Heart Rate Variability as a Predictor of $+G_z$ Tolerance During the High-G Selective Test

Nenad Bacevic; Milica Ninkovic; Milijana Drvendzija; Jelena Vidakovic; Marina Bacevic; Pavle Stepanic

INTRODUCTION: Preselection of pilot candidates in the military is critical and determines the quality of subsequent selection. The Aero Medical Institute in Belgrade uses the following centrifuge endpoints: peripheral vision loss, heart rate above 180 bpm, cardiac arrhythmias, and G-induced loss of consciousness to assess relaxed $+G_z$ tolerance. The aim of this study was to evaluate heart rate variability (HRV) associated with cardiovascular adaptability to different types of stress as a predictor of $+G_z$ tolerance.

METHODS: Thirty-six candidates were exposed to centrifuge runs, consisting of the following $+G_z$-acceleration phases: a 2-G plateau followed by an increase to 5.5 G, a decrease to 2 G, and ending with a plateau. Time-domain HRV indices were calculated for candidates, for a 60-s 2-G plateau, and for the entire test. The correlation was made between the groups that did (Group 1) and did not meet the criteria (Group 2).

RESULTS: The results show significantly lower values in all time domain HRV indices, namely standard deviation of the normal-to-normal interval (SDNN) and root mean square of successive differences, in Group 2. Mean SDNN values were 45.98 ± 24.80 ms (2-G plateau) and 109.99 ± 39.64 ms (entire test) in Group 1, while the SDNN were 22.99 ± 12.04 ms and 69.70 ± 33.45 ms in Group 2. Root mean square of successive differences was higher in Group 1 for the 2-G plateau and for the entire test.

DISCUSSION: The results suggest that HRV is positively correlated with $+G_z$-tolerance and can be used as an additional selection tool for military aircrew.

KEYWORDS: human centrifuge, initial selection, heart rate variability, endpoint, GOR.

Bacevic N, Ninkovic M, Drvendzija M, Vidakovic J, Bacevic M, Stepanic P. *Heart rate variability as a predictor of $+G_z$ tolerance during the high-G selective test*. Aerosp Med Hum Perform. 2024; 95(2):93–100.

The new generation of fighter aircraft, with a wide range of speed and great maneuvering capabilities, cause significant physiological changes in many human organs which attempt to compensate for these changes and have a significant effect on the pilot's performance during a flight of modern combat aircraft.[7,9] It is well known that improvements in $+G_z$ tolerance due to physiological and mechanical protection are limited. The anti-G straining maneuver, G-protective systems, and avoidance of additional stresses cannot increase the individual pilot tolerance for more than about 4 G.[2] These are clear reasons to pay attention to the "relaxed tolerance" of pilot candidates with respect to G acceleration.

The part of the pilot's body that is most responsive to high $+G_z$ accelerations is the cardiovascular system (CVS). Due to high $+G_z$ acceleration, blood moves as fluid tissue and retreats to the lower parts of the body, causing symptoms and signs from various organ systems, such as visual effects or G-induced loss of consciousness (G-LOC). In addition to blood redistribution, the hydrostatic head-cardiac gradient and the characteristic baroreceptor reflex (BR) are significant factors influencing $+G_z$ tolerance.[7] When the baroreceptors register a decrease in blood pressure, the sympathetic nervous system (vasoconstrictor response) is activated. Activation of the sympathetic nervous

From the Department of Aviation Physiology, Aero Medical Institute, Serbian Air Force and Air Defence, Zemun, Serbia.

This manuscript was received for review in May 2023. It was accepted for publication in December 2023.

Address correspondence to: Nenad Bacevic, M.D., Department of Aviation Physiology, Aero Medical Institute, Dr. Petra Markovića 4, 11080 Zemun, Belgrade, Serbia; nenad.bacevic@vs.rs.

DOI: https://doi.org/10.3357/AMHP.6319.2024

system results in an increase in heart rate (HR), cardiac contractility, and overall vasoconstriction, leading to increased peripheral resistance. The BR is a compensatory mechanism and should maintain pressure at the head level during the $+G_z$ exposure. However, the BR takes time to activate so that the recovery of blood pressure begins after 6–12 s, while the return to pre-exposure values occurs after 15 s. HR is the indicator of the autonomic nervous system (ANS) response to $+G_z$ stress and increases proportionally to the acceleration level and reaches a maximum a few seconds after the onset of exposure. For example, an acceleration of $+4\ G_z$ results in a maximum HR of about 120–140 bpm, while higher exposures result in a maximum rate of up to 200 bpm. Changes in HR are regulated by the vagus nerve and occur much more rapidly compared with sympathetic regulation of cardiac contractility and peripheral vascular resistance. Venous blood return to the right atrium begins 10–15 s after the onset of acceleration exposure, immediately followed by an increase in left ventricular stroke volume. This increase continues over the next 20–40 s, tending to maintain blood pressure at the level it was before exposure to acceleration.[7]

