Self-Generated Lower Body Negative Pressure as a No-Power Countermeasure for Deep Space

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ABSTRACT

The absence of gravitational forces experienced during spaceflight produces headward fluid shifts which probably cause Spaceflight Associated Neuro-Ocular Syndrome (SANS). In order to counteract these fluid shifts and prevent SANS, especially when power is limited and a human centrifuge is unavailable, other strategies are needed. One possible strategy is the use of self-generated, lower body negative pressure (LBNP) which meets the low power and safety requirements of deep-space missions. **PURPOSE:** In this study we explored acute physiologic responses to self-generated LBNP in a horizontal model of simulated microgravity. **METHODS:** Participants of the study were tested during static 25 mmHg LBNP and compared dynamic self-generating 25 mmHg LBNP chamber as well as upright and supine postures without LBNP. After informed, written consent was obtained, five female and six male subjects' heart rates and blood pressures were recorded along with cross sectional areas (CSA) of left and right internal jugular veins (IJV) by quantitative ultrasound. **RESULTS:** Upright IJV CSAs increased significantly when compared to both static and dynamic LBNP. There was a large standard error in the supine posture and no significant differences when comparing the supine posture to the upright posture or either LBNP condition. However, static LBNP reduced IJV CSA by 70% when compared to the supine posture, while dynamic LBNP reduced IJV cross sectional area by 62% compared to supine posture. **CONCLUSION:** The administered self-generated LBNP and supine LBNP tests and analyses demonstrated that the dynamic, self-generated LBNP may have a similar impact on reducing IJV CSA when compared to traditional static LBNP, thus warranting longer-term tests of self-generated LBNP. In summary, our results suggest that self-generated LBNP at 25 mmHg is as a low-mass, low-volume, unpowered replacement for traditional LBNP hardware (for example, Chibis Suit) during deep-space missions.

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EXPANDED ABSTRACT

BACKGROUND/PURPOSE:

Body fluids shift headward in a microgravity environment. The cephalad fluid shift may contribute to the development of Spaceflight Associated Neuro-ocular Syndrome (SANS) and other spaceflight-related adaptations [1]. While on Earth, postural changes generate hydrostatic forces which alter intracranial pressure (ICP). In microgravity, astronauts experience a headward fluid shift because there is no gravitational vector to produce a hydrostatic gradient [2]. This leads to a mild, but chronically elevated ICP which generates a gradient between ICP and intraocular pressure (IOP) [3]. The pressure gradient may at least partially underlie the pathogenesis of SANS [4]. In 2011, Mader et al. published a landmark paper that identified ocular pathologies in astronauts after long-duration spaceflight [10]. Mader et al. were the first to hypothesize that cephalad fluid shifts and venous congestion may be the mechanism behind ocular structural and functional changes. The cephalad fluid shift may also affect venous flow, specifically affecting volume and outflow in the internal jugular vein (IJV) which is responsible for venous outflow from the head [11]. LBNP offers a potential countermeasure to reverse cephalad fluid shifts in microgravity. Researchers explored this concept and found LBNP effectively reduced ICP, IOP, and internal jugular vein cross-sectional area in simulated microgravity [4], [12]– [14]. More recent publications indicate daily LBNP exposure reduces choroid thickening observed in HDT [15]. However, in 2021, Marshall-Goebel et al. found LBNP reduced IOP in astronauts during spaceflight but did not reduce choroidal thickening [16]. While LBNP did not reduce choroid thickening in astronauts, Marshall-Goebel et al. found LBNP reduced internal jugular vein cross-sectional area and restored stagnant or reversed flow in the IJV [17]. While LBNP does not address all associated pathologies, it may be an integral countermeasure to protect against SANS.

However, LBNP chambers are large, heavy, and electrically powered. Volume, mass, and electrical power are limited resources in spaceflight. A low mass, collapsible, unpowered LBNP device can minimize the impact on resources [18]. The purpose of this study is to evaluate a self-generated LBNP device and to compare acute physiological responses between a traditional, static LBNP chamber and a self-generated LBNP chamber. We hypothesize that self-generated LBNP will produce similar physiological responses when compared to a traditional static LBNP chamber.

METHODS:

Subjects

Eleven healthy subjects (6 males, 5 females; avg. weight 142.8 lbs.; avg. height 67.2 inches; and avg. waist circumference 31.4 inches) participated in self-generated LBNP exercise along with static trials of LBNP. As a group, subjects were of average fitness based on their average height and weight. Participants were selected for the trial based on height and BMI. Subjects were between 5’1” and 6’4” with a BMI of less than 30 kg/m^2. Subjects gave informed, voluntary consent to participate in the study.

