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Pupillary response in air force and air defence pilots when exposed to +Gz acceleration

Reakcija zenice oka pilota ratnog vazduhoplovstva i protivvazduhoplovne odbrane tokom izlaganja +Gz ubrzanju

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Abstract

Background/Aim. In aviation, visual functions are important for the simultaneous monitoring the instrument panel and signs in the environment. From the very beginning of the development of aviation, visual function has been deemed particularly important. The effect of +Gz acceleration on the organ of vision is very significant for investigations in aviation medicine. Visual functions are the most important of all sensory functions where flight safety and quality of flight performance are concerned. High acceleration onset rates may cause changes in pupil diameter of a pilot with significant changes in visual function. However, it is important to maintain visual functions due to rapid pilot's orientation in the space. The aim of this study was to establish whether there was any pupillary response in Air Force and Air Defence pilots or changes in pupil diameter when exposed to +Gz acceleration in the human centrifuge. **Methods.** The study was conducted on 65 Air Force and Air Defence pilots aged from 28 to 45 years of age. The pilots were exposed to an acceleration of +5.5Gz to +7Gz. We examined the obtained differences in pupil diameter according to a rate of acceleration in the period of three consecutive days. **Results.** Changes in pupil diameter during the pilot's exposure to different high values of acceleration in the course of three days, measured before, during and after the exposure, generated statistically significant results. No statistically significant differences in pupil diameter were noticed when the pilots were exposed to the same values of acceleration before the testing on the first, second or third day. During the test, pupil diameter was statistically significantly larger than before the test. **Conclusion.** Transient changes in pupil diameter occurred in pilots exposed to a +7Gz acceleration. Pilots were able to withstand exposure to a +5.5Gz acceleration, without any major changes in the pupil diameter. Physiological training of pilots in the human centrifuge mimicking conditions of real G acceleration, improves tolerance to acceleration, which is important for flight safety.

Key words:
acceleration; aerospace medicine; centrifugation; pilots; reflex, pupillary; vision, ocular; vision tests.

Apstrakt

Uvod/Cilj. U avijaciji su vidne funkcije značajne zbog praćenja signala na instrument tablama, kao i znakova okoline. Od samog početka razvoja vazduhoplovstva, funkciji vida se pridaje izuzetan značaj. Uticaj +Gz ubrzanja na organ vida je veoma važan za istraživanja u vazduhoplovnoj medicini. Vidne funkcije su najvažnije od svih čulnih funkcija kako u pogledu bezbednosti letenja, tako i za kvalitet izvršavanja letačkih zadataka. Visok početni stepen ubrzanja može izazvati promene u dijametru zenice oka pilota i izazvati značajne promene u funkciji vida. Međutim, važno je održati vidne funkcije zbog brze orijentacije pilota u prostoru. Cilj istraživanja je bio da se utvrdi da li postoji reakcija zenice oka kod pilota ratnog vazduhoplovstva (RV) i protivvazduhoplovne odbrane (PVO), kao i promene u njenom dijametru tokom izlaganja +Gz ubrzanju u humanoj centrifugi. **Metode.** Ispitivanje je izvršeno kod 65 pilota RV i PVO starosti od 28 do 45 godina. Piloti su izlagani ubrzanju od +5,5Gz do +7Gz. Posmatrali smo dobijene razlike u širini zenice u zavisnosti od stepena ubrzanja, u periodu od tri uzastopna dana. **Rezultati.** Promene dijametra zenice tokom izlaganja različitim visokim vrednostima ubrzanja tokom tri dana testiranja, merene pre, tokom i nakon izlaganja različitim vrednostima ubrzanja, bile su statistički značajno različite. Nije uočena statistički značajna razlika u vrednostima dijametra zenica izme

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renih pre testa prvog, drugog i trećeg dana kada su piloti izlagani istim vrednostima ubrzanja. U toku testa, dijametar zenica bio je statistički značajno veći nego pre testa. **Zaključak.** Došlo je do prolaznih promena u dijametru zenice pilota podvrgnutih +7Gz ubrzanju. Izlaganje vrednostima od +5,5Gz ubrzanja piloti mogu da podnesu bez većih promena u dijametru zenice. Fiziološka trenaža pilota u humanoj centrifugi, gde su prisutni uslovi realnog G ubrzanja, poboljšava njihovu toleranciju na ubrzanje što je važno za bezbednost letenja.