The sensitivity of baroreceptors depends on many factors, including age and the extensibility of the arterial wall. Adaptation or resetting of the BR to a new blood pressure value can be caused by central and peripheral factors. In aviation, the term lay-off is well known, which means that crew who have not flown in high $+G_z$ modes for 7 or more days have a reduced tolerance to acceleration. Several experimental studies have shown that repeated exposure to high levels of constant $+G_z$ acceleration results in significant physiological adaptation associated with improved regulation of blood pressure and consequent protection of cerebral flow.[6] Recorded values of high blood pressure and total peripheral resistance at rest after exposure to $+G_z$ acceleration suggest increased tolerance to subsequent exposures. Research in recent years has shown that adaptation occurs, but only when subsequent exposures occur in short periods of time, that is, for <20 s.[27] It has also been demonstrated that simulating aerial combat in a human centrifuge leads to an increase in cardiovascular tolerance to orthostatic stress but not in relaxed tolerance to $+G_z$ acceleration during a gradual increase in acceleration.[23] The central setting of the BR probably plays a key role in this adaptation, but these mechanisms have not been fully elucidated. Lehrer et al. also demonstrated the neuroplasticity of the BR and found that the reflex becomes adaptive during physical exertion.[13]

Heart rate variability (HRV) is a physiological phenomenon associated with cardiovascular adaptability to different types of stress, correlated with a person's overall health and ability to self-regulate.[15] Heart HRV can be measured in both a time domain and a frequency domain. Time-domain HRV indices represent the variability in the time intervals between successive heartbeats. The standard deviation of the normal-to-normal interval (SDNN) and the root mean square of successive differences between normal heartbeats (RMSSD) are the two most commonly used HRV time-domain indices.[24] SDNN represents the total heart rate variability correlated with ANS activities, while RMSSD is an indicator of parasympathetic regulation of the heart.[11] The aim of this study was to evaluate HRV as a predictor of $+G_z$ tolerance.

Functional "endpoints" are previously established criteria for terminating the centrifuge run at the Aero Medical Institute (AMI) as indicators of inappropriate baroreceptor reflex[21] and are used in this study as well. These include loss of peripheral vision (gray-out), HR above 180 bpm (tachycardia), arrhythmias, and G-LOC.[21] A brief description of the predetermined endpoints is provided herein.

Arterial blood pressure lower than the intraocular pressure in the retinal artery leads to inadequate oxygenation and then to the loss of peripheral vision, a phenomenon known as gray-out. Loss of peripheral vision manifests as a graying of the visual field, sometimes as tunnel vision. Flashes or spots may appear in the visual field. These changes can also be asymmetrical, especially if the head has been moved under the influence of acceleration. Gray-out is the first sign of uncompensated G stress and a very common symptom experienced by almost every military pilot. In a Royal Australian Air Force study, 98% of surveyed pilots reported experiencing a gray-out.[20] With a further increase in acceleration to +4 to $+5\ G_z$, the pressure in the central retinal artery decreases below the level of intraocular pressure, and the loss of peripheral vision transitions to complete vision loss; this phenomenon is called blackout. Blackout is much less common: 29% of Royal Australian Air Force pilots surveyed experienced a blackout, whereas, in a Brazilian Air Force study, 20% of pilots reported complete vision loss.[1] Most importantly, visual disturbances represent a physiological limit to G-tolerance and warn the pilot of impending loss of consciousness (LOC).

It is well known that acceleration during centrifuge training provokes cardiac arrhythmias. Arrhythmias occur as a physiological response to a high $+G_z$ load and are related to profound changes in HR caused by autonomic imbalance, a specific endocrine response (increased release of catecholamines), and mechanical distension of the heart [sinus arrhythmia, premature atrial contraction, and premature ventricular contraction (PVC)].[5]

Cardiac arrhythmias that are contraindications to continued centrifuge training are: atrial fibrillation, atrial flutter, paroxysmal supraventricular tachychardia, sustained ventricular tachycarida, ventricular fibrillation, and type Mobitz II. Further studies of centrifugal students revealed a significant proportion of them had cardiac abnormalities. Other arrhythmias such as PVC (Lown graded >1), repetitive PVC, repetitive premature atrial contraction, bigeminy, trigeminy, PVC pairs (couplet), nonsustained ventricular tachycardia (including PVC in groups of triplet or more), etc., have been considered borderline abnormalities; whether training may continue depends on the decision of the physicians monitoring the training.[8,17]