Device Descriptions

SELF Device

The self-generating lower body negative pressure device (SELF) consists of a collapsible cylindrical chamber that covers the user’s lower limbs and a neoprene skirt fitted around the waist to provide a seal (Figure 1). A belt is used to ensure an adequate seal around the subject. Air leakage is minimized using gaskets and vinyl cement. 24” metal rings maintain the structure of the chamber, allowing it to expand and contract lengthwise.

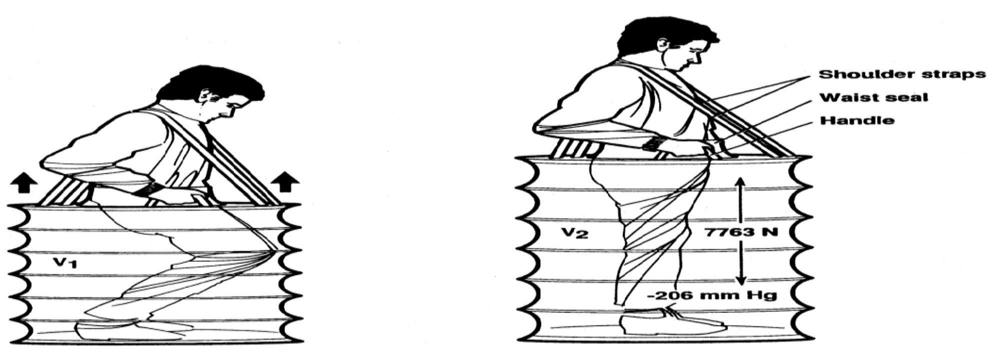

Figure 1: Diagram of the SELF. The user operates adjustable valves near the handles to adjust airflow. The user closes the valves while pushing the bottom plate with their feet to expand the chamber (left). Volume within the sealed chamber increases and pressure consequently decreases to effectively generate negative pressures (right). Opening the valves equalizes the pressure. Subjects can then pull both legs back before closing the valves and repeating the procedure.

Subjects use the SELF device while in a supine posture. The upper body is supported by a stationary, raised platform. The bottom metal plate of the chamber is positioned over a rollable platform, allowing the chamber to expand and collapse in the supine posture. The top plate of the chamber is attached to a vest which distributes loads evenly across subjects' shoulders.

Static LBNP Chamber

The static LBNP chamber consists of a stationary, rigid chamber (Figure 2). A neoprene skirt maintains a seal around the waist. A belt and shoulder straps were used to ensure a tight seal. Subjects were in the supine posture with their lower body within the chamber and their upper body and head supported by a padded platform. A vacuum attached to the chamber generated the negative pressure.

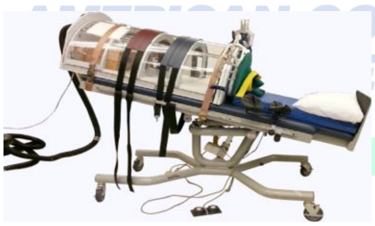

Figure 2: The static LBNP chamber. Subjects place their lower body within the chamber. A powered vacuum attaches to the chamber to generate negative pressure. The chamber is positioned horizontally (not tilted) with the subject in a supine posture.*

<u>Data Acquisition</u>

Cross-sectional images of both the left and right internal jugular vein were obtained via ultrasonography (Phillips, Amsterdam, Netherlands). Images were taken in triplicate just caudal to the bifurcation of the common carotid artery. Measurements of the IJV CSA were manually delineated using an image computing software (3D Slicer) by two independent sonographers. For each set of images, sonographers identified and analyzed the smallest IJV CSA just before a carotid pulse. The Finometer system (Finapres, Enschede, Netherlands) monitored and recorded subjects' heart rate and blood pressure throughout the experiment.

