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REVIEW ARTICLE

REVIEW OF LOWER BODY NEGATIVE PRESSURE APPLICATIONS TO SIMULATE +GZ-INDUCED CARDIOVASCULAR STRAIN: RESEARCH HISTORY

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Introduction: In the paper, a general overview of the development and applications of lower body negative pressure (LBNP) technology have been provided. The article also describes the LBNP designs used to investigate the relationship between tolerance to negative pressure around the lower body and tolerance to acceleration (+Gz).

Methods: A systematic review of the literature on the development and application of LBNP in the scope not limited to the time or geography framework was explored. Searches were performed using predefined keywords and filters for LBNP (e.g., aerospace, medicine, cardiovascular, space, acceleration, Gz). Databases such as PubMed, IEEE Xplore, ScienceDirect, and others relevant to this field of study were selected for the search.

Results: The results of the review were organized by thematic categories (LBNP development, applications and use to simulate +Gz-induced cardiovascular strain). Syntheses of the results are presented, highlighting key themes and insights.

Discussion and Conclusion: The use of LBNP to simulate cardiovascular strain, typically induced by positive G forces (+Gz) in fighter jet flight, has played an important role in our understanding of the cardiovascular response to gravitational forces. This knowledge not only benefits pilots, but also has wider implications for healthcare and working conditions where individuals may face similar physiological challenges. Although numerous reports support the development of LBNP for space mission applications, there is no evidence for the use of LBNP to simulate accelerations greater than +1 Gz over the past two decades. However, further research in this area is still warranted.

Keywords: aviation medicine, LBNP, negative pressure, acceleration stress

Figures: 6 • **Tables:** 4 • **References:** 79 • **Full-text PDF:** http://www.pjambp.com • **Copyright** © 2023 Polish Aviation Medicine Society, ul. Krasińskiego 54/56, 01-755 Warsaw, license WIML • **Indexation:** Index Copernicus, Polish Ministry of Science and Higher Education

INTRODUCTION

Lower Body Negative Pressure (LBNP) is a physiological technique which involves creating a negative pressure (pressure below atmospheric level) around the lower extremities. It is often used in research and medical settings to study the cardiovascular and physiological responses that occur under conditions similar to those encountered during upright posture and gravitational stress [71,77]. The primary purpose of LBNP is to investigate how the body responds to changes in pressure, particularly in relation to blood circulation. When a person is in an upright position (Fig. 1), gravity causes blood to pool in the lower extremities, which can lead to a decrease in venous return to the heart (orthostatic intolerance research). LBNP can simulate this effect by creating a negative pressure around the lower body, redistributing blood and inducing physiological changes [25,26].

During LBNP, the individual lies supine with their legs positioned in the chamber up to the level of the iliac crest (Fig. 1). The air pressure within the chamber is reduced using a vacuum pump. As per the principles of fluid dynamics, blood flows from the higher pressure region (the upper body, which is outside the chamber) towards the lower pressure region (the lower abdomen and legs within the chamber).

The applied negative pressure increases the transmural pressure in the blood vessels of the lower part of the body and stops some of the blood in this venous system [25]. This increase mainly affects the superficial blood vessels, especially the veins, because of the fragility of their walls [41]. The resulting increase in venous bed volume leads to a general reduction in venous pressure, including central venous pressure. A reduction in central venous pressure leads to a consequent reduction in left ventricular end-diastolic volume, which in turn leads to a reduction in cardiac stroke volume [24–26,61].

In recent years, there has been a significant increase in research interest using LBNP [2,8,31,63]. Although several reviews have already been conducted on these studies [16,31], the authors of the presented paper decided to focus on a review of LBNP designs in applications to simulate +Gz-induced cardiovascular strain.

METHODS

To comprehensively identify, evaluate, and synthesize all available research evidence on LBNP applications to simulate +Gz-induced cardiovascular strain we conducted a systematic literature review. This method involves a structured and rigorous approach to literature searching, screening, and selecting articles based on predefined criteria.