During sudden exposure to high levels of G-acceleration, the ability of the CVS to maintain intact blood flow to the brain may be impaired. Arterial blood pressure is unable to overcome the hydrostatic pressure in the blood column caused by high G levels. Blood flow to the brain is interrupted and the pilot loses consciousness. This phenomenon is referred to as G-LOC. In relaxed individuals without protective equipment, it typically occurs above +5.5 G_z and represents the greatest and most dangerous risk to supersonic pilots.[21] The period during which the pilot is unable to control the aircraft due to G-LOC is referred to as total incapacitation. Total incapacitation can last a minute or longer and that is sufficient to cause fighter aircraft to hit the ground and cause an aircraft crash. The duration of the incapacitation depends on the onset of acceleration rate and +G_z value at which G-LOC occurred. Houghton states that total incapacitation is significantly shorter in LOC caused by rapid acceleration onset compared to gradual acceleration onset.[9] In the literature, it is claimed that a previously experienced G-LOC in a human centrifuge can reduce incapacitation by 17 s.[28] Between 1982 and 2001, the U.S. Air Force lost 29 aircraft due to G-LOC.[14]

METHODS

Subjects

The study protocol was approved by the Ethics Committee of the Military Medical Academy, Belgrade. Each subject provided written informed consent before participating.

Subjects, the candidates for the Serbian Air Force Academy ($N = 36$), with an average age of 19 yr, range 18–20 yr, successfully passed the medical and psychological examination in the Department of Medico-Psychological Expertise and were asymptomatic and considered healthy.

Equipment

Two ECG leads (lead I and lead III), respiration, and HR were monitored continuously during the test. The mentioned biodynamic signals are monitored with the microprocessor data acquisition system described in Stepanic et al.[26] In the presented selective test, a backrest angle of 21° is used.

Procedure

A retrospective study using the test results from the standard selection process at AMI in the period from 2017 to 2019 was conducted. Within the mentioned period, the centrifuge parameters administered during the centrifuge runs (G-load profile), biodynamic signals, and functional endpoints within the actual selection process at AMI were stored. In order to assess the possibility of using HRV as a predictor of +G_z tolerance, time-domain indices of HRV (SDNN, RMSSD) have been calculated for each candidate from the stored ECG recordings, and the results of the statistical analysis are presented herein.

Candidates did not wear an anti-G suit or perform an anti-G straining maneuver. Candidates were subjected to centrifuge runs of +2 G_z for 60 s (plateau), returned to 1 G, accelerated gradually to +5.5 G by a rate of $0.1\,G \cdot s^{-1}$ (gradual onset run: GOR), decelerated to 2 G, and then subjected to another plateau of +2 G for 60 s (**Fig. 1**).

GOR ($0.1\,G \cdot s^{-1}$) is used in the selection test and that allows compensatory BRs to fully develop during the application of the G-load. Baroreceptor sensitivity is modified by several factors, and it can be responsible for the large variation in tolerance between individuals. Visual symptoms usually occur before LOC, so GOR is considered appropriate for the primary selection used in this study. Functional endpoints are established criteria for terminating the centrifuge run.

Statistical Analysis

From the original R-R interval sequence, time-domain indices of HRV (SDNN, RMSSD) were calculated for each candidate pilot for a 60-s plateau at 2 G and for the entire test. While the conventional minimum recording is 5 min, researchers have also proposed ultra-short time periods of 10 s, 30 s, and 60 s.[18] Correlation of time-domain indices of HRV was made between the group that met the criteria and the group that did not. For data processing, the Mann-Whitney *U*-test [also called the Mann-Whitney-Wilcoxon (MWW/MWU), Wilcoxon rank-sum test, or Wilcoxon-Mann-Whitney test] is used herein, as was the statistical software product IBM SPSS Statistics.[10]

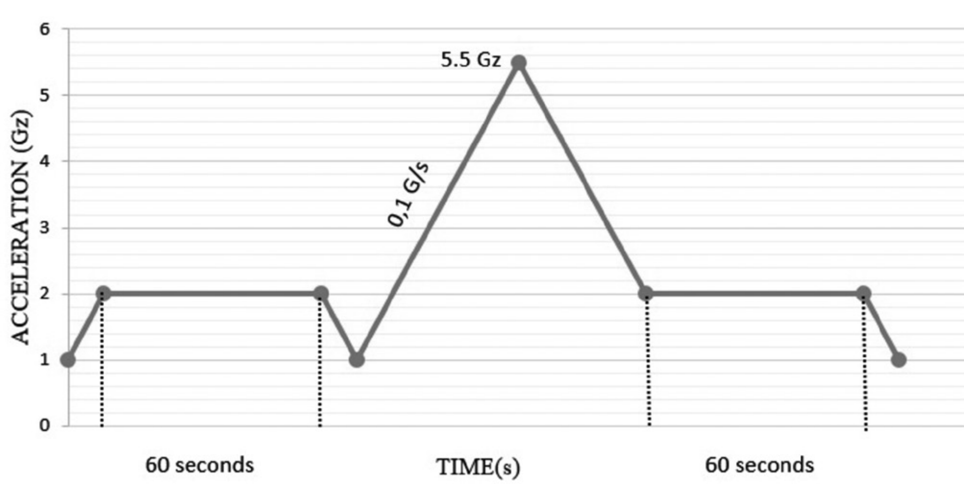

Fig. 1. Selective +G_z acceleration test in the Serbian Air Force.