Ključne reči:
ubrzanje; medicina, vazduhoplovna; centrifugovanje; piloti; refleks, pupilarni; vid; vid, testovi.

Introduction

The development of modern aviation has placed loads on the human body that are ten and more times greater than the force of gravity. Such loads cause changes that are brought about by forces of inertia occurring due to changes in acceleration. In aviation, the applied acceleration is commonly called G load, and it represents the ratio of acceleration to the gravitational force. From the aspect of aviation physiology, the important forces are inertial forces that act on the human body and to which a pilot is exposed during acceleration. In +Gz acceleration, inertial forces act on the pilot's body along its longitudinal axis, causing the pilot to be pressed back into the seat. In any flight maneuver, forces act on the body along its longitudinal axis (z) and they are referred to as +Gz loads. The sign + shows that the force acts in the direction of the head, and the resultant force acts from the head towards the feet, while G is used for comparing the magnitude of the acting force with the gravitational force of 1G. The force of +9 Gz acts in the direction of the head and it is nine times greater than the gravitational force. The force acting on the pilot is the inertial (centrifugal) force, acting from the head towards the feet, which originates as a result of the force keeping the plane on a curved path (centripetal force). Because of its considerable practical importance in air combat, this load is very important for research [1].

From the very beginning of the development of aviation, visual function has been attached great importance. Of all sensory functions that a man is endowed with, vision is the most important one for both flight safety and quality of performance of flight tasks. Owing to its great practical importance in air combat, the effect of +Gz acceleration on the organ of vision is very significant for research. Information we receive by means of our sense of sight is the most important for maintaining orientation on the ground and in the air during flight. In conditions of poor visibility, spatial orientation may be compromised [2].

Maneuverability of modern aircraft enable considerable acceleration which affects the organ of sight. If acceleration exceeds +3.5 Gz and its duration is longer than 6–12 sec, visual functions become impaired. Spatial disorientation and loss of consciousness in flight occurring as a result of +Gz acceleration, represents the greatest danger to flight safety and ranks as number one cause of accidents [3]. That is the reason why visual acuity of Air Force and Air Defence pilots of the Serbian Armed Forces was tested in the human centrifuge before and after exposure to +Gz acceleration, with aim being to increase their individual capacity to tolerate +Gz acceleration. Namely, the main sensory functions, primarily the organ of vision, may be affected when exposed to high +Gz acceleration.

Over a short period time, new generations of aircraft that are capable of extremely high increase in acceleration and extraordinary maneuverability have already posed a challenge to aviation physiology, which deals with a selected healthy population and investigates the influence of ecophysiological factors of flight (altitude, dynamic flight factors, noise, vibrations, sudden changes in temperature, and the like), to determine the ultimate physiological limits of endurance for every pilot, for each type of flight stress, thus selecting pilots with the best physiological defense mechanism against flight stress [4]. The pilot profession, as a highly demanding and responsible occupation, requires that the best possible pilots be selected.

The pupil is a circular opening in the centre of the iris. Through this opening, light comes into the inside of the eye and transforms into visual energy in the retina. The amount of light going into the eye is regulated by the pupil itself expanding or constricting. The pupillary light reflex is controlled by the parasympathetic system when constricting and the sympathetic system when expanding. Changes in pupil diameter are conditioned by two muscles, the one that helps the pupil constrict [*musculus* (*m) sphincter pupillae*] and the other that expands it (*m. dilator pupillae*). *M. sphincter pupillae* is a round muscle in the pupillary portion of the iris that is innervated by *nervus oculomotorius*, and apart from the parasympathetic innervation, it is also innervated by the sympathetic system. In response to the sympathetic stimulus, it relaxes immediately. *M. dilator pupillae* is, for the most part, located in the ciliary portion of the iris and is innervated by the sympathetic system. Peripheral parts of the sympathetic and parasympathetic segments of the pupillomotor pathway are controlled by the top layers of the cerebral cortex and hypothalamus. Pupil size differs from one person to another. In any person, pupil diameter depends on different factors. According to diameter, there is the dilated pupil (mydriatic) whose diameter is 4 mm and more, mid-dilated, and constricted (myotic) pupil, up to 2 mm in diameter. The average pupil diameter is 3 to 5 mm. Even in complete absence of external and internal influences on the organism, the pupil is never absolutely immovable as it changes its diameter by 0.5 mm while constricting, the number of constrictions being 30 to 120 per min [5]. There are two normal pupillary responses: a constriction response which is quick and intensive, and a dilation response, which is milder in intensity and slower than the former. The dilation response includes: the pupillary