Databases such as PubMed, IEEE Xplore, ScienceDirect, and other subject-specific databases were selected for the search. Searches were performed using predefined keyword ‘LBNP’ or phrase ‘lower body negative pressure’. The filters applied were not limited to publication date range, language and study type. The inclusion criteria included studies that addressed at least one of the following issues ‘aerospace’, ‘medicine’, ‘cardiovascular’, ‘space’, ‘acceleration’, and ‘Gz’. Exclu-

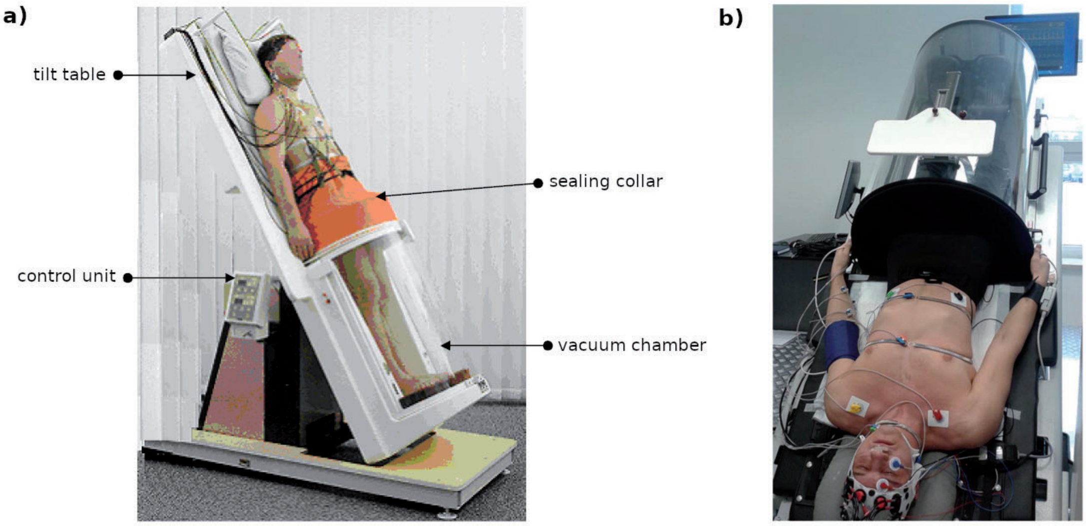

Fig. 1. The lower body negative pressure (LBNP) chamber connected to both the old (a) [70], and new (b) [17] versions of the tilt table developed in Military Institute of Aviation Medicine (Warsaw, Poland) used under CC BY 4.0 [15] .

Tab. 1. Number of papers found in the databases.

Keyword	phrase	Number of papers found in the database		
		PubMed	IEEE Xplore	ScienceDirect
LBNP or 'lower body negative pressure'	-	3529	45	646
	medicine	1309	29	418
	cardiovascular	1565	19	528
	aerospace	189	6	95
	space	464	8	324
	acceleration	78	2	140
	Gz	49	5	43

sion criteria included non-peer-reviewed articles. The results of the search, conducted according to the specified criterion across the three databases, are presented in Tab. 1. After a comprehensive search, 56 papers were identified for analysis.

LBNP development

The concept of using negative pressure to study and counteract the physiological effects of microgravity dates back to the 1960s and 1970s when space agencies like NASA began to explore the challenges of extended space travel. Researchers recognized the importance of understanding how the lack of gravity could impact the cardiovascular system. LBNP technology gained more attention in the 1980s when it was developed and implemented for use in space missions. It became a part of the countermeasures against the negative effects of prolonged weightlessness experienced by astronauts during space travel. LBNP devices were incorporated into space shuttles and space stations to help maintain astronauts' cardiovascular health. The benefits of LBNP were not limited to space travel. Researchers and medical professionals began exploring its applications on Earth for studying cardiovascular responses, orthostatic intolerance, and other conditions. LBNP was utilized in various research settings to simulate the physiological effects of gravity on the cardiovascular system. In aerospace medicine it is used for training astronauts, understanding cardiovascular deconditioning in microgravity, and developing countermeasures to mitigate the health risks associated with space travel [78]. Beyond aerospace, LBNP technology has found applications in clinical settings and rehabilitation. Researchers have explored its potential for improving orthostatic tolerance in individuals with conditions like postural orthostatic tachycardia syndrome and for enhancing cardiovascular fitness in patients with various health conditions.