RESULTS

Out of the 36 candidates tested, 18 (50%) met the G_z tolerability criteria for initial jet training. Loss of peripheral vision was observed in 12 candidates, extreme pulse rate (more than 180 bpm) was observed in 4 candidates, 1 candidate showed cardiac arrhythmia, and 1 candidate experienced G-LOC (**Fig. 2**). Thus, it can be concluded that 18 candidates (50% of candidates) poorly tolerated +G_z loading.

Loss of peripheral vision (more than 60° of central visual axis) was noted in 12 candidates. To minimize the subjectivity of this endpoint parameter, in this study loss of peripheral vision is assumed to occur when there are two consecutive delays in response to photo stimulation of peripheral vision. The lights appear randomly within a defined angular range according to the method of unpredictable random numbers (every 2, 3, 4, or 5 s). The situation in which the candidate focuses their eyes on the light with both eyes unilaterally is also assumed to be a loss of peripheral vision, resulting in the termination of the centrifuge run.

An increase in HR is the main indicator of the magnitude of the applied +G_z. In **Fig. 3**, the graphical user interface used for real-time monitoring and offline analysis of biomedical signals used in the human centrifuge at AMI[26] is presented. It is divided into two TFT monitors. The upper screen shows the graphs of the biomedical signals: ECG from two channels, vertical nystagmus, horizontal nystagmus, pulse rate, breathing, feedback response from the stick, and the achieved G_z load. The lower screen displays the real-time video from the centrifuge cabin and the current values of the G-force, the time distance between the two RR intervals in ms, and HR in bpm.

In this study, a prespecified maximum HR of 180 bpm at +5.5 G_z is assumed. Extreme pulse rate was observed in four candidates; one of the test runs is shown in **Fig. 4A**, where the candidate's measured HR was 185 bpm at 4.1 G_z. Acceleration during a centrifuge run is known to provoke cardiac arrhythmias. One candidate exhibited bigeminy (**Fig. 4B**).

One candidate experienced G-LOC. The episode of G-LOC occurred without warning symptoms (loss of peripheral vision, blackout). Absolute incapacitation time was 17 s, while relative incapacitation time was 11 s (total incapacitation time was 28 s).

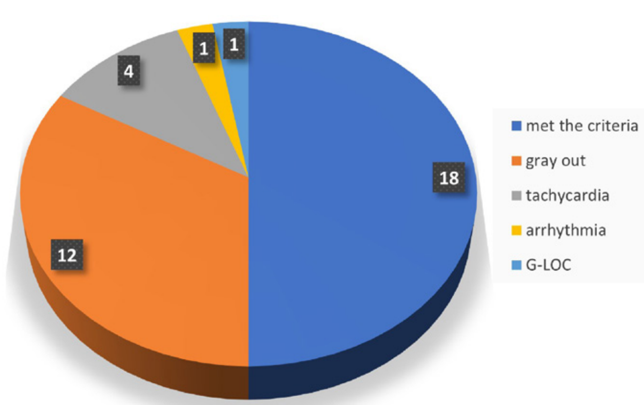

Fig. 2. Results of selective G_z tolerance testing.

The first part of the test (plateau at 2 G) is extracted and considered a separate test. HRV indices (SDNN and RMSSD) were calculated for the first part of the test as well as for the entire test.

The Mann–Whitney *U*-test was used for data processing. The results are presented in **Table I**. The results show that there is a statistically highly significant difference in HRV parameters (SDNN, RMSS) for the first plateau of 2 G between candidates who passed the test, which makes them eligible for training on jet trainer aircraft (Group 1), and those who failed the test (Group 2) ($P < 0.01$). There is also a statistically highly significant difference between the two groups ($P < 0.01$) when the entire test is considered.

DISCUSSION

The relationship between cardiovascular index responses (HR, mean arterial pressure, stroke volume, cardiac output, and total peripheral resistance) and G tolerance (maintaining consciousness) is complex and difficult to measure with physical (fitness) training parameters.[16] Chiang et al. have successfully introduced a new cardiac output index (CFI) that is related to body weight and HR and has a positive correlation with +G_z tolerance.[4] However, compared to CFI, HRV is a more comprehensive +G_z tolerance indicator due to its dependence on various organ systems, such as the autonomic, cardiovascular, central nervous, endocrine, and respiratory systems, and consequently provides for a more thorough +G_z tolerance assessment. For the purposes of this study, HRV parameters in candidates for jet trainer aircraft have been calculated.

