRED). The ARED primary goal is to maintain astronaut muscle mass and strength during their space missions. It simulates free-weight exercises up to 1675 N of load, and allows crew members to follow a personalized exercise plan [11].

Additional countermeasures are also being used during spaceflight. Leg cuffs are used soon after reaching orbit to reduce the amount of fluid shift from the lower extremities to the upper extremities, ameliorating the symptoms resulting from fluid distribution such as facial edema, engorgement of the external neck veins, nasal congestion, and headache [6]. The Lower Body Negative Pressure (LBNP) system consists of a chamber that covers the lower extremities and induces a cardiovascular stress by applying negative pressure over the lower body. It increases blood pressure to the legs and restores the blood pressure gradient, creating a cardiovascular state similar to upright standing on Earth. The LBNP system is mostly used one month before landing to improve orthostatic stability upon landing and to reduce the risk of pre-syncope and loss of consciousness [12]. LBNP is used in association with fluid loading, which consists of the consumption of water and salt tablets to increase plasma volume [3]. Figure 2 shows the Russian “Chibis” LBNP device currently on board.

Nutrition is also a very important aspect of spaceflight. It has been shown that astronauts usually burn more calories than they take in and therefore are in negative caloric balance. This fact, combined with an intense exercise program, may lead to a significant mass loss (in particular muscle mass) and strength reduction.

3. ARTIFICIAL GRAVITY AS COUNTERMEASURE

Despite the large variety of countermeasures in place, their effectiveness has not been demonstrated in terms of maintaining preflight levels of bone, muscle, aerobic fitness, and cardiovascular conditions [2], [3], [13]. Each countermeasure targets one particular aspect of human deconditioning in space, making it very difficult and time-consuming to maintain an overall good state across systems. For example, different exercise protocols are designed to counteract muscle loss (resistive exercise), cardiovascular deconditioning (aerobic exercise), or bone loss (high peak forces during treadmill exercise) and therefore, the crew members spend more than 2 hours/day exercising. On the other hand, these exercise protocols have not been shown to fully protect astronauts from weightlessness deconditioning during long duration spaceflight (6 months in Low Earth Orbit (LEO)) [13]. Hence, even with these countermeasures, astronauts will certainly suffer the negative effects of weightlessness during longer missions in the future such as a trip to Mars (up to 30-month round-trip mission). After the 6-month trip to Mars, the crew members will have suffered bone loss, muscle atrophy, cardiovascular deconditioning, and vestibular changes, and they will not have the support to deal with these changes that they have when they return to Earth. In addition, the reduced Mars gravity (0.38g) may not be sufficient to maintain a good enough physiological conditioning without additional countermeasures [3].

Artificial gravity is introduced as a multi-system countermeasure. It consists in the recreation of a gravity environment that challenges all the physiological systems like on Earth. Artificial gravity will not mitigate all the risks associated with human spaceflight (for example, it will not be effective against psychological issues or radiation exposure), but it is proposed as a solution for the physiological deconditioning associated with long duration spaceflight, including bone loss, muscle atrophy, cardiovascular deconditioning, neurovestibular disturbances, space anemia, and immune system deficiency [2], [3]. In addition, besides reducing or eliminating physiological deconditioning, artificial gravity could potentially improve hygiene, habitability and medical operations [3].

Figure 2: “Chibis” LBNP device [12]

General Principles of AG

AG in a spacecraft can be generated using various techniques such as linear acceleration (accelerating or decelerating in a straight line), or centrifugal force (artificial gravity generated by rotation). In the second category, two main methods can be differentiated: continuous artificial gravity, and intermittent artificial gravity by rotation on an on-board small radius centrifuge.

Continuous artificial gravity—Continuous artificial gravity can be generated by rotation of a large spacecraft. This concept was first proposed by Tsiolkovsky in 1883. In the 1950s, Von Braun envisioned a large spinning space station in order to generate continuous artificial gravity. A different option refers to the rotation of a rigid truss, which would have the astronaut's habitat in one side, and a counterweight or perhaps a nuclear power plant on the other side. It could also have another module at the center of rotation to perform 0g gravity experiments. Providing continuous artificial gravity is highly desirable from the physiological point of view. However, many engineering challenges arise with this concept, and a very large budget would be necessary to carry out such an endeavor.

Intermittent artificial gravity by rotation on an on-board small radius centrifuge—A small radius centrifuge is a more affordable approach to generate artificial gravity in space. The engineering challenges as well as budget constraints would certainly be reduced. In this scenario, astronauts would experience intermittent artificial gravity for short periods of time. It is unknown if the reduced gravity in Mars will be enough to maintain a healthy physiological state, and this concept would provide a way to create artificial gravity on the Mars surface as well as in space.

In a small radius centrifuge, the centrifugal force is directed radially towards the rim of the centrifuge. It recreates the gravity force and hence, objects (or people) on the centrifuge are stressed as if they were subjected to a true gravity environment (except for the gravity gradient, see below). In a rotating environment, the magnitude of the centrifugal force is:

$$F_{centrifugal} = m\omega^2 r \qquad (1)$$

where m is the mass of the object (kilograms), ω is the angular velocity (radians per second), and r is the radius from the object to the center of rotation (meters). The force generated depends on the angular velocity and the radius. Thus, a small radius centrifuge needs to rotate faster to generate the same amount of force as a big rotating station, affecting how people feel in this rotating environment. This is mainly due to the presence of other inertial forces generated by rotation, namely the Coriolis forces. The Coriolis forces appear as a result of linear movement in a rotating environment and are perpendicular to the direction of the movement. The Coriolis forces are:

$$F_{coriolis} = -2m\Omega \times v \qquad (2)$$

where m is the mass of the object (kilograms), Ω is the angular velocity vector which has magnitude ω and is directed along the axis of rotation (radians per second), and v is the velocity vector of the linear movement (m/s). Thus, the Coriolis forces are zero if $\boldsymbol{v}$ is zero or if $\boldsymbol{v}$ is parallel to the rotation axis. On the other hand, if $\boldsymbol{v}$ is in a plane normal to the rotation axis, the Coriolis forces are perpendicular to both the velocity and the rotation axis.

The gravity gradient is another extremely important parameter in a small radius centrifuge. The centrifugal forces generated by rotation depend on the distance to the center of rotation and therefore, there is a force gradient along the centrifuge radius. As an example, when a subject of height h is lying down on a centrifuge of radius r, with her head located at or near the center of rotation and her feet at the rim of the centrifuge, she will experience different gravity levels along her body. The general expression for the gravity gradient is:

$$\text{Gravity gradient} = 1 - \frac{a_{head}}{a_{foot}} = 1 - \frac{\omega^2(r-h)}{\omega^2 r} = \frac{h}{r} \qquad (3)$$

where $(r-h)$ is the radius of rotation of the head. In the extreme case where the head is located at the center of rotation $(r-h)=0$, it will experience no force, and the subject will experience a gravity gradient of 100%.

Many questions regarding the appropriate artificial gravity configuration and parameters still need to be answered. First of all, the level of artificial gravity required to maintain the physiological state of the astronauts is not known. Ground-based bed rest studies suggest that gravity levels up to 2 g at the feet could be useful, in particular if they are combined with exercise [3]. In addition, the tradeoff between angular velocity and radius to generate the desired gravity level needs to be further explored. Furthermore, most of the ground-based studies have been done using long-radius centrifuges. Hence, the physiological effects of the gravity gradient have not been thoroughly investigated [3].

Artificial Gravity Coupled With Exercise in a Short-Radius Centrifuge

Performing exercise during centrifugation in a short-radius centrifuge has several advantages. Exercise during centrifugation may help increase tolerance to acceleration. The physiological stress of the centrifuge may be too high, inducing some degree of orthostatic intolerance. Active exercise during centrifugation activates the leg muscle pumps facilitating the venous return, keeping blood from pooling in the legs and therefore, protecting the astronauts against syncope or fainting [3], [14].

In addition, centrifugation combined with exercise has been shown to be effective in preventing cardiovascular deconditioning [15]–[20]. Few ground-based studies have evaluated the combination of intermittent artificial gravity in a short-radius centrifuge with exercise as a comprehensive countermeasure for long duration spaceflight. One of the most implemented exercise devices used is a cycle ergometer. Greenleaf et al. showed that exercise in a short-radius centrifuge (1.9 m) adds a significant physiological stress that could attenuate orthostatic intolerance [15]. Iwase and his colleagues demonstrated that combining intermittent artificial gravity with ergometric exercise is effective in preventing cardiovascular deconditioning [16], [17]. Yang et al. confirmed the improvement of the cardiovascular function due to combined use of a short-arm centrifuge and aerobic exercise during a one-week training [18]. Katamaya et al. demonstrated that the use of a short-arm centrifuge combined with exercise training is effective in maintaining respiratory and cardiovascular responses to upright exercise during 20 days of -6° Head Down Bed Rest [20]. In addition, researchers have also implemented other types of exercise during short-radius centrifugation, such as squats [21], [22] and stair-steppers [4], demonstrating the feasibility of these types of exercise protocols in hypergravity rotating environments.

Confounding Factors

Although several studies have investigated the effectiveness of artificial gravity exposure, these studies have been done in different conditions, making it very difficult to get clear conclusions about the parameters needed to maintain physiological conditioning in space. Confounding factors include centrifuge configuration, exposure time, gravity level, gravity gradient, and use/intensity of exercise. Table 1 summarizes the short-radius centrifuges currently operational. This table gives an indication of the variety of centrifuge designs from study to study.

Kaderka et al. identified differences in research design among 14 AG studies used in a meta-analysis performed to compare the efficacy of AG with more traditional countermeasures. Differences included centrifuge configuration, subject selection criteria, experiment protocol (i.e. time of exposure, study duration, g level, gravity gradient, etc.) and choice of dependent measures [14].

These findings highlight the need for more exhaustive AG studies, blocking some of the confounding factors. In addition, more standardized approaches to AG studies among the international community are needed, fostering collaboration between the different facilities around the world.

The purpose of this research is to take a first step towards a full trade space exploration of the most important artificial gravity parameters, analyzing through experimentation, modeling, and simulations the effects of different artificial gravity and exercise workload levels on the cardiovascular system using the MIT Compact Radius Centrifuge.

Table 1 - Existing short-radius centrifuges [3], [8]

Name	Location	Radius	Max g	Mode	Exercise
Space Cycle	UC Irvine, Irvine, USA	1-2 m	5.0 g	Gondola	Cycling /Squats
Short Arm Human Centrifuge	Nihon U, Nishi-Funabashi, Japan	1.8 m	3.0 g	Gondola	N/A
NASA Ames Human Powered Centrifuge	Moffet Field, USA	1.9 m	5.0 g	Bed	Cycling
Short-Radius Human Centrifuge	Nagoya U, Japan	1.4 m	2.0 g	Chair	Cycling
MIT Compact Radius Centrifuge	MIT, Cambridge, USA	2.0 m	1.8 g	Bed	Cycling
Short-Arm Centrifuge	Fourth Military Medical U, Xi’An, China	2.0 m	4.0 g	Chair	Cycling
Short-Radius Centrifuge	IBMP, Moscow, Russia	2.5 m	2.0 g	Bed	Cycling
DLR Short-Radius Centrifuge	DLR, Cologne, Germany	2.8 m	5.0 g	Bed/Chair	N/A
ESA Short-Arm Centrifuge	MEDES, Toulouse, France	2.9 m	3.5 g	Bed/Chair	N/A
EnviFuge	DLR, Cologne, Germany	3.8 m	6.0g	Bed	Cycling

3. EXPERIMENTAL METHODS

Centrifuge Configuration

Human experiments are conducted at the Man Vehicle Laboratory (Massachusetts Institute of Technology) using a new configuration of the MIT Compact-Radius Centrifuge (CRC). The facility has undergone major upgrades, which were motivated by the 2011 Artificial Gravity with Ergometric Exercise (AGREE) project [23], in order to be compatible with a future use in the International Space Station. In particular, the radius has been constrained to 1.4 meters, and the subject has been positioned sideways facing the direction of movement. This positioning also avoids lateral knee movements due to Coriolis forces [8]. A detailed description of the MIT CRC modifications can be found here [24].