The findings of the literature review on LBNP devices and the observations made by scientists during research using this technology are presented in Tab. 2.

Tab. 2. The development of LBNP applications [31].

Year	Researchers	Findings
1962	Graveline [32]	The first prototype LBNP device was developed and used for spaceflight-related research. The -30 mmHg LBNP was shown to induce cardiovascular responses similar to those that seen when standing upright at 1G.
1963	Greenfield et al. [33] Brown et al. [7]	The effects of sudden LBNP-induced overload on the cardiovascular system were observed.
1965-1969	Stevens and Lamb [74]	Use of LBNP to assess orthostatic intolerance. LBNP has been shown to have advantages over the tilt table test, and has been shown to improve orthostatic tolerance in bedridden patients.
1969	Musgrave et al. [60]	LBNP of -40 mmHg in the supine position induces similar changes in lower limb blood volume to those occurring during standing. It was observed that the lack of stimulation of the carotid baroreceptors during LBNP means that more negative pressure is required to induce the same cardiac responses as during upright standing.
1971	Musgrave et al. [59]	It was observed that the body responses evoked by a 70° tilt were similar to those evoked by an LBNP of -40 mmHg (in the supine position).
1971	Gazenko et al. [28]	An LBNP was used in flight. Subsequently, a Chibis-LBNP suit was developed.
1974	Berry [5]	LBNP was used before and after spaceflight (the Apollo programme) to investigate orthostatic intolerance.
1977	Johnson et al. [39]	LBNP was found to be a good predictor of orthostatic intolerance after spaceflight (Skylab programme study). Astronauts adapted to LBNP-induced orthostatic intolerance after a 4 week stay in space.
1989-1995	Lathers and Charles [46]	LBNP used during the flight to mitigate orthostatic intolerance after spaceflight.
1998	Ertl et al. [19]	The first recordings of muscle sympathetic nerve activity) during LBNP were made during the Neurolab mission in space. The German space agency developed a flexible LBNP chamber with zips on the side to allow access to the sagittal nerve.

Tab. 3. Applications of LBNP.

Area of application	Purpose of application
Understanding cardiovascular responses	to investigate how the cardiovascular system responds to changes in gravitational forces. This includes examining alterations in heart rate, blood pressure, cardiac output, cerebral blood flow and venous return when a person is subjected to simulated gravitational stress [21,27,36,37,40,43,58,62,72]
Orthostatic intolerance research	to simulate the physiological challenges associated with standing up or being in an upright position. Research in this area helps understand the mechanisms behind orthostatic intolerance, where individuals may experience symptoms such as dizziness, lightheadedness, or fainting upon standing [1,17,18,30,68,69,71]
Microgravity research	in the field of aerospace medicine, to simulate the effects of microgravity on the cardiovascular system. This research is crucial for understanding how astronauts' bodies respond to the absence of gravitational forces during space travel [29,50,51]
Space medicine	to develop different countermeasures against the physiological changes experienced by astronauts in space. Strategies to mitigate the negative effects of prolonged weightlessness on the cardiovascular system and other body functions are explored. Chibis pressure suit (Fig. 2a) has the ability to apply negative pressure on the lower half of an astronaut's body. This technique may prevent fluid from accumulating in an astronaut's brain [54]
Rehabilitation and physical conditioning	to help individuals who may have difficulty with upright posture. Additionally, it can be used to investigate the potential benefits of simulated gravitational stress for physical conditioning [38]
Clinical	to understand and potentially treat conditions such as orthostatic hypotension, where a person experiences a significant drop in blood pressure upon standing [9,34,42,48]
Emergency medicine	To identify individuals prone to rapid development of circulatory collapse following hemorrhage [10]. Studies of physio-pathological mechanisms in the body's response to hemorrhage simulated with LBNP (10-20 mmHg simulates the loss of ~400-500 ml of blood, while in the 20-40 mmHg range the loss of 500-1000 ml of blood, while greater than 40 mmHg reflect the loss of more than 1000 ml of blood) [8,11–14,31,63,66,67,77]
Aviation psychology	to assess cognitive and psychomotor performance under conditions of brain hypoxia and pressure changes [3]

LBNP applications

LBNP has been used in various contexts, including aerospace medicine to study the effects of microgravity on the cardiovascular system, as well as in cardiovascular research to understand the mechanisms involved in orthostatic intolerance and conditions like orthostatic hypotension. It was first applied to cardiovascular research in 1965 [74]. Overall, the aim of LBNP studies is to gain insights into the physiological responses of the human body to changes in gravitational forces. This research has implications for a wide range of fields, from space exploration to clinical medicine and rehabilitation as well as aviation psychology. Some of these goals were shown in Tab. 3.

The core of the application of LBNP is to understand how LBNP can be used to study the complex nature of physiological responses to a specific negative pressure agent. It is important to note that the application of LBNP should be done under controlled conditions and with consideration of individual health conditions. Researchers and healthcare professionals use LBNP as a tool to gain insights into physiological responses and adaptations, however, it is not a therapy or treatment for medical purposes in itself.

Simulation of +Gz-induced cardiovascular strain with the use of LBNP

As shown in Tab. 3, the LBNP chamber has found many applications. Researchers choose devices based on factors such as the level of negative pressure needed, the participant's position (sitting, standing, laying or exercising), and the overall goals of the study. These factors influence the way in which the chamber is designed. The design of the chamber can take a number of different forms [17,20,23]. Other examples include the LBNP-based devices for spaceflight [2,9,54,64] and clinical applications [9,34,42]. Tab. 4 shows the LBNP technologies and their applications. It is important to remember that advances in technology and ongoing research may lead to the development of new and more sophisticated LBNP devices in the future.

Tab. 4. The LBNP technology.

Technology	Design
Customized chambers	Some studies (mainly clinical) use custom-built chambers (Fig. 2d) that can be sealed around the lower body. These chambers are equipped with a vacuum system to create negative pressure, allowing researchers to control the level of pressure applied [14]
LBNP treadmill	Treadmill-based LBNP systems combine negative pressure with treadmill exercise [47,55–57,73]. Participants walk or run on a treadmill within a sealed chamber, and negative pressure is applied to the lower body. This setup is often used to study the cardiovascular responses to exercise under simulated gravitational conditions
LBNP chairs	Specialized chairs equipped with LBNP capabilities have been developed for research studies. Participants sit in these chairs, and negative pressure is applied to the lower body (Fig. 2c). These chairs are used to simulate the gravitational stress in the upright and seated positions [71,75].
Portable LBNP devices	Some portable LBNP devices have been designed for ease of use and mobility [2,64]. These devices may be used for specific applications, such as studying the effects of simulated gravitational stress during daily activities e.g., on the International Space Station or on a journey to Mars (Fig. 2).
Water immersion systems	Water immersion LBNP systems are used to study the effects of simulated gravity in a buoyant environment [35]

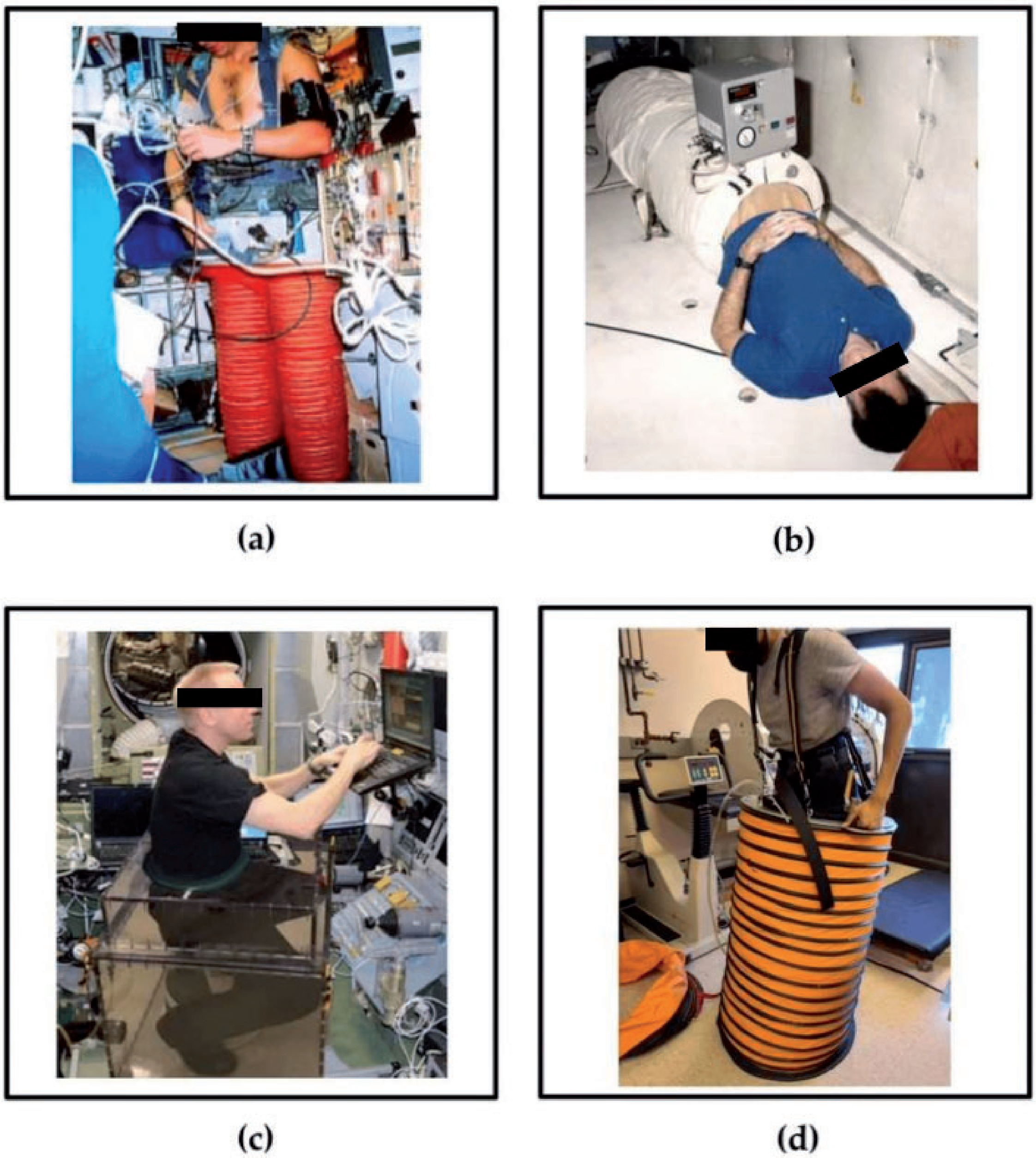

Fig. 2. Applications of the LBNP chambers: (a) Russian Chibis suit, (b) traditional static LBNP chamber, (c) seated LBNP device, and (d) self-generated LBNP device. [54] used under CC BY 4.0 [15].

The use of LBNP technology to study the effects of acceleration stress, that occurs during military fast-jet aircraft flying or exposure in a human centrifuge, required the use of an appropriate body position and chamber design. Studies [4,6,22,39,49,53,79] in which the authors investigated the relationship between LBNP and tolerance to +Gz acceleration have neglected to address the issue of differing body positions commonly observed during LBNP and +Gz testing. Specifically, LBNP is conducted in the supine position while +Gz testing is conducted in the upright seated position. The LBNP technologies that has been used to study the mapping of physiological phenomena occurring during +Gz flights [44,52,65,76], when the subject was in the upright seated position, are shown in Figs. 3-6.