During the standard selection process, the relaxed G_z tolerance of a candidate, which is in direct correlation with the cardiovascular ability to respond to +G_z acceleration, has been assessed using established criteria (functional endpoints). Loss of peripheral vision and extreme pulse rate are the most common causes for failed tests for the candidates (16 out of 18 failed tests); one candidate failed the test due to cardiac arrhythmia, and one candidate experienced G-LOC, which is expected considering the magnitude and onset of the acceleration (5.5 G_z, $0.1\,G \cdot s^{-1}$).[7]

Looking at the results of the first part of the test with constant acceleration, i.e., the 60-s 2-G_z plateau, the results have shown that there are significantly lower values in all time domain indices of HRV (SDNN and RMSSD) in Group 2 (comprised of candidates who failed the test). The mean values for SDNN were 45.98 ± 24.80 ms in Group 1 (candidates who successfully passed the test), while the SDNN was 22.99 ± 12.04 ms in Group 2. Similarly, mean values for RMSSD are higher in Group 1 (46.43 ± 27.08 ms) compared to Group 2 (23.18 ± 12.18 ms). Considering the constant acceleration value of 2 G during this phase, HRV variation between candidates can be explained by individual overall physical status and reaction to present emotional and psychological stressors (anticipation of impending acceleration, fear of the unknown, and

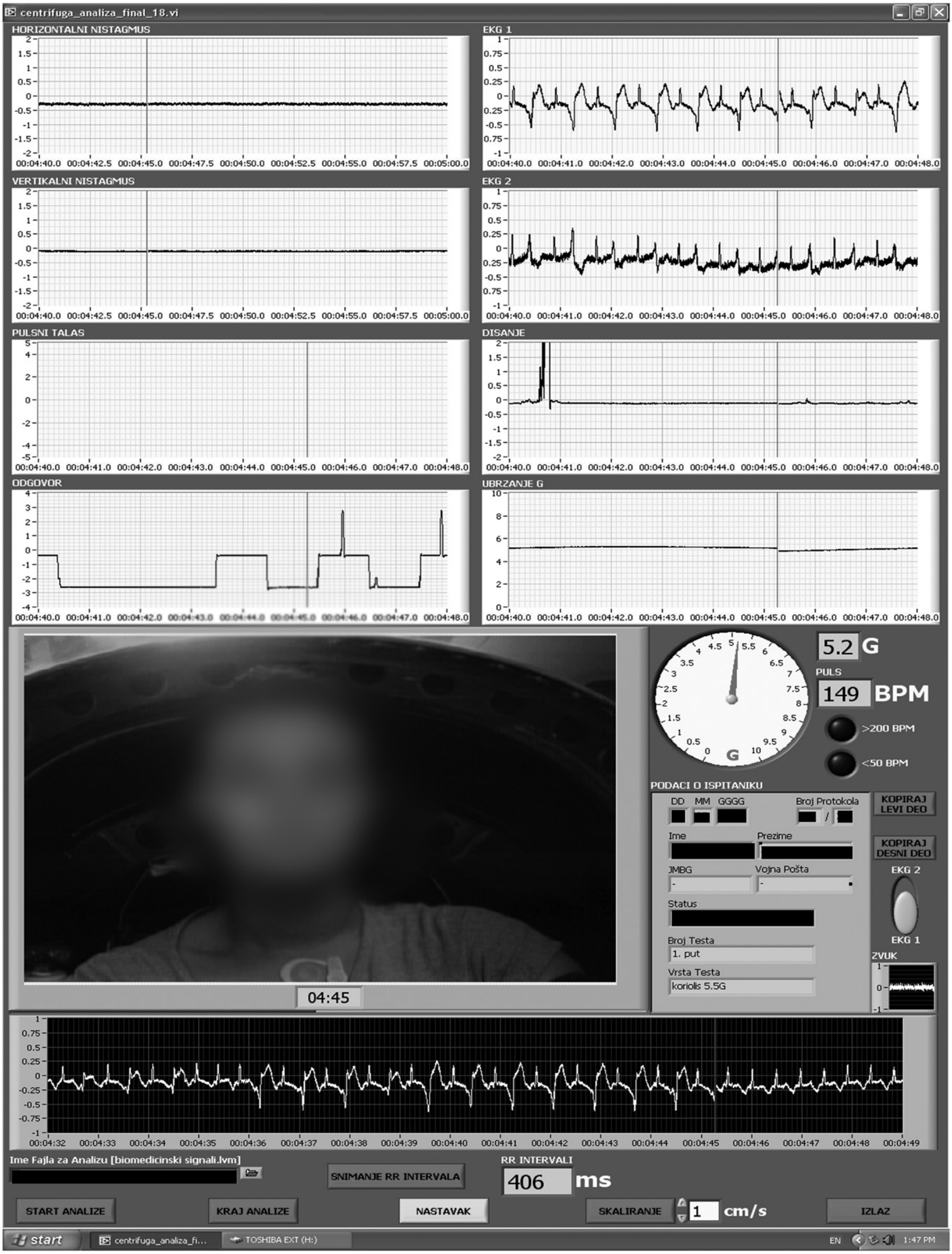

Fig. 3. Graphical user interface for biomedical signals monitoring.