Protocol

Baseline measurements of heart rate, blood pressure, and IJV CSA were recorded after the subject gave informed consent. Trial conditions included 10 minutes of seated posture, 10 minutes of supine posture, 15 minutes of static LBNP in supine posture, and 15 minutes of dynamic SELF LBNP in supine posture. Negative pressure conditions were carried out at 25 mmHg. The horizontal supine posture was used as an analog for microgravity. The order of conditions was randomly assigned for each subject and all trials were completed during a 1.5-hour, single day study. During the 10-minute supine and seated upright conditions, subjects remained stationary in each respective posture without negative pressure. During static LBNP, subjects were positioned supine with their lower extremities inside the LBNP chamber and remained stationary while constant negative pressure was generated by a vacuum. Dynamic SELF exercise was also performed in supine posture. Subjects performed repetitive leg press movements in the SELF device, generating negative pressure when the adjustable valves were closed during leg extension. Subjects were instructed to maintain extension for as long as possible, until leaks caused negative pressure to drop to approximately -23 mmHg. At this point, subjects opened the adjustable valves of the chamber to equilibrate pressure inside the device. Subjects returned both legs into a flexed position and began the dynamic process again. This procedure was repeated for the duration of the trial. Subjects practiced the dynamic motions before the trial to ensure pressure consistently reached -25 mmHg.

Statistical Analysis

Statistical analyses were performed using SPSS version 27 (IBM, Chicago, IL). Statistically significant results were determined with $\alpha = 0.05$. The longitudinal study was analyzed using repeated measures ANOVA. Our data violated the assumption of sphericity and were corrected using the most conservative lower bound. We utilized Bonferroni correction to account for multiple comparisons. P-values less than 0.05 were considered significant.

RESULTS:

IJV CSA measurements at different time points were not significantly different. Our data suggest IJV CSA does not change over the course of 15 minutes of static or dynamic LBNP. Similarly, we did not observe trends or significant differences when comparing IJV CSA responses between the left and right sides, or between men and women. Because there were no trends or significant differences based on time, gender, or side, data were combined into 4 conditions: Upright, supine, static LBNP, and SELF LBNP. Data are presented in Table 1.

Condition	Mean	Std. Error
Upright	7.415	1.115
Supine	56.264	15.214
Static LBNP	16.933	2.720
SELF LBNP	21.570	3.934

Table 1

Pairwise comparisons indicate significant differences between upright posture and static LBNP as well as upright posture and SELF LBNP (Figure 3). The supine condition was not significantly different when compared to any other condition. Static and SELF LBNP were not significantly different.

DISCUSSIONCONCLUSION:

Our results indicate there is a significant difference between the upright posture and static LBNP conditions. These findings are in accordance with previous studies in which LBNP reduced ICP in a supine posture, but not to upright levels [3]. The IJV CSA was slightly larger in SELF LBNP when compared to static LBNP, but the difference was not significant. Our data suggest that both static and SELF LBNP have similar effects on IJV CSA. Despite the established efficacy of LBNP at reducing IJV CSA, our data do not indicate either LBNP condition significantly reduced IJV CSA when compared to the supine condition. Additionally, the supine condition was not significantly different when compared to the upright condition. There are several factors which may have reduced significance. We had a small number of subjects with N=11. Variances were not equal, requiring large correction factors. Shorter subjects could not expand the chamber as much as taller subjects and struggled to reach 25 mmHg. Finally, there was a very large variability in IJV CSA in the supine posture between subjects. These factors increased the standard error, and in turn reduced power and significance. While neither LBNP condition reached statistical significance, both conditions demonstrated trends toward reducing IJV CSA when compared to supine posture. Previous studies established the efficacy of static LBNP at reducing IJV CSA and ICP. Because both the static and SELF LBNP conditions reduced IJV CSA to a similar extent, our results suggest dynamic, self-generated LBNP may have a similar effect of reducing IJV CSA, and potentially ICP, when compared to traditional static LBNP. These results warrant further investigation into self-generated LBNP as it may be a low-mass, low-volume, unpowered replacement for traditional LBNP chambers in long-duration spaceflight.

References

[1] L.-F. Zhang and A. R. Hargens, "Spaceflight-Induced Intracranial Hypertension and Visual Impairment: Pathophysiology and Countermeasures," *Physiol Rev*, vol. 98, pp. 59–87, 2018, doi: 10.1152/physrev.00017.2016.-Visual.

[2] A. R. Hargens and S. Richardson, "Cardiovascular adaptations, fluid shifts, and countermeasures related to space flight," *Respir. Physiol. Neurobiol.*, vol. 169, pp. 30–33, 2009, doi: 10.1016/j.resp.2009.07.005.

[3] J. S. Lawley *et al.*, "Effect of gravity and microgravity on intracranial pressure," *Authors. J. Physiol. C*, vol. 595, pp. 2115–2127, 2017, doi: 10.1113/JP273557.