An ergometer exercise device (Lode BV, Groningen, Netherlands) has also been incorporated into the centrifuge and subjects can cycle at the same time as they are being centrifuged. This same exercise device is also being used on centrifuges at the Institute for Biomedical Problems (IBMP), the German Aerospace Center (DLR), and NASA Ames, opening the door to future research collaborations. The Lode Angio ergometer includes the Lode Ergometry Manager (LEM) software package to control the ergometer from the on-board computer, allowing the experimenter to create custom exercise protocols, enter subject data, and save/export results for further analysis. Figure 3 shows an individual on the MIT CRC final configuration.

Experimental Design

One subject (male, 23 years old) was tested under three different levels of AG: 0g (or no rotation), 1g, and 1.4 g (AG levels measured at the feet). Each AG level was tested in a different day of the same calendar week. In addition, all three centrifuge tests were scheduled in the morning, and the subject was instructed not to drink caffeine or do exercise prior to the test.

Figure 3: MIT Compact Radius Centrifuge

The subject was positioned in the centrifuge with the head near the center of rotation, and he was secured with a three-point seat-belt. A wireless camera mounted on the centrifuge monitors the facial expression of the subject for any signs of discomfort or presyncope.

At each AG level, the subject completed an ergometer exercise protocol including three different exercise intensities: warm up (3 minutes at 25W), moderate (5 minutes at 50W) and vigorous (5 min at 100W). Transitions were included between phases to facilitate the changes between workload levels. In addition, extra time was added at the beginning and at the end of exercise to capture the initial state of the subject, the spin-up and spin down process, and the recovery phase after exercise. The entire protocol lasted 25 min and is depicted in Figure 4.

Cardiovascular Measurements

Cardiovascular variables were continuously recorded using a ccNexfin monitor (Edwards Lifescience). This non-invasive system monitors beat-to-beat cardiovascular parameters derived from the arterial pressure waveform. A finger cuff is used to continuously monitor changes in finger arterial volume using photo-plethysmography techniques [25], [26]. The subject was instructed to keep his hand at the heart level to avoid changes in blood pressure readings due to hydrostatic effects caused by the strong gravity gradient. Figure 3 shows the positioning held by the subject during the centrifuge experiments. The ccNexfin monitor can be appreciated at the bottom left of the figure, as well as the subject's hand position at the heart level.

Cardiovascular recordings include heart rate (HR), systolic (SBP), diastolic (DBP), and mean blood pressure (MBP), stroke volume (SV), cardiac output (CO), systemic vascular resistance (SVR), and pulse pressure (PP). Raw signals are filtered using a low-pass Butterworth filter, both in forward and reverse directions.