Lategola & Trent [44] were probably the first who developed and tested an upright seated version of the supine LBNP box (Fig. 3). It was found that a negative pressure of approx. -40 mmHg is considered the equivalent of a 2 ±G(z) stress [45]. The researchers also noted that the LBNP box could generate and withstand a test pressure of approx. -120 mmHg.

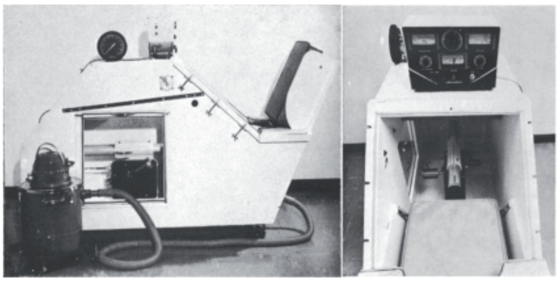

Fig. 3. LBNP device for +Gz simulation [44].

Another LBNP simulator, which is quite similar in design to the device used in the study by Lategola and Trent [44], is shown in Fig. 4. This device was used in the study [65] to compare hemodynamic changes in subjects exposed to LBNP in an upright seated position, with the change to the supine position. The results of this study were compared with the hemodynamic changes during the simulated acceleration occurring when a shuttle's re-entry into the Earth's atmosphere. This comparison provided evidence that the negative pressure of -40 mmHg at LBNP in an upright seated position induces similar hemodynamic changes, such as changes in heart rate and mean arterial pressure, to those that occur during the gradually increasing acceleration of the shuttle returning to Earth.

In the study [76], an LBNP chamber (Fig. 5) was developed in which negative pressure can be applied to a subject in an upright and an upright seated position. The authors concluded that the chamber can be used to assess the tolerance of individuals who may be exposed to high +Gz acceleration.

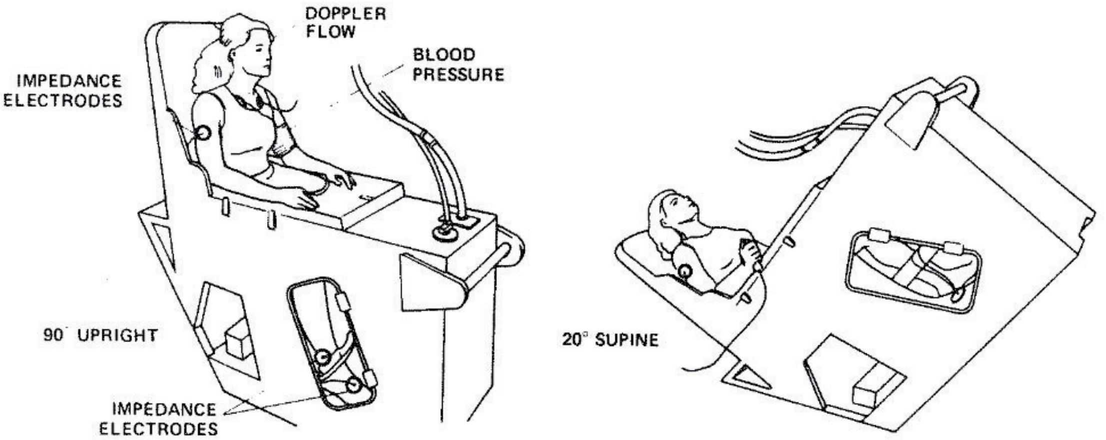

Fig. 4. LBNP to study hemodynamic changes in an upright seated and supine positions [65].