[4] L. G. Petersen *et al.*, "Lower body negative pressure to safely reduce intracranial pressure," *J. Physiol.*, vol. 597, no. 1, pp. 237–248, Jan. 2019, doi: 10.1113/JP276557.

[5] A. R. Hargens, R. T. Whalen, D. E. Watenpaugh, D. F. Schwandt, and L. P. Krock, "Lower body negative pressure to provide load bearing in space," *Aviat. Sp. Environ. Med.*, vol. 62, no. 10, pp. 934–937, 1991.

[6] J. B. Charles and C. M. Lathers, "Summary of Lower Body Negative Pressure Experiments During Space Flight," *J. Clin. Pharmacol.*, vol. 34, no. 6, pp. 571–583, Jun. 1994, doi: 10.1002/j.1552-4604.1994.tb02009.x.

[7] I. B. Kozlovskaya, A. I. Grigoriev, and V. I. Stepantzov, "Countermeasure of the Negative Effects of Weightlessness of Physical Systems in Long-term Space Flights," 1995.

[8] K. I. Iwasaki *et al.*, "Human cerebral autoregulation before, during and after spaceflight," *J. Physiol.*, vol. 579, no. 3, pp. 799–810, Mar. 2007, doi: 10.1113/jphysiol.2006.119636.

[9] B. D. Levine *et al.*, "Human muscle sympathetic neural and haemodynamic responses to tilt following spaceflight," *J. Physiol.*, vol. 538, no. 1, pp. 331–340, Jan. 2002, doi: 10.1113/jphysiol.2001.012575.

[10] T. H. Mader *et al.*, "Optic Disc Edema, Globe Flattening, Choroidal Folds, and Hyperopic Shifts Observed in Astronauts after Long-duration Space Flight," *Ophthalmology*, vol. 118, pp. 2058–2069, 2011, doi: 10.1016/j.ophtha.2011.06.021.

[11] P. Arbeille, · R Provost, · K Zuj, and · N Vincent, "Measurements of jugular, portal, femoral, and calf vein cross-sectional area for the assessment of venous blood redistribution with long duration spaceflight (Vessel Imaging Experiment)," *Eur. J. Appl. Physiol.*, vol. 115, pp. 2099–2106, 2015, doi: 10.1007/s00421-015-3189-6.

[12] B. R. Macias, J. H. K. Liu, N. Grande-Gutierrez, and A. R. Hargens, "Intraocular and intracranial

pressures during head-down tilt with lower body negative pressure," *Aerosp. Med. Hum. Perform.*, vol. 86, no. 1, pp. 3–7, 2015, doi: 10.3357/AMHP.4044.2015.

[13] W. Watkins, A. R. Hargens, S. Seidl, E. M. Clary, and B. R. Macias, "Lower-body negative pressure decreases noninvasively measured intracranial pressure and internal jugular vein cross-sectional area during head-down tilt," *J Appl Physiol*, vol. 123, pp. 260–266, 2017, doi: 10.1152/japplphysiol.00091.2017.-Long.

[14] K. Marshall-Goebel *et al.*, "Mechanical Countermeasures to Headward Fluid Shifts," *J. Appl. Physiol.*, p. japplphysiol.00863.2020, Apr. 2021, doi: 10.1152/japplphysiol.00863.2020.

[15] J. S. Lawley *et al.*, "Daily generation of a footward fluid shift attenuates ocular changes associated with head-down tilt bed rest," *J. Appl. Physiol.*, vol. 129, no. 5, pp. 1220–1231, 2020, doi: 10.1152/japplphysiol.00250.2020.

[16] S. H. Greenwald *et al.*, "Intraocular pressure and choroidal thickness respond differently to lower body negative pressure during spaceflight," 2021.

[17] K. Marshall-Goebel *et al.*, "Assessment of Jugular Venous Blood Flow Stasis and Thrombosis During Spaceflight," *JAMA Netw. open*, vol. 2, no. 11, p. e1915011, Nov. 2019, doi: 10.1001/jamanetworkopen.2019.15011.

[18] D. E. Watenpaugh, R. E. Ballard, G. A. Breit, and A. R. Hargens, "Self-Generated Lower Body Negative Pressure Exercise," *Aviat. Sp. Environ. Med.*, vol. 70, no. 5, pp. 522–526, 1999.