light reflex, the trigeminal pupillary reflex, the accommodation-convergence reflex, eyelid closure reflex and the Galvanic skin response – Bumke. The dilation response also consists of the following reflexes: pupil dilation response to sensory stimuli (pain, touch, physical exertion), acoustic and otogene response, vestibular ocular reflex, pupil dilation response caused by mental stress, and pupil response to horizontal eye movement. The dilation response may occur as a result of two factors: reducing the tone of *m. sphincter pupillae* when dilation is a passive phenomenon, or active contraction of *m. dilator pupillae*, where it is an active phenomenon. This means that the dilation response of the pupil is basically either an inhibition of *nuclei nervi oculomotorius* or a stimulus by the sympathetic system travelling from the cervical spine to the eye [6]. Besides contrast and the sharpness of the edge of the observed object, identification of details is also affected by the adaptation of the eye to different levels of brightness in our field of vision. Furthermore, visual acuity is also affected by the size of the pupil opening [7]. Higher intensity of light reduces pupil diameter and increases visual acuity, thus reducing the refractive error of the eye, if it exists [8]. The size of the pupil opening is much more affected by the portion of the retina responsible for central visual acuity than the peripheral retina [9]. The connection between intensity of light and the size of the pupil opening is important for visual acuity only when the intensity of light is low [10–12].

The aim of this study was to establish whether there was any pupillary response in Air Force and Air Defence pilots or changes in pupil diameter when exposed to +Gz acceleration in the human centrifuge.

Methods

The investigation was carried out on a defined population of 65 respondents (pilots) from 28 to 45 years of age. All the respondents were males. We examined the prevalence of exposure to positive acceleration of +5.5Gz to +7Gz and investigated the effect of acceleration on pupil diameter and its response before, in the course of and after the exposure to acceleration. The investigation was performed in the gravity-altitude laboratory (human centrifuge). All of the respondents were highly selective, with no history of ocular or system diseases. The pilots had to have good distance and near visual acuity, good stereo and color vision, normal pupil diameter, absence of any changes in the fundus, absence of ocular diseases such as glaucoma, cataract, or uveitis, and no hypertension or any heart rhythm disorder. Pupil diameter was not measured in the pilots with poor tolerance to +Gz acceleration, those who had had interruption in the continuity of consciousness when exposed to acceleration, or in those who had exhibited two consecutive delayed responses to photostimulation of peripheral vision. The pilots were tested over the period of three consecutive days, when they were exposed to different values of acceleration. The size, diameter, shape and evenness of the pupil before, in the course of and after exposure to +Gz acceleration were measured by the pupilometer, a ruler for measuring pupil diameter, and the values were expressed in millimeters. The measuring was performed upon entering the human centrifuge and on exiting it, as well as in the course of exposure to +Gz acceleration on the screen, as there was a camera inside the centrifuge cabin enabling the monitoring of the pilots' responses. The testing took place over the course of three days. On the first day, the test of linear increase in acceleration was applied, the linear increase of acceleration being +5.5Gz without the anti-G suit, with acceleration gain of 0.1 G/s. On the second day the test of tolerance to acceleration was performed, with acceleration increasing linearly to +7Gz, the acceleration gain being 0.1 G/s, without the anti-G suit, with the decelleration of also 0.1 G/s. On the third day, the test of intermittent increase in acceleration was performed in the same way as on the second day, except that now the pilots had a 2-min recess after being exposed to a +5.5 Gz acceleration before the acceleration was upped to +7 Gz for 10 s, when the pilots were requested to use a stick and respond to light signals, simultaneously activating the anti-G suit. The investigation was performed in groups of 5 to 7 respondents each day.

