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Mechanisms and Prevention of Acceleration Exposure-Induced Cardiovascular Injuries

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Abstract

Background: The development of high-performance flighter aircraft requires better anti-G ability of aircrew. Under the influence of continuous ±Gz or ±Gx acceleration, aircrew can suffer from cardiovascular change or injuries, which pose a huge threat to flight safety. In recent years, some achievements have been made in the physiological research of sustained ±Gz or ±Gx acceleration, especially the research on the cardiovascular physiological mechanism of sustained ±Gz or ±Gx acceleration. This paper analyzes the research progress. **Methods:** Original studies of any related fields will be included in the analysis. Searching of databases and manual scanning of the reference lists of the articles found during the original search will be performed. The following data items of included studies will be abstracted for analysis: publication year, first author, country, institution, journal and research priorities. **Results:** 28 papers were included in this study. The annual number of publications showed an ascending tendency as a whole and reached its peak in 2014 with a total of 6 documents. The country with the most publications was China. The journals of these papers focused on different fields, including military medicine, integrative medicine, preventive medicine, space medicine, environmental medicine and pharmacology. Research priorities mainly covered cardiac arrhythmia, cardiac structure, cardiovascular function, myocardial injury and myocardial enzyme. **Conclusions:** This paper analyzes the progress of research in the cardiovascular compensatory response. It is expected to provide reference for subsequent exploration of the mechanism of sustained ±Gz or ±Gx acceleration and the selection of ways to protect against anti-G.

Keywords

Acceleration, Cardiovascular Injuries, ±Gz, ±Gx, Mechanisms, Prevention

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1. Introduction

With the development of actual combat training of naval aviation. the take-off and landing tasks of carrier-borne aircraft pilots are more and more frequent, which are vulnerable to the effect of vertical acceleration (±Gz) and horizontal acceleration (±Gx), which has a negative impact on the health of pilots. During the training combat mission, the acceleration experienced by the pilot is characterized by fast growth rate, large G value, long action time and high frequency [1]. Studies have shown that the cumulative high acceleration load in a short period of time will have a series of negative effects on the pilot body, including damage to the spine, cardiovascular system, and optical system [2] [3]. With the development and installation of high-performance carrier-based aircraft, the damage of acceleration load to pilot body will become more prominent. Therefore, focusing on the cumulative acceleration damage effect is the focus of carrier-borne aviation medicine research.

Up to now, many studies have shown that a series of changes and injuries can occur in the heart under the effect of acceleration, such as frequent tachyarrhythmia, significant decrease in left ventricular systolic function, significant increase in serum myocardial enzyme profile activity, and significant damage to myocardial ultrastructure [4]. Some studies suggested that the relevant mechanisms include hemodynamic changes, neuroendocrine stress response, energy metabolism changes and oxidative stress damage [5]. Repeated exposure to acceleration is likely to cause arrhythmia, electrophysiological abnormalities, cardiac function abnormalities, and cardiac remodeling. However, what are the specific effects and mechanisms of action? This paper analyzes the research progress in the cardiovascular compensatory response. It is expected to provide reference for subsequent exploration of the mechanism of sustained ±Gz or ±Gx acceleration and the selection of ways to protect against anti-G.

2. Methods

Original studies of any related fields will be included in the analysis. We search Ovid MEDLINE, Ovid EMBASE, and Web of Science-Science Citation Index Expanded from inception to 30 September 2024. The search strategy will combine medical subject heading terms and keywords of acceleration, ±Gz, ±Gx and cardiovascular injuries. The search strategy will be first developed for Ovid MEDLINE because of its comprehensive search functions, and appropriate modifications will be made as required for the other databases. Additionally, manual scanning of the reference lists of the articles found during the original search will be performed by reviewers to identify studies that were not found from the general search or not indexed in the databases used. All references will be imported into EndNote X21 (Thompson Reuter, CA), and duplicates will be removed. The following data items of included studies will be abstracted: publication year, first author, country, institution, journal and research priorities.

3. Results

We originally screened 346 articles in the database. 94 articles were excluded through manual screening. A total of 224 articles were deemed unfit for inclusion in our analysis due to their stylistic type. Finally, 28 papers were included in this study (Table 1). The annual number of publications showed an ascending tendency as a whole and reached its peak in 2014 with a total of 6 documents. The country with the most publications was China. The journals of these papers focused on different fields, including military medicine, integrative medicine, preventive medicine, space medicine, environmental medicine and pharmacology. Research priorities mainly covered cardiac arrhythmia, cardiac structure, cardiovascular function, myocardial injury and myocardial enzyme.

Table 1. 28 papers included in this study.

Number	Publication year	First author	Country	Journal	Research priorities
1	1994	Skyttä J	Finland	Military Medicine	Cardiac arrhythmia
2	1994	Tripp LD	The United States	Journal of Clinical Pharmacology	Cardiac volumes
3	2001	Guiying Ji	China	Space Medicine & Medical Engineering	Cardiac arrhythmia
4	2001	Zheng Zhang	China	Infection Inflammation Repair	Cell adhesion molecules
5	2002	Zheng Zhang	China	Chinese Journal of Applied Physiology	Cell adhesion molecules
6	2003	Lvjiang Shi	China	Journal of Preventive Medicine of Chinese People's Liberation Army	Apoptosis
7	2004	Lvjiang Shi	China	Journal of Preventive Medicine of Chinese People's Liberation Army	Metallothionein
8	2004	Zawadzka-Bartczak EK	Poland	Aviation, Space, and Environmental Medicine	Cardiac arrhythmia
9	2006	Suhong Guo	China	Journal of Jilin Medical College	Myocardial injury
10	2008	Ying Zhou	China	Acta Physiologica Sinica	Connexin 43
11	2008	Bo Shao	China	Medical Journal of Chinese People's Liberation Army	Heart function
12	2009	Chunmei Song	China	Journal of Hygiene Research	Myocardial enzyme
13	2010	Carter D	Israel	Experimental and Clinical Cardiology	Cardiac dimensions and performance
14	2012	Xijuan Li	China	Journal of Modern Integrative Medicine	Myocardial enzyme
15	2012	Öztürk C	Türkiye	The Anatolian Journal of Cardiology	Cardiac responses
16	2013	Yaping Li	China	Academic Journal of Chinese PLA Medical School	Myocardial microstructure

Continued

17	2013	Jamshidi M	Iran	Journal of the Mechanical Behavior of Biomedical Materials	Finite element method
18	2014	Bo Ye	China	China Medical Herald	Myocardial injuries
19	2014	Lujian Duanmu	China	Shandong Medical Journal	Transmural dispersion of repolarization
20	2014	Liangen Chen	China	Chinese Journal of Comparative Medicine	Glucocorticoid receptors
21	2014	Yaping Li	China	Medical Journal of Air Force	Interleukin
22	2014	Jiangdong Zhao	China	Academic Journal of Chinese PLA Medical School	Microtubule-associated protein light chain 3
23	2014	Lan Wang	China	Medical Journal of Air Force	Connexin 43
24	2016	Tianhua Wang	China	Aerospace Medicine	Myocardial enzyme
25	2018	Hao Liu	China	Shanxi Medical Journal	Inflammatory factors
26	2020	Biye Zhou	China	Chinese Journal of Applied Physiology	Cardiac structure
27	2023	Nannan Sun	China	Academic Journal of Chinese PLA Medical School	Cardiovascular function
28	2024	Jia Zhai	China	Journal of Army Medical University	Heart rate variability

4. Discussion

This paper analyzes the research progress in the cardiovascular compensatory response. It is expected to provide reference for subsequent exploration of the mechanism of sustained ±Gz or ±Gx acceleration and the selection of ways to protect against anti-G. Research priorities in this area includes cardiac arrhythmia, the change of cardiac function, cardiac structure and myocardial enzymes, myocardial injuries and protective measures.

4.1. Cardiac Arrhythmia in Acceleration Exposure-Induced Cardiovascular Injuries

The study by Zhai *et al.* [6] showed that positive acceleration exposure significantly affects heart rate, respiratory rate, and heart rate variability. The results suggest that the exposure leads to increased tone in human sympathetic nerve and significant increment in HRV. The study by Wang *et al.* [7] showed that the reduction of Connexin 43 may be involved in the mechanism of myocardial ischemia arrhythmia induced by acceleration. The study by Duanmu *et al.* [8] showed that the monophonic action potential (MAP) of ventricu1ar muse1e cells decrease and the transmural dispersion of repolarization (TDR) increase, maybe the electrophysiological mechanisms of arrhythmia induced by +Gz, and propafenone can antagonize this effect. The study by Zhou *et al.* [9] showed that the results demonstrated that the expression decrease and distribution disturbance of Cx43 in the ventricles of rats after repeated +Gz exposures could be recovered. These findings facilitate our understanding of the mechanisms of arrhythmia caused by +Gz and provide new protective measures. The study by Skyttä *et al.* [10] focused on twenty-four pilots monitored with a Holter monitor during 26 hours including a high-Gz flight in order to evaluate heart rate (HR) and cardiac rhythm. They recorded maximally 27 ventricular and 97 supraventricular ectopic beats, 10 junctional rhythms, 5 gray-out, 1 vestibular symptom, and 1 instance of numbness of the feet during the flight. The study by Zawadzka-Bartczak *et al.* [11] showed that abrupt onset and offset of acceleration induces hemodynamic changes that activate a number of reflex cardiovascular responses. At high +Gz on a centrifuge, apparently healthy subjects occasionally develop serious cardiac arrhythmia such as supraventricular tachycardia or asystole.

4.2. Cardiac Function in Acceleration Exposure-Induced Cardiovascular Injuries

The study by Shao *et al.* [12] aimed to investigate the harmful effects of repeated positive acceleration (+Gz) in medium intensity on cardiac function of pilots. The centrