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REVIEW ARTICLE

POLISH STUDIES ON HUMAN AND ANIMAL TOLERANCE TO ACCELERATION

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Abstract: The objective of this article is the description and attempt at systematization of Polish aviation medicine studies. For over 60 years, I was involved in numerous research and development studies that brought about the unprecedented growth of this scientific discipline in Poland. In this article, I classified my research interest into four main categories to which appropriate commentaries were provided. Summarizing my research activities, I point out to the needs and possibilities for further development.

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INTRODUCTION

The main direction of my research interests consisted in problems related to the effect of in-flight conditions on human and animal systems. My scientific accomplishments may be divided into the following 4 subject groups:

1. Studies on the effects of short-term acceleration occurring during emergency and training ejections.
2. Studies on the physiological reactions of humans and animals to various types of acceleration.
3. The search for novel methods for examination and assessment of systemic tolerance to acceleration.
4. The use of physical factors and physiological reactions to increase the systemic tolerance to acceleration.

VERY SHORT ACCELERATIONS

The first subject group consists of the studies of the effects short-term acceleration occurring during ejections on pilots' bodies. In these studies, first of this type to be conducted in Poland, Jasiński, Drobisz, and I focused on physiological and psychological reactions of humans subjected to high acceleration [16,27,52,78]. As the results of the studies, we observed a number of changes related to the reactions within the cardiovascular system and the release of catecholamines and 17-ketogenous steroids due to excessive stimulation of the sympathetic nervous system. The conclusions of the studies conducted together with Podgórski and Domaszuk were presented in numerous publications [42,52,67,82]. As shown by the findings presented therein, even short-lasting acceleration stimulate the pituitary-adrenal hormonal axis, largely dependent on the accompanying stimulatory excitations and emotions. Notably, the increase in hemodynamic reactions and hormonal secretion is a good indicator of psychological excitation in emergency situations, also in-flight situations.

Significant emotional excitations of subjects provided the ground for introduction of compulsory ejection trainings to prepare pilots for abandoning their planes in a safe manner. Being the only Polish researcher authorized to perform ejection trainings, I personally carried out all tests using the training ejection device. I was also the first subject, who ejected himself 18G with a full

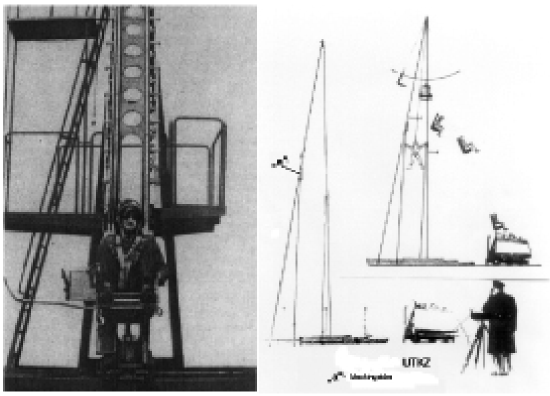


Fig. 1. Training catapults NKTŁ-3 and UTKZ.

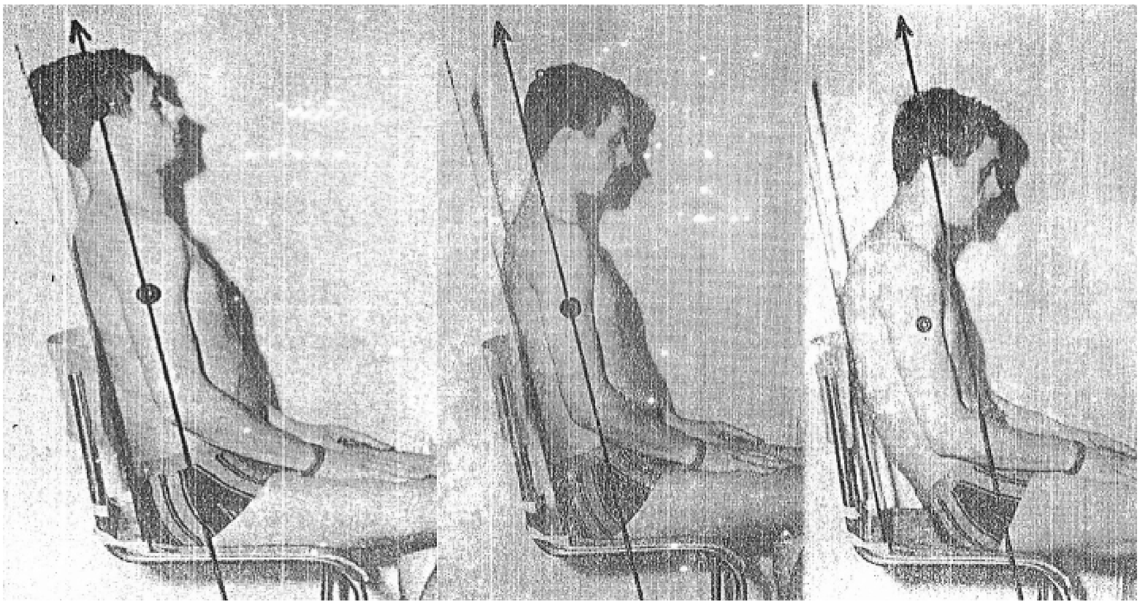


Fig. 2. Studies on the distribution of the centers of gravity at various positions of body within the ejection seat.

cartridge gunpowder, from a newly developed ejection device UTKZ (Fig. 1.).

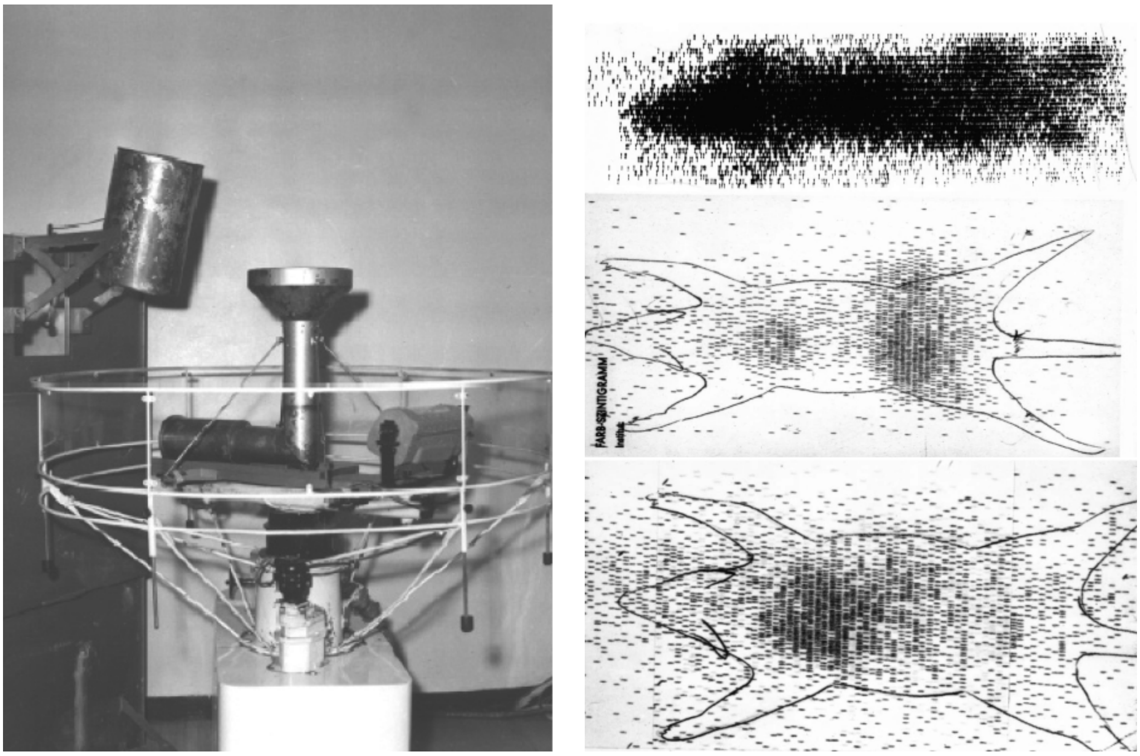
Another article published by the same group [69] focusing on the distribution of body centers of gravity in relation to the G-force vectors, was of particular theoretical as well as practical importance. Together with the co-authors, I determined the pilot body positions which, when adopted within the ejection seat, may result in the risk of spinal injuries (Fig. 2.). This study, which received the third-degree prize in the research competition announced by the Minister of Defense served as the basis for my expert's opinion on the changes introduced to the design of ejection seats in training devices.

Also of practical importance were the results of studies carried out together with Jasiński and Szajnar [31,32,76] concerning optimization of the ejection process as it was demonstrated that the efficiency of the seat ejection system could be improved in relation to the conventional solutions. In the studies, we presented a method for solving the problem of reduction of gravitational forces experienced by the pilot during the seat ejection phase.

Further conducted scientific assessment of the effects of impact of G-forces upon rapid restrainment falls from the heights in the devices aimed at preventing falls of humans working on elevated structures. I also analyzed the risks of spinal fractures due to improperly worn harness gear. These studies were conducted in collaboration with the occupational safety experts of the Central Institute for Labour Protection in Łódź. Together with Domaszuk, Truszczyńska, and Lewkowicz, I moreover studied the problem of spinal pains in pilots and the methods to prevent them [11,34,35,87,89].

SLOWLY INCREASED AND PROLONGED ACCELERATIONS

The second group of studies focused on the reactions of humans [80,81] and animals [17,68,90] to various acceleration conditions. Most of these studies were team efforts of numerous authors studying these problems worldwide. A number of hemodynamic, electrophysiology, radiology, radioisotope and morphological methods were applied in these studies. Most studies focused on hemodynamic disturbances due to blood flowing in the direction of the G-force vectors and to the



a) b)

Fig. 3. a) The animal centrifuge (examination of rats following intravenous administration of radioisotopes in an isotonic solution). b) Administration of radioactive sodium (22Na), c) apparent blood displacement (131I-albumins) in simulated zero-gravity conditions, d) caudal dislocation of blood (51Cr-globulin) under a directional gravitational force.

stasis of blood within the vessels, organs, and tissues.

In relation to the animal studies, of note was the introduction of a new Polish centrifuge for animals (Fig. 3a.) with the feature of liquid nitrogen-freezing of animals subjected to acceleration. I was also involved in the development of the guidelines regarding the technical requirements of this centrifuge. Introduction of the animal centrifuge made it possible to conduct studies on animal tissues and organs which are inaccessible in human studies. The methodology of the studies consisted in determination of the location of intravenously administered isotopes and the assessment of this location in organs and tissues (Fig. 4b.). Studies conducted in collaboration with Barański, Edelwejn, Jurczak, Czerski, Domaszuk, and Stojanowski involved examination of Wistar rats (Fig. 4.) in various experimental settings [1,3,12,56,85].

This allowed for determination of hemodynamic disturbances resulting from acceleration of varied durations; the results of the animal studies were published as scientific articles [6,7,8,9,18,53]. The aforementioned studies allowed for the formulation of following conclusions:

- In centrifuge settings, displacement of systemic fluids and proteins of varied molecular mass occurs as confirmed by isotopic examinations [3,9];
- In repeated experiments involving long durations of exposure to G-forces, capillary hypertrophy and dilation of extracellular spaces occur together with an increase in permeability of vascular walls resulting in morphological changes within the muscles, kidneys, and liver as confirmed by isotopic assays following prolonged hypodynamia [7,8];
- Change in rat's position involving pelvis being elevated at an angle of 30 degrees led to prolonged hypodynamia imitating zero-gravity conditions, muscle ischemia and plethora of the organs within the upper part of the body. The disturbances in the muscular circulation in limbs are maintained much longer than those within the kidneys, liver, and brain; on the other hand, no dilation of capillaries occurs in pulmonary circulation;
- Hemodynamic and bioelectric disturbances within the skeletal muscles as observed upon centrifugation are much stronger when observed after long-term hypokinesis (Fig. 4b.).

The behaviors of the circulatory system under extreme acceleration exceeding the maximum tolerance of humans were also studied in aggressive baboon monkeys (Fig. 5.). The studies were carried out in collaboration with Zbigniew Edelwejn who assessed the brain function. The objective of those studies was to assess the behavior of the circulatory system after the maximum tolerance of acceleration manifested by G-force induced loss of consciousness (G-LOC). Therefore, it was interesting to study the changes in the function of the circulatory system increasing up to the threshold of animal's death. After resuscitation, the circulatory function went back to normal. The acceleration used in the studies were adequate to those used in the line training of pilots, thus confirming the epistemic value of these studies of extreme circulatory disturbances that occur following a prolonged loss of consciousness.

The analysis of changes in circulatory function in the critical phase was particularly valuable as

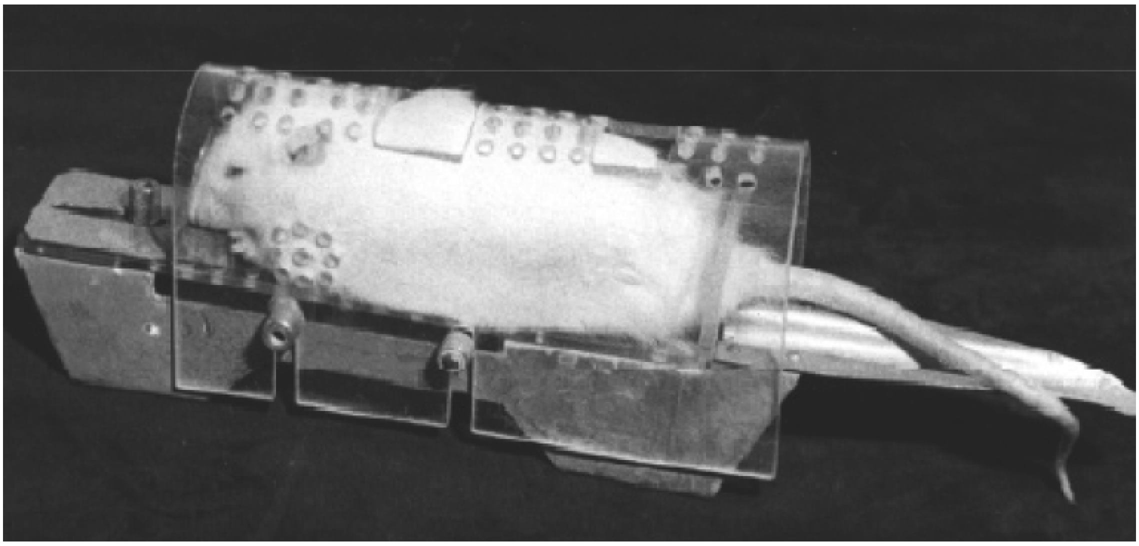


Fig. 4. Rat placed in the animal centrifuge cabin cage.

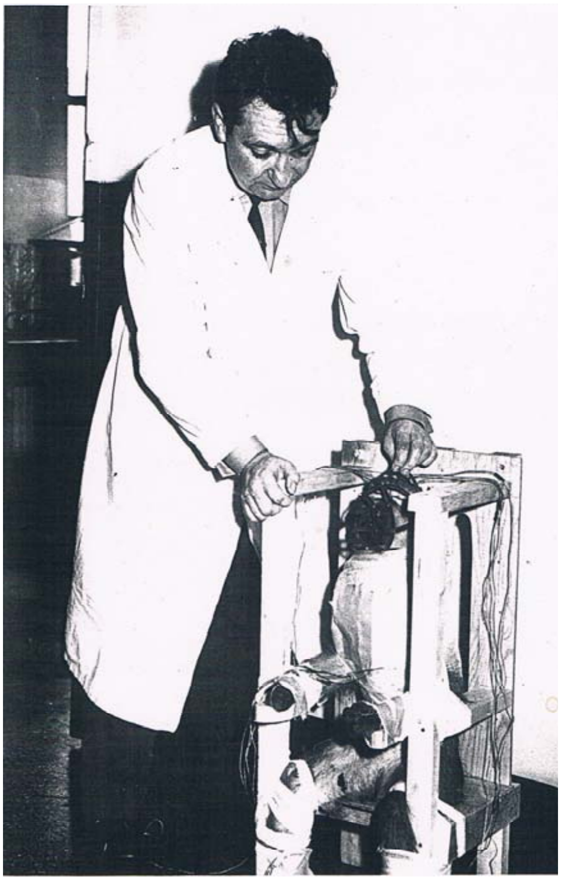


Fig. 5. A baboon being prepared for examination in the animal centrifuge.

it allowed the assessment of the resilience of the heart. Results of studies [14] conducted together with Edelwejn and Kwarecki allowed to monitor hemodynamic disturbances increasing in proportion to the acceleration. This practical aspect of the results consisted in the gravitational force exposure program corresponding to the characteristics of stimuli used in the evaluation of acceleration limits in pilots [10].

The analyses of cardiac arrhythmias in pilots undergoing human centrifuge evaluations (Fig. 6.) may also be included in this group of studies [15,21,29,83,90]. In collaboration with German researchers: Papenfuss, Kollande, Wirth, and Ponisch [30,41,77] I proposed a classification of this types of disturbances including their incidence rates and described their importance in aviation medicine certifications. Similar studies were conducted with Lech Kopka [20] in a group of 80 pilots, of whom 5 experienced a G-LOC. Physiological changes observed in these pilots were described in detail by means of cardiological analysis to observe that the behavior of the cardiovascular system during the centrifuge tests depended largely on the status of the autonomic nervous system.

Rapid changes of potentials within the system observed during the tests in the conditions of cardiac ischemia are very valuable for the assessment of the efficiency of the electrical conduction

Fig. 6. Human centrifuge at the Military Institute of Aviation Medicine.

system of the heart. In addition, we observed that a reduction in the heart rate occurring already at the increasing G-force phase is a signal of disturbed compensation capabilities of the electrical conduction system and an indication for immediate discontinuation of the test.

In another studies conducted together with Marks, Zużewicz [29] as well as with Ponish and Wirth [51,83], we observed that the principal cause of arrhythmias occurring during the exposure to acceleration consists in rapid changes in the potential within the autonomic nervous system as well as to the fact that in subsequent trials, even when conducted in the same subjects, the G-force stimulus does not stimulate the system in the same manner. One of the conclusions drawn from these studies is that higher accelerations are between tolerated by pilots with hyperactive and intermediate type of parasympathetic nervous system.

An example record of physiological parameters measured to determine the limits of tolerance to acceleration presented in Fig. 7. includes the following standard parameters: ECG, respiratory wave, acceleration curve and time of response to visual stimulus appearing within the peripheral visual field. It should be noted that Fig. 7 also presents newly introduced physiological measurement parameters such as the temporal artery flow rate assessed by Doppler ultrasonography.

The use of a proprietary Doppler method for the measurement of temporal artery blood flow rates in subjects tested in the human centrifuge [45,48,62] allowed for precise identification of the moment when visual disturbances occurred. The moment of change in the direction of the blood flow is marked on the mean flow rate curve (Fig. 7. "maximum acceleration point"). The time span of the change in the direction of the blood flow measured until the disappearance of momentary flow pulsation indicated the time until the loss of peripheral vision. The moment of disappearance of momentary flow pulsation indicated the acceleration tolerance limit. Also included in Fig. 7. is the phase of centrifuge deceleration when venous flow rapidly returns into the vascular system of the head.

The developed method for the assessment of tolerance to acceleration allowed for full objectivization of hitherto subjective evaluation of results, thus facilitating unquestionable identification of simulating or dissimulating subjects [46]. Due to the long time span between the start of blood outflow within the temporal artery and the loss of peripheral vision, the method increased the safety of centrifuge tests by preventing cases of G-LOC. Fig. 8. presents the instrumentation and the technique for the Doppler probe used to measure the flow of blood within the temporal artery being mounted on the subject's head [84].

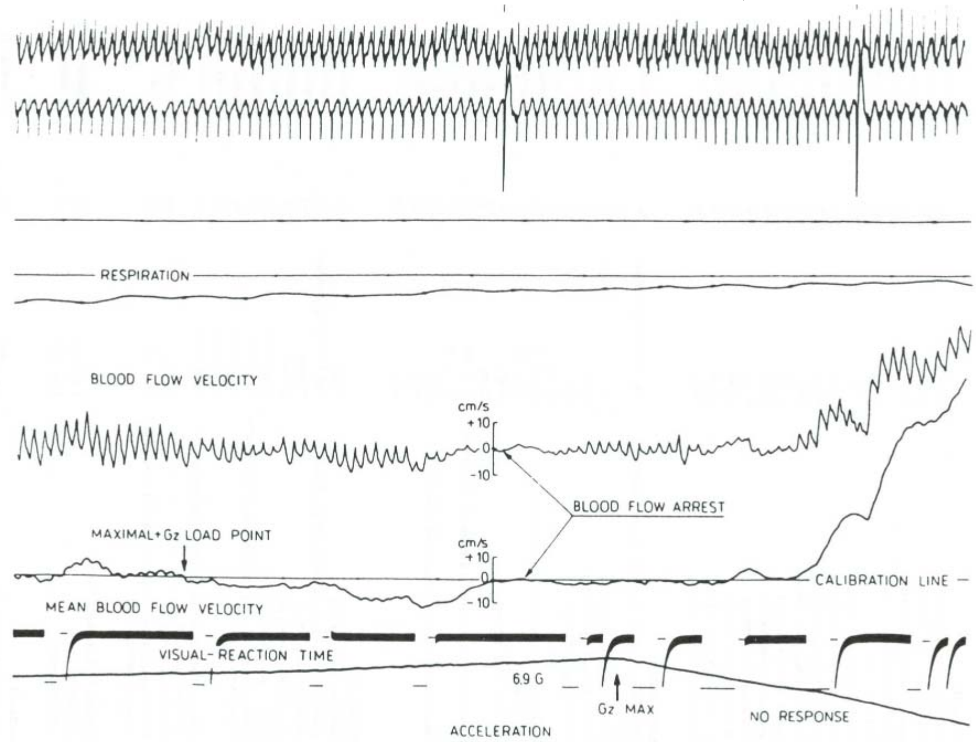


Fig. 7. A fragment of the record of parameters measured in a person subjected to human centrifuge test while approaching the maximum acceleration and during subsequent deceleration.

Other studies in this group were related strictly to ophthalmological problems [23,24, 25,36,37,38,44,72]. Principally, they pertained to two important research directions. The first direction, pursued together with Kożuchowska and Tajchert, involved isotopic verification of the impact of sudden dislocations of large blood volumes on intraocular pressure and on the permeability of the blood-ocular barrier for blood proteins [25]. The other direction or research, pursued together with Kożuchowska and Zawitkowski [23,24,72], was aimed at elucidation of the role of intraocular pressure in the development of visual disturbances that always preceded the loss of consciousness in routine trials. The results of these studies partially explained the role of intraocular pressure in the development of visual disturbances while also pointing to the possibility of G-LOC occurring without preceding visual disturbances in pilots with low intra-ocular pressure.

Other studies that may be included in this group were biochemical analyses of blood under varying acceleration.

Fig. 8. Set up of the Doppler sensor to measure the blood flow rate at the temporal artery level.

HUMAN CENTRIFUGE STUDIES

The third subject group consists of studies devoted to the development of methodologies of human centrifuge test for airborne personnel and to the assessment of the results of these tests. As part of this group of studies, and in collaboration with Jasiński, we analyzed the relationships between the age and morphotic features of pilots and the limits of tolerance to acceleration [40,54,58,75]. These studies were of considerable epistemic value. Of particular note is the practical applicability of these studies in routine tests of the airborne personnel with the aim of determining the limits of systemic endurance and for medical certification-related purposes. These studies [20,61] facilitated an objective assessment of compensatory reactions within the circulatory system in various in-flight conditions, thus providing a potential basis for routine diagnostic examinations of pilots. Articles on the subject were published in Polish as well as international journals [5,22,30,41,43,59,60,70,77]. In these studies, conducted together with Bembnowski, Kotovskaya, Barański, Papenfuss, and Kollande, we described e.g. the human centrifuge tests making use of three different acceleration programs. The first program, referred to as the linear program, facilitated precise determination of acceleration at which visual disturbances resulting from the reduced pressure within the ocular artery are observed. The second program, referred to as the temporal program, allows for the assessment of the duration of the efficiency of compensatory mechanisms of the circulatory system while the third program, referred to as the interval program, exposes subjects to conditions similar to those experienced during the flight with regard to compensation of rapidly increasing multidirectional accelerations.

Following appropriate verification and determination of grading scales, the developed programs [43,70] were introduced to routine examinations of the airborne personnel. Of particular importance was the development of a visual field meter facilitating the assessment of visual perception within the peripheral field upon the exposure to acceleration (in collaboration with Wołkanowski) [91].

The first visual field meter (Fig. 9.) facilitated the assessment of peripheral perception of light stimuli traveling along the arms at stochastic speeds until the loss of peripheral vision indicative of the limit of tolerance to acceleration. Introduction of the second field meter (Fig. 9.) was aimed at determination of the peripheral perception of stationary objects changing their shapes until the loss of peripheral vision and the lack of response to the shape changes.

The aforementioned field meters were used in my collaborations with Truszczyński and Lewkowicz [33,39,70] aimed at the assessment of the effects of acceleration of various characteristics on simple reaction times in pilots.

METHODS TO INCREASE THE TOLERANCE ACCELERATION

The fourth subject group consists of studies [2,26,28,50,65,71,74,86,88] on the applicability of certain forms of physical training for increasing the systemic tolerance to acceleration. Also included in this group are the studies [13] conducted together with Dziuk and Sulejnis regarding the assessment of correlations between the development of selected motor abilities and the tolerance to acceleration (Fig. 10.).

Together with Bembnowski, Błaszczakiewicz, and Zaremba [4], I demonstrated that among the different training devices used to increase the tolerance to in-flight conditions, looping exercises are too burdensome for the cardiovascular system and therefore their intensity should be reduced. The tolerance of a trained body to acceleration depends to some degree on the motor characteristics developed during the training, including strength, speed, or speed-endurance [13] which improve the tolerance to acceleration. Exercises aimed at the development of the aforementioned motor skills were included in the physical education curricula of pilot candidates of the Polish Air Force Academy in Dęblin (PAFA) and as a compulsory element of training for pilots undergoing annual trainings a Military Training and Fitness Centers (MTFC). The developed training program consisted of 2 stages. The first stage consisted of isometric training of selected muscle groups along with respiratory exercises and maximum muscle straining [79]. The second stage consisted of type L1 circo-respiratory trials to increase the blood pressure in coordination with muscle straining and increasing acceleration within a centrifuge [47]. These forms of the training turned out to be an efficient method for significant enhancement of tolerance to slowly and rapidly increasing acceleration.

The tolerance to acceleration was the major problem in the period of the first space flights, and therefore the training I held together with Jan Marks at MTFC was aimed at increasing this tolerance. Coordination of the entire specialized training and candidate selection program was in the hands of Krzysztof Klukowski. The exercise program included individual gymnastic elements verified at PAFA. Following appropriate physiological development of each exercise, the exercise set was introduced into the pilot training curricu-

Fig. 9. Visual field meter (first on the left) installed in the centrifuge chamber.