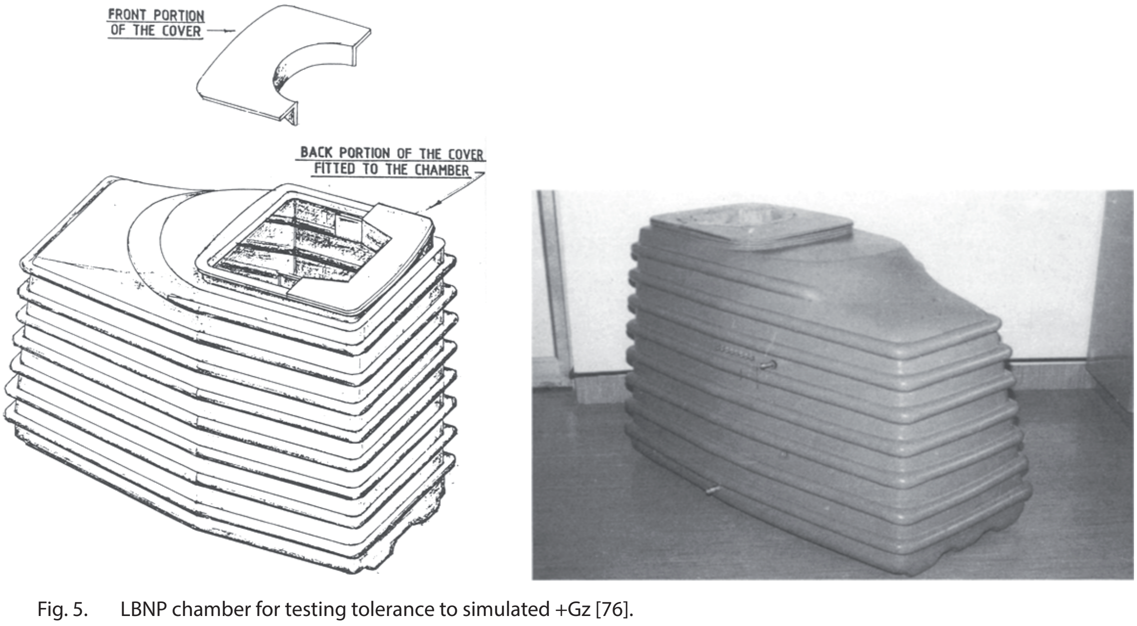

Fig. 5. LBNP chamber for testing tolerance to simulated +Gz [76].

Studies that have attempted to establish a link between the response to LBNP and +Gz acceleration have often overlooked the moderating effects of negative pressure and +Gz onset rate.

Ludwig et al. [52] conducted research comparing relaxation acceleration tolerance in a human centrifuge using three different +Gz onset rates and an LBNP chamber. Fig. 6 shows a scheme of the LBNP chamber.

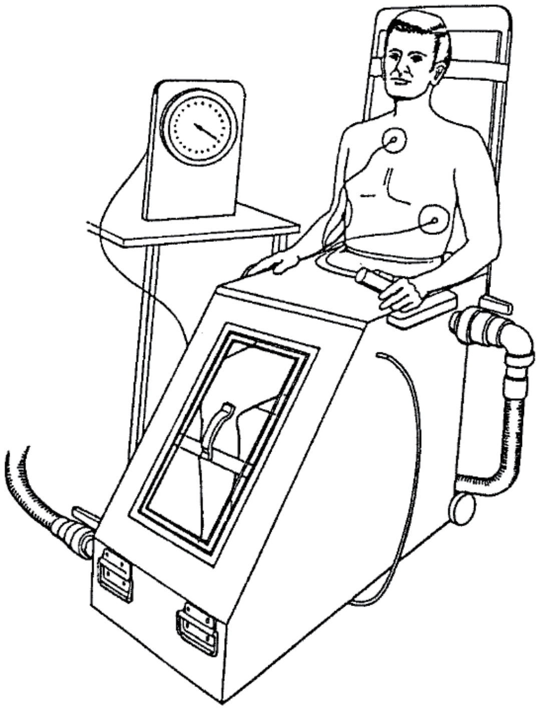

Fig. 6. Chamber LBNP to study the relationship between human response to lower body negative pressure and +Gz acceleration [52].