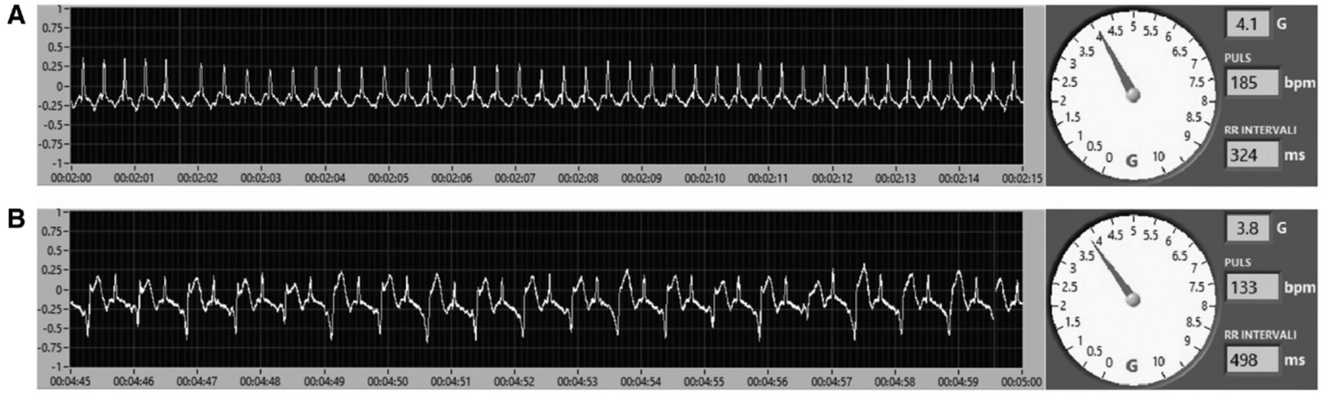

Fig. 4. A) Tachycardia and B) bigeminy observed in some of the pilot candidates.

fear of failing the test). A study from the Portuguese Air Force[22] similarly found that the main factor causing stress and increased sympathetic modulation observed in pilots is uncertainty about the event occurring. Pilots exhibited lower HRV, even in relation to simulated air combat maneuvers.[22] Furthermore, Chen et al. found by monitoring 24-h ECG that pilots who experienced G-LOC (or vasovagal syncope) had significantly reduced time domain parameters of HRV, which may be due to an increase in sympathetic tone and a decrease in parasympathetic tone.[3] The results obtained in this study show particularly low values of HRV parameters for one candidate who experienced G-LOC (SDNN 18.22 ms, RMSSD 18.37 ms) compared to general results reported in the literature.[18,24] These findings show that the first part of the test (60-s $+2\text{-}G_z$ plateau), although physically tolerable for all candidates, demonstrated significantly lower HRV parameters for candidates who later failed the test.

Looking at the results for the entire test (initial 2-G acceleration plateau, constant-rate acceleration increase, followed by the constant-rate acceleration decrease, and ending with the 2-G plateau, Fig. 1), there is also a significant difference in HRV parameters between the candidates who passed the test and those who failed it ($P < 0.01$). Average RMSSD values were 110.2 ± 39.75 ms in Group 1, while the RMSSD was 69.84 ± 33.50 ms in Group 2. Similarly, SDNN values were higher in Group 1 (109.99 ± 39.64 ms) compared to candidates in Group 2 (69.70 ± 33.45 ms). This can be explained by the effects of the onset of acceleration, which changes the HR itself, decreasing the interval between two consecutive heartbeats and decreasing HRV. Similar results were obtained in the Indian study, where 17 healthy male subjects were exposed to the acceleration of $+3\ G_z$.[19] The results showed a reduction in all the time domain indices of HRV (namely variance, SDNN, pNN50, and RMSSD) due to the activation of the sympathetic nervous system and the reduction of parasympathetic influence. The parameters returned to baseline values immediately after exposure to acceleration.[19] The results obtained in this study indicate the individual sensitivity of the cardiovascular system to $+G_z$ acceleration, which is attributed to the specific response of the BR. During the recovery phase (2-G plateau after the acceleration decrease), the vagally mediated parasympathetic nervous system predominates, which increases HRV. RMSSD, as a general indicator of parasympathetic regulation of the heart, is generally used to investigate topics like the impact of training loads and recovery processes. Additionally, the presented research findings demonstrate large individual differences in HRV related to G tolerance during the 2-G plateau acceleration recovery phase,

Table I. HRV Time Domain Parameters.

HRV INDEX & CATEGORY	MEAN	SD	MEDIAN	MIN	MAX
SDNN plateau 2 G					
Group 1	45.98 ms	24.80 ms	42.47 ms	9.35 ms	105.87 ms
Group 2	22.99 ms	12.04 ms	23.81 ms	5.27 ms	46.92 ms
RMSSD plateau 2 G					
Group 1	46.43 ms	27.08 ms	42.84 ms	9.42 ms	106.69 ms
Group 2	23.18 ms	12.18 ms	24.00 ms	5.31 ms	47.24 ms
SDNN entire test					
Group 1	109.99 ms	39.64 ms	112.92 ms	38.13 ms	187.20 ms
Group 2	69.70 ms	33.45 ms	60.54 ms	30.40 ms	160.84 ms
RMSSD entire test					
Group 1	110.2 ms	39.75 ms	113.14 ms	38.20 ms	187.74 ms
Group 2	69.84 ms	33.50 ms	60.67 ms	30.46 ms	161.17 ms

SDNN: standard deviation of the normal-to-normal interval; RMSSD: root mean square of successive differences.
Group 1: candidates met criteria; Group 2: candidates did not meet criteria.

which can give valuable information on the reduced resilience of the CVS in conditions of $+G_z$ stress.

The results obtained in this study show that candidates in Group 1 had significantly higher HRV parameters compared to Group 2 candidates within both testing phases, i.e., within the first $+2\text{-}G_z$ plateau phase and during the entire test. This leads to the conclusion that HRV within the first phase can be used as a predictor of $+G_z$ tolerance for the entire high-G selective test.

In the end, it can be concluded that the increased values of $+G_z$ acceleration to which pilots are exposed during a flight of modern combat aircraft lead to changes in the balance of the ANS, which can be assessed by heart rate variability. The results suggest that HRV is positively correlated with G-tolerance in both phases of the considered high-G selective test and can be used as an additional selection tool. The results presented in this study refer to Air Force Academy selection candidates. One of the compound factors that could potentially influence the individual candidate's results, namely a candidate's physical fitness,[25] has not been considered in this study. Certainly, one of the limitations of this study is the relatively small number of test subjects. For example, the sample of female applicants (only three candidates) is especially small for a relevant general conclusion to be drawn. An additional direction for further research is to consider measuring HRV at rest, where the psychological excitement factor would be excluded, and to compare obtained results with the established $+G_z$ tolerance of a candidate. Further studies are needed to quantify the effect of heart rate variability on acceleration endurance and flight performance during an operational flight (high-G human centrifuges) in trained pilots. One of the future research directions is to investigate if the techniques for increasing HRV and HRV-guided training could considerably increase $+G_z$ tolerance.[12,13]

ACKNOWLEDGMENTS

The authors acknowledge Prof. Dr. Andja Cirkovic from the Department of Medical Statistics and Informatics, Medical Faculty, University of Belgrade, for her assistance with statistical analysis.

Financial Disclosure Statement: This research was funded by the University of Defence of the Republic of Serbia, grant number MFVMA 02/22-24, and by the research grants of the Serbian Ministry of Science, Technological Development and Innovations, grant No. 451-03-68/2023-14/200066. The authors have no conflict of interest to report for this study.

Authors and Affiliations: Nenad Bacevic, M.D., Medical Faculty, University of Belgrade, Belgrade, Serbia, and Department of Aviation Physiology, Aero Medical Institute, Zemun, Serbia; Milica Ninkovic, Ph.D., Full Professor, Medical Faculty of the Military Medical Academy, University of Defence, Belgrade, Serbia, and Institute of Medical Research, Belgrade, Serbia; Milijana Drvendzija, M.D., Medical Faculty, University of Belgrade, Belgrade, Serbia, and the Department of Aviation Physiology, Aero Medical Institute, Zemun, Serbia; Jelena Vidakovic, Ph.D., M.M.E., Research Associate, Faculty of Mechanical Engineering, University of Belgrade, and the Lola Institute, Belgrade, Serbia; Marina Bacevic, M.D., Medical Faculty, University of Belgrade, Belgrade, Serbia, and General Hospital, Pancevo, Serbia; and Pavle Stepanic, M.E.E., Faculty of Electrical Engineering, University of Belgrade, and the Lola Institute, Belgrade, Serbia.