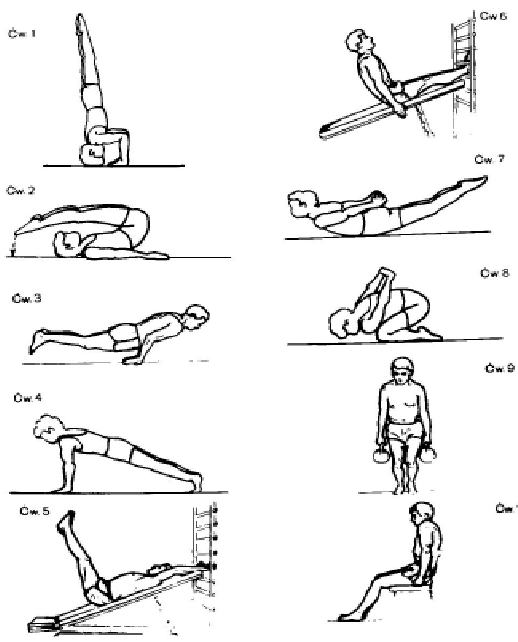


Fig. 10. A set of exercises aimed at preparing pilots for the correct performance of L1 straining maneuver.

lum at MTFC. The results of physiological studies carried out at MTFC were published in [55], with the general forms of physical and fitness training being described by Dr. Jan Marks. Let me also mention that I also took part in the program for the selection of the first Polish cosmonaut [66] as regarded the assessment of the candidates' tolerance to acceleration. The G-force tolerance tests were conducted in the MIAM's human centrifuge.

The assessment of physical fitness indicators for use in aviation performed together with Jethon, Sarol, and Dziuk [19] showed that the Crampton's indicator and Skibinski circo-respiratory indicator were sufficient for determination of adjustment to hypoxic conditions while the Mondurant index was sufficient for determination of G-force compensation.

Maximum systemic tolerance to acceleration depends on the age and body structure and is observed in pilots below the age of 38, with lowest values being observed in tall and lean individuals [54].

Studies on the methods to increase the tolerance to acceleration also included the studies of anti-gravity suits of various designs aimed at protecting individuals from the effects of G-forces [30,49,57,63,64]. As part of my collaborations with Papenfuss, Kollande, Ponish, and Wirth of the German Air Force Institute of Aviation Medicine in Königsbrück, I studied the the effectiveness of LIBELLE hydrostatic anti-G suit. Similar studies were conducted in collaboration with Albery and Bolia as part of individual research contract for joint Polish-American studies on the efficacy of various types of anti-gravity apparel [63,64,73].

SUMMARY

During the 60 years of my employment at the Military Institute of Aviation Medicine, I gathered rich experimental as well as medical experience in examinations of various types of consequences of acceleration and other conditions exerted on living organisms during continuous or periodic exposure of humans and animals in centrifuges. With regard to these studies, I was able not only of making use of the established hemodynamic, electrophysiology, radiology, radioisotope and morphological methods, but also of developing original examination methods established on the basis of proprietary technical solution ideas.

Technological advances in the coming years will undoubtedly increase the burden to pilots, creating the need for the search for appropriate psychophysiological characteristics of candidates as well as for appropriate aviation medicine-related training and education. As the speed and complexity of in-flight maneuvers would increase, so will be the importance of ophthalmological examinations aimed at the assessment of the speed of near-to-distant vision shifts, times of perception and correct identification of objects both within the central and the peripheral visual fields. Therefore, the importance of specific ophthalmological trainings aimed at the improvement of accommodation speeds as well as the times of perception and correct identification of objects will also increase.

AUTHORS' DECLARATION:

Study Design: Mieczysław Wojtkowiak; **Data Collection:** Mieczysław Wojtkowiak; **Manuscript Preparation:** Mieczysław Wojtkowiak; **Funds Collection:** Mieczysław Wojtkowiak. The Author declares that there is no conflict of interest.

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