The results of the above studies showed that LBNP is effective in simulating the cardiovascular strain experienced by pilots during exposure to increased gravitational forces (+Gz) in flight. By creating a negative pressure environment around the lower body, LBNP helps researchers study and develop countermeasures against the physiological effects of high G-forces. These effects can include cardiovascular deconditioning and orthostatic intolerance.

Recently, attempts are also being made to combine LBNP technology with a flight simulator. One example is the project aimed to build a system that could be a useful tool for assessing pilot performance (acceleration stress tolerance) as an alternative to expensive centrifuge-based simulators (project funded by the National Centre for Research and Development, Poland under Grant No. DOB-BIO-12-05-001-2022). The flight simulator will feature a replica of a simplified fast-jet aircraft cabin and an aircraft ejection seat integrated with the LBNP chamber. This technology is designed to allow blood flow to be controlled during a test while a person is in a seated position, i.e. the position occupied by a pilot in a seat while flying an aircraft. The LBNP chamber creates a negative pressure that causes blood to pool in the lower parts of the body, similar to what happens when accelerations are applied along the longitudinal axis of the pilot's body from head to leg (+Gz force). The change in negative pressure, and therefore the amount of blood accumulated in the lower parts of the body, is synchronized with the change in Gz force during the simulated flight. The consequences of blood shift to the lower extremities as a result of LBNP and the effects of acceleration in real conditions will be monitored using carotid artery blood flow recorders and cerebral oxygenation and blood supply.

LBNP provides a controlled and reproducible method for inducing physiological responses similar to those observed during exposure to +Gz. Therefore, the use of LBNP for simulating +Gz stress may be a useful in training pilots to adapt to the physical challenges associated with the flight with sustained G-forces. Understanding how the cardiovascular system responds to simulated +Gz stress and how this stress factor affects cognitive performance may contribute to the development of interventions and coping strategies for individuals who experience similar physiological challenges, such as fighter pilots. Finally, compared to a human centrifuge, which is capable of producing high sustained +Gz acceleration, the use of LBNP to study cardiovascular responses has several important advantages. Some of them include [9,10,25]:

- possibility of using measurement techniques that are sensitive to movement or require a supine or seated position,
- ability to maintain central hypovolemia in the supine or sitting position, minimizing the impact of skeletal muscle activity,
- there are no stimulation of the vestibular organ by rotation and no cross-coupled stimulation of angular acceleration (Coriolis), which affects autonomic responses related to blood pressure regulation,
- enables quick interruption and termination of the test, as well as easy dosing of stimuli and rapid restoration of atmospheric pressure in the chamber.

Therefore, the use of LBNP to assess +Gz tolerance still appears to be an interesting alternative to human centrifuge studies.

CONCLUSIONS

In this paper we have provided a general overview of the development and applications of LBNP technology in different fields. Details about the methods used to investigate the relationship between LBNP and +Gz acceleration are provided. Although the development of LBNP applications to simulate the cardiovascular load induced by accelerations greater than +1 Gz has not been identified over the last two decades, further research in this area cannot be excluded.

In conclusion, the use of LBNP to simulate cardiovascular strain, typically induced by positive G forces (+Gz) in fighter jet flight, has played an important role in our understanding of the cardiovascular response to gravitational forces. This knowledge not only benefits pilots, but also has wider implications for healthcare and working conditions where individuals may face similar physiological challenges.

AUTHORS' DECLARATION:

Study Design: Rafał Lewkowicz, Mariusz Krej, Paulina Baran, Mirosław Dereń, Łukasz Dziuda. **Data Collection:** Rafał Lewkowicz, Mariusz Krej, Paulina Baran, Mirosław Dereń, Łukasz Dziuda. **Manuscript preparation:** Rafał Lewkowicz, Mariusz Krej, Paulina Baran, Mirosław Dereń, Łukasz Dziuda. The Authors declare that there is no conflict of interest.

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