REFERENCES

1. Alvim KM. Greyout, blackout, and G-loss of consciousness in the Brazilian Air Force: a 1991–92 survey. Aviat Space Environ Med. 1995; 66(7): 675–677.
2. Burton RR. A conceptual model for predicting pilot group G tolerance for tactical fighter aircraft. Aviat Space Environ Med. 1986; 57(8):733–744.
3. Chen TX, Huang YG, Wang L, Sun SZ, Wang LJ, Ji GY. Assessment of autonomic nervous function during orthostatic stress in pilots with history of syncope. Space Med Med Eng (Beijing). 2002; 15(2):89–92.
4. Chiang KT, Tu MY, Lin YJ, Hsin YH, Chiu YL, et al. A cardiac force index applied to the G tolerance test and surveillance among male military aircrew. Int J Environ Res Public Health. 2021; 18(16):8832.
5. Chung KY, Lee SJ. Cardiac arrhythmias in F-16 pilots during aerial combat maneuvers (ACMS): a descriptive study focused on G-level acceleration. Aviat Space Environ Med. 2001; 72(6):534–538.
6. Convertino VA. High sustained +Gz acceleration: physiological adaptation to high-G tolerance. J Gravit Physiol. 1998; 5(1):P51–P54.
7. Green ND. Effects of long-duration acceleration. In: Gradwell DP, Rainford D, editors. Ernsting's aviation medicine, 4th ed. London (UK): Hodder Education; 2006:137–158.
8. Hanada R, Hisada T, Tsujimoto T, Ohashi K. Arrhythmias observed during high-G training: proposed training safety criterion. Aviat Space Environ Med. 2004; 75(8):688–691.
9. Houghton JO, McBride DK, Hannah K. Performance and physiological effects of acceleration-induced (+ Gz) loss of consciousness. Aviat Space Environ Med. 1985; 56(10):956–965.
10. IBM Corporation. IBM SPSS Statistics for Windows. Version 21.0. Armonk (NY): IBM; 2012.
11. Kim HG, Cheon EJ, Bai DS, Lee YH, Koo BH. Stress and heart rate variability: a meta-analysis and review of the literature. Psychiatry Investig. 2018; 15(3):235–245.
12. Kiviniemi AM, Hautala AJ, Kinnunen H, Tulppo MP. Endurance training guided individually by daily heart rate variability measurements. Eur J Appl Physiol. 2007; 101(6):743–751.
13. Lehrer PM, Gevirtz R. Heart rate variability biofeedback: how and why does it work? Front Psychol. 2014; 5:756.
14. Lyons TJ, Davenport C, Copley GB, Binder H, Grayson K, Kraft NO. Preventing G-induced loss of consciousness: 20 years of operational experience. Aviat Space Environ Med. 2004; 75(2):150–153.
15. McCraty R, Shaffer F. Heart rate variability: new perspectives on physiological mechanisms, assessment of self-regulatory capacity, and health risk. Glob Adv Health Med. 2015; 4(1):46–61.
16. McIntee MFM, Kinchen MJ, Ennis EM, Horning DS, Geier BA, et al. F-22 pilot heart rate response to+ Gz and relationship to pilot fitness using U.S. Air Force fitness test scores. Wright-Patterson AFB (OH): Aerospace Medicine Department, School of Aerospace Medicine; 2015. Report No: AFRL-SA-WP-SR-2015-0024.
17. McKenzie I, Gillingham KK. Incidence of cardiac dysrhythmias occurring during centrifuge training. Aviat Space Environ Med. 1993; 64(8): 687–691.
18. Munoz ML, Van Roon A, Riese H, Thio C, Oostenbroek E, et al. Validity of (ultra-) short recordings for heart rate variability measurements. PLoS One. 2015; 10(9):e0138921.
19. Pipraiya R, Tripathi KK, Dogra MM. Effects of+ Gz acceleration on indices of heart rate variability. Indian J Aerosp Med. 2005; 49(1):37–47.
20. Rickards CA, Newman DG. G-induced visual and cognitive disturbances in a survey of 65 operational fighter pilots. Aviat Space Environ Med. 2005; 76(5):496–500.
21. Rudnjanin S, Arsic-Komljenovic G, Pavlovic M, Vujnovic J. Loss of consciousness as criterion of+ Gz tolerance at Institute of Aviation Medicine MMA during+ Gz acceleration selective test. Acta Physiol Hung. 2006; 93(4):371–376.
22. Santos S, Parraca JA, Fernandes O, Villafaina S, Clemente-Suarez VJ, Melo F. The effect of expertise during simulated flight emergencies on the autonomic response and operative performance in military pilots. Int J Environ Res Public Health. 2022; 19(15):9141.

23. Scott JP, Jungius J, Connolly D, Stevenson AT. Subjective and objective measures of relaxed +Gz tolerance following repeated +Gz exposure. Aviat Space Environ Med. 2013; 84(7):684–691.
24. Shaffer F, Ginsberg JP. An overview of heart rate variability metrics and norms. Front Public Health. 2017; 5:258.
25. Souza HCD, Philbois SV, Veiga AC, Aguilar BA. Heart rate variability and cardiovascular fitness: what we know so far. Vasc Health Risk Manag. 2021; 17:701–711.
26. Stepanic P, Bacevic N, Krosnjar A, Vidakovic J. Development and implementation of human centrifuge acquisition system. In: Lisov M, Radović Lj, editors. Aircraft – A. Proceedings of the 9th International Scientific Conference on Defensive Technologies - OTEH 2020; 15-16 October 2020; Belgrade, Serbia. Belgrade (Serbia): Military Technical Institute; 2020:73–76.
27. Stevenson AT, Scott JPR, Chiesa S, Sin D, Coates G, et al. Blood pressure, vascular resistance, and +Gz tolerance during repeated +Gz exposures. Aviat Space Environ Med. 2014; 85(5):536–542.
28. Whinnery JE, Burton RR. +Gz-induced loss of consciousness: a case for training exposure to unconsciousness. Aviat Space Environ Med. 1987; 58(5):468–472.