Results

No statistically significant differences were noticed between pupil diameter values measured prior to testing on the first, second or third day (p = 0.559) (Table 1). Considering the measuring periods, neither were any statistically significant differences noticed in the pupil diameter values measured in the course of the test (p = 0.262) or after the test (p = 0.412). Measurements taken on

Table 1

Changes in pupil diameter before, in course and after exposure the pilots to acceleration of +5.5Gz to +7Gz in human centrifuge

Time of testing	mean ± SD (median; minimum–maximum), mm			p (Fridman's test)
	first day	second day	third day	
Before the test	4.02 ± 0.65 (4.0; 3.0–5.0)	4.01 ± 0.51 (4.0; 3.0–4.8)	3.97 ± 0.57 (4.0; 3.0–5.0)	0.559
During the test	4.46 ± 0.64 (4.5; 3.5–5.5)	4.49 ± 0.48 (4.5; 3.5–5.2)	4.37 ± 0.57 (4.2; 3.5–5.5)	0.262
After the test	4.14 ± 0.61 (4.0; 3.0–5.5)	4.21 ± 0.45 (4.0; 3.5–5.0)	4.12 ± 0.54 (4.0; 3.5–5.5)	0.412
p (Fridman's test)	0.000	0.000	0.000	

SD – standard deviation.

all three days produced a statistically significant difference in pupil diameter before the test (p = 0.000), in the course of the test (p = 0.000) and after the test (p = 0.000) (Table 1). Intergroup comparisons showed a statistically significant difference in pupil diameter in all the measuring periods: before the test, in the course of the test and after the test (Table 2). In the course of the test, pupil diameter was statistically considerably larger than before the test. Even though the diameter of the pupil decreased after the test, the pupils were still statistically larger than before the test (Figure 1).

Table 2

Intergroup comparisons of pupil diameter before, during and after the acceleration test in human centrifuge, over a period of three days of monitoring

Time of testing	Before the test (p)*	During the test (p)*
First day		
during the test	0.000	
after the test	0.002	0.002
Second day		
during the test	0.000	
after the test	0.000	0.000
Third day		
during the test	0.000	
after the test	0.000	0.000

***Wilcoxon's – test.**

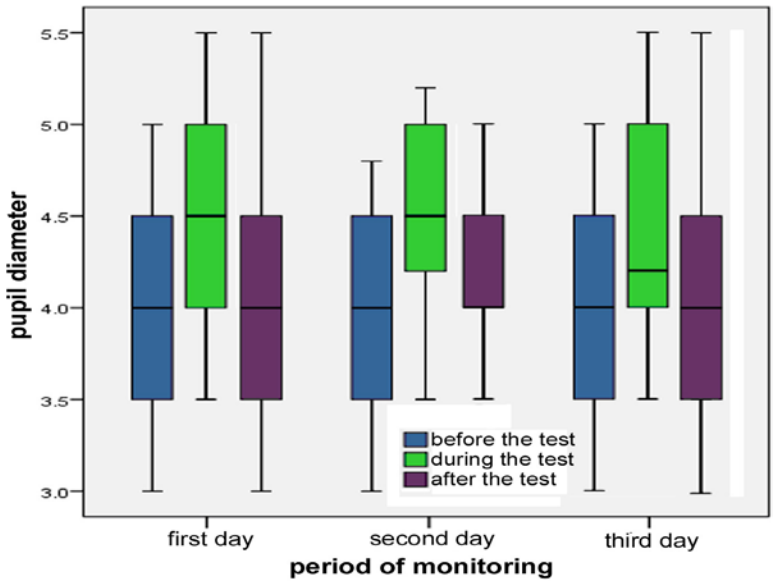


Fig. 1 – Pupil diameter (mm) before, during and after the acceleration test in human centrifuge, measured over a period of three days.

Discussion

The pilot profession is a job involving optimum mental and physical fitness, full personal integrity and excellent health. In aviation medicine, the journey from theory to practice is somewhat longer since any research calls for complex tehnical innovations and high level of security for their verification [13]. Aviation medicine includes a wide range of tasks, the end goal of which is continuous creation of measures and procedures which would best equip the pilot for flight and performance of duties he/her has been entrusted with, at the same time reducing risks to life, health and material resources to a minimum. In the field of physiology of acceleration, notable variations in tolerance to G acceleration have been noticed. The real response of a human organism to acceleration differs from the response that can be anticipated in theory. Within 20 sec from the onset of acceleration, pulse rate increases, a response also noticed in the air force pilots who were exposed to an acceleration of +7 Gz without the anti-G suit, while at the same rate of acceleration and with the anti-G suit, the increase in the pulse rate was slightly lower. With high onset rate of acceleration, significant changes in pupillary response and its diameter may occur, which then may affect the maintenance of visual acuity, colour vision and stereo vision. This is important because a pilot has to be able to orientate himself in space rapidly, visually scan the configuration of