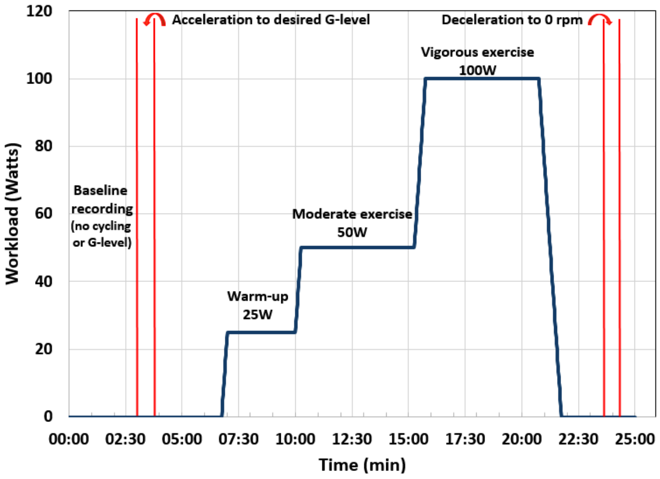


Figure 4: Exercise protocol

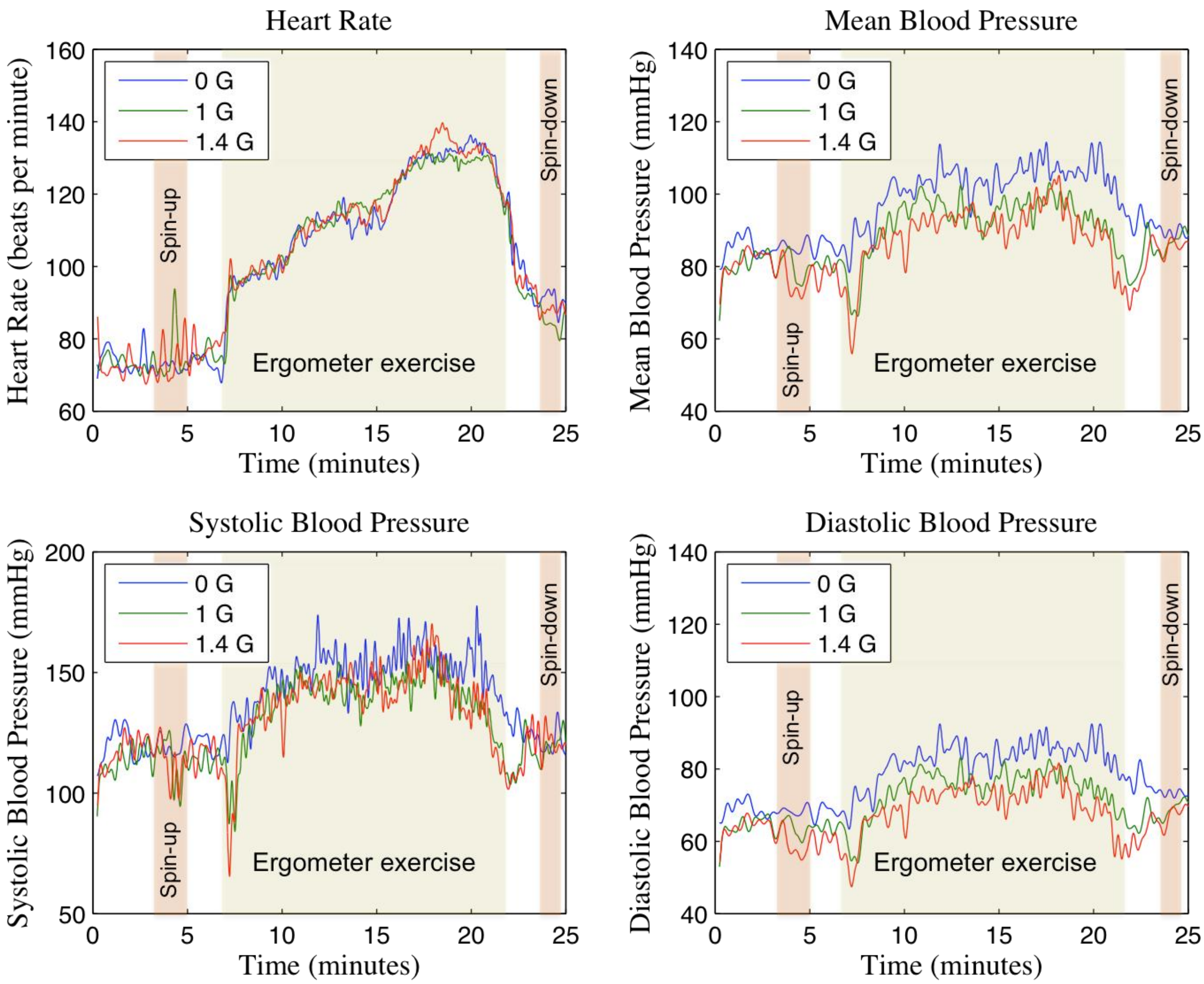


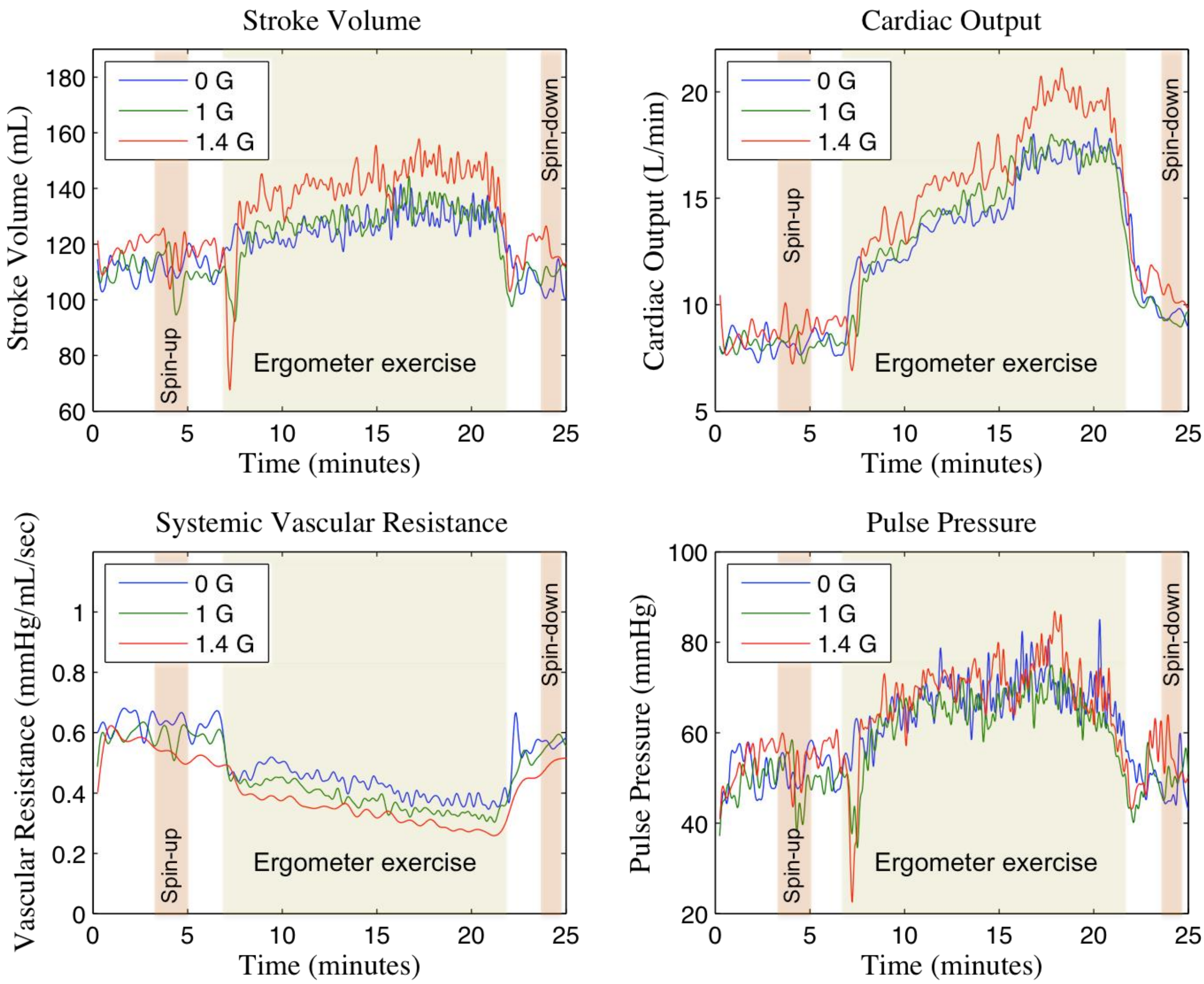
Figure 5 – Cardiovascular variables (Heart rate, Mean Blood Pressure, Systolic Blood Pressure, and Diastolic Blood Pressure) from one subject during the 25-min protocol recorded at each one of the three gravity levels: 0g (blue line), 1g (green line), and 1.4g (red line). Gravity levels are measured at the feet.

4. RESULTS

Cardiovascular variables gathered during the centrifuge runs are shown in Figure 5 (heart rate, mean blood pressure, systolic blood pressure, and diastolic blood pressure) and Figure 6 (stroke volume, cardiac output, systemic vascular resistance, and pulse pressure). Each figure contains three cardiovascular responses corresponding to the three AG level experienced: 0g (blue line), 1g (green line), and 1.4g (red line). In addition, the spin-up phase (starting at T = 3 min) and spin-down phase (starting at T = 23:45 min), as well as the exercise phase (from T = 6:45 min, to T = 21:45 min) are also indicated in all figures.

Spin-up phase

During the spin-up phase, the artificial gravity force created by centrifugation starts pulling the blood to the lower part of the body. Initially, this causes a slight decrease in blood pressure that can be appreciated in Figure 5, both in systolic and diastolic blood pressure. This causes a decrease in mean blood pressure, which we take here as MBP = DBP +1/3(SBP−DBP). This reduction is higher at the higher AG level (1.4g), and is non-existent when the subject is not being centrifuged (0g). Stroke volume, and pulse pressure (defined as PP = SBP – DBP), also show a transient reduction that can be appreciated in Figure 6.


Stroke Volume

Cardiac Output

Systemic Vascular Resistance

Pulse Pressure

Figure 6 – Cardiovascular variables (Stroke Volume, Cardiac Output, Systemic Vascular Resistance, and Pulse Pressure) from one subject during the 25-min protocol recorded at each one of the three gravity levels: 0g (blue line), 1g (green line), and 1.4g (red line). Gravity levels are measured at the feet.

When there is a significant blood pressure drop, the autonomic nervous system increases sympathetic stimulation triggered by the arterial baroreceptors, which are stretch receptors located in the carotid sinus and the aortic arch areas. The baroreceptors are the primary receptors for short-term control of the cardiovascular system. Consequences include an increase in heart rate and contractility of the heart to maintain the appropriate amount of blood flow to all the organs, in particular the brain (CO = SV×HR). In our experiment, several heart rate bursts can be observed during the spin-up phase at 1g and 1.4g, followed by a more continuous heart rate increase in the 1.4g condition phase (between T = 5 min and T = 6:45 min), due to the cardiovascular response to a higher artificial gravity environment (Figure 5, top left).

The cardiac output, displayed in Figure 6 (top right), does not show a net change from the spin-up phase until the onset of exercise. In the 1.4g condition, it presents some oscillations following the regulatory effect of the sympathetic stimulation, in particular the changes experienced by the heart rate.

Exercise phase

Important physiologic changes occur during exercise. The significant metabolic demand at the onset of exercise causes the blood pressure to suddenly decrease, causing the stroke volume to be reduced immediately, particularly at the most demanding 1.4g condition.

As expected, the heart rate increases rapidly at the beginning of the exercise phase. In addition, the heart rate experiences significant increases right after exercise workload transitions (from 25W to 50 W at T = 10min, and from 50W to 100W at T=15:15 min). Blood pressure also increases during exercise, particularly in the 0g condition. In this condition, the subject is not being centrifuged and therefore, there is not artificial gravity to pull blood towards his legs. The higher the artificial gravity force, the stronger the blood pulling to the legs, and therefore, the lower the blood pressure, as can be appreciated in Figure 6.

Stroke volume and cardiac output also increase according to exercise workload level, particularly cardiac output in which the three exercise phases can be distinguished (Figure 6, top right). Results indicate that these variables also increase with the artificial gravity level during the ergometer exercise. Thus, in the 1.4g condition, stroke volume and cardiac output show the largest changes across all exercise intensities. Recordings at 1g and 0g do not differ as much compared to the 1.4g data, but a slight difference can still be appreciated between the two conditions.

Exercise increases muscle metabolism and, even though the level of sympathetic stimulation is high, vascular smooth muscle in the exercise muscles dilates. As a consequence, the vascular resistance decreases as seen in Figure 6 (bottom left).

5. DISCUSSION

Exercise is a stressful condition to the cardiovascular system. During vigorous exercise, the cardiac output can increase to 6 or 7 times the normal values [27]. Muscle activation increases mean systemic pressure and therefore venous return. Autonomic stimulation increases heart rate and heart contractility. As a consequence, cardiac output also increases to meet the new metabolic demands imposed by the exercise activity. In addition, the higher muscle metabolism causes vasodilatation and the peripheral resistance decreases. These cardiovascular changes due to exercise are well captured in the cardiovascular data collected during our centrifuge experiment. The three exercise phases corresponding to the different exercise intensities (warm up at 25W, moderate exercise at 50W, and vigorous exercise at 100W) are highly recognizable in the heart rate and cardiac output data. Changes in these variables are the primary mechanism for the central nervous system to regulate the cardiovascular system.

The application of artificial gravity introduces a new stress condition that the cardiovascular system needs to overcome in order to assure the appropriate amount of blood flow to all parts of the body. This additional stress is reflected on the blood pressure drop that occurs when the subject is first exposed to artificial gravity. The higher the artificial gravity, the higher the cardiovascular stress, and therefore, the larger the initial blood pressure drop. Data collected during this experiment suggest that, although the heart rate doesn't seem to change between artificial gravity conditions, the stroke volume, and as a consequence, the cardiac output, increase with AG level to maintain a proper cardiovascular regulation. Cardiac output data gathered at 1.4g differ substantially from the other two conditions (0g and 1g), although slight differences can still be appreciated between these conditions.

It is important to acknowledge the strong gravity gradient when interpreting these results. The subject's head is located at the center of rotation and, as stated in previous sections, the gravity level is being measured at the feet. Cardiovascular sensors, in particular the baroreceptors, are located in the upper part of the body, and therefore, they are not exposed to gravitational changes as large as the feet or, more in general, the lower part of the body. Data show that significant cardiovascular changes (particularly in cardiac output) occur when artificial gravity at the feet is 1.4g, which corresponds to an artificial gravity level around 0.38g at the baroreceptors (assuming that they are located at 30 cm from the center of rotation). Similarly, when the feet are exposed to 1g, the baroreceptors are subjected to just 0.28g. This fact may explain why results concerning the 0g and 1g conditions do not differ too much, even though there is a considerable difference in the g level applied at the feet. On the other hand, the effects of the gravity gradient on the cardiovascular regulation remain an open and particularly interesting question, and is the object of our future research efforts.

6. CONCLUSION

Artificial gravity is a potential multisystem countermeasure for human deconditioning in weightlessness conditions. A new configuration of the MIT compact radius centrifuge is currently in use to study cardiovascular responses under artificial gravity and ergometer exercise. The MIT centrifuge has experienced several modifications in order to be compatible with a future use in the International Space Station. In particular, its radius has been constrained to 1.4 meters and the subject has been positioned sideways facing the direction of movement. (This positioning also avoids lateral knee movements due to Coriolis forces.)

One subject has completed the same ergometer exercise protocol under three different artificial gravity conditions: 0g (no centrifugation), 1g, and 1.4g (where g levels are measured at the feet). Results show that the amplitude of the cardiovascular responses adapts to the stress level generated not only by the exercise intensity, but also by the artificial gravity level to which the subject is exposed. In particular, cardiac output increases with the g level, increasing the overall cardiovascular activity and therefore, suggesting that artificial gravity may be effective as a countermeasure against cardiovascular deconditioning in space.

Future work includes additional human testing to expand our results and get statistical significance across artificial gravity conditions. In addition to the experimental work, we are developing a lumped-parameter cardiovascular model in order to capture the cardiovascular responses under centrifugation and ergometer exercise. As mentioned in previous paragraphs, of particular interest is the effect caused by the 100% gravity gradient present in such a short-radius centrifuge, where the head is positioned at the center of rotation. The effect of different gravity gradients will be explored as well as other parameters such as gravity level, centrifuge radius, exercise intensity, and actual level of deconditioning.

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