terrain, positions of enemy aircarft and also monitor the instrument panel in the cockpit [14]. Tolerance to +Gz acceleration, and the ensuing changes in visual functions, including pupillary response, may be compromised if pilots do not fly in the conditions of high +Gz acceleration over a longer period of time [15]. This is why there is a question of how much air combat training a pilot needs in order to maintain good tolerance. It is a known fact that a pilot who flies in the conditions of air combat at least once a week tolerates +Gz acceleration better than pilots who do this once in two weeks or once a month [16]. When exposed to an acceleration of +5.5 Gz, the air force pilots showed greater tolerance to acceleration and fewer changes in pupil diameter compared to when they were exposed to an acceleration of +7 Gz.

The effect of positive acceleration on pupil diameter shows that pupils dilate throughout the pilot's exposure to acceleration [17]. The study by Cheung and Hofer [17] states that pupils automatically dilate when exposed to acceleration as a response of the sympathetic nervous system to an onslought of a powerful stimulus, that is +Gz acceleration of high values. The increased width of the pupil represents a response of the sympathetic nervous system to increased acceleration [18]. The response time of the pupil to changes in +Gz acceleration differs. The changes were observed on the monitor as there was a camera inside the centrifuge cabin recording what was going on in the cabin and the pilots' responses to acceleration. In the group of Air Force and Air Defence pilots, there was a statistically significant change in pupil diameter (p = 0.022) that did not occur until the pilots were exposed to acceleration values of +5 Gz to +7 Gz. Changes were also statistically significant after being exposed to a +7 Gz acceleration, without the anti-G suit. Darkening of vision or a blackout due to pupil dilation when exposed to acceleration, which pilots may experience while turning or pulling the plane out of a dive, may prove dangerous in combat. In a paper by Johnston et al. [19] that dealt with this problem, it was noticed that pilots exposed to positive acceleration in the human centrifuge experienced a subjective feeling of loss of peripheral vision and that pupil diameter reached its maximum. In our investigation, when the pilots were exposed to an acceleration of +5.5 Gz, they did not experience any statistically significant reduction in vision as the noticed difference in pupil diameter was not statistically significant. Pupil size is dependent on numerous external, physiological and psychological factors, such as light, fatigue, eye movement, eye pressure, hearing, smell [20]. We did not notice any impact of external factors on our respondents' pupil diameter. Fear, pain, and the level of difficulty of combat task may also affect pupil diameter. Tsai et al. [20] have claimed that an increase in pupil diameter when a pilot was exposed to a +6 Gz acceleration lasted 15 minutes after the exposure and pupil diameter ranged from 3.56 ± 0.72 mm to 5.65 ± 0.56 mm. Exposure to a +9 Gz acceleration caused the dilation ranging from 3.54 ± 0.73 mm to 5.56 ± 0.67 mm and lasted 30 minutes after the acceleration ceased. Pupil dilatation also causes decrease in distance of visual acuity when exposed to positive acceleration and it is a useful quantitative parameter for assessing response to a positive acceleration [21].

The results we obtained expand the knowledge base necessary for quality selection of pilots, the most expensive population in any army. It is important to know the limits of tolerance to positive acceleration and find a way to tolerate acceleration successfully, with fewest possible consequences for visual functions and pupillary response of pilots flying modern high-performance combat aircraft.

The objective of further investigations and research in the field of aviation physiology is to consolidate data obtained by sensory means and measuring instruments and classify them using information technology, have them represented on graphs and projected onto the pilot's visor in three dimensions, which will make flying safer, more secure and efficient. It is necessary to carry out further research that will generate more precise information on how +Gz acceleration affects visual functions and what kinds of responses of human organism this impact induces.

Conclusion

One of the most sensitive physiological indicators is the response and change in pupil diameter when exposed to high values of acceleration. In the Air Force and Air Defence pilots, a change in pupil diameter occurs when they are exposed to a +7Gz acceleration. Pilots tolerate exposure to a +5.5Gz acceleration without any major changes in pupil response or its diameter. By receiving physiological training in the human centrifuge, which simulates real G acceleration conditions, pilots will improve their tolerance to acceleration and become familiar with their body's response to excessive acceleration, which is important for flight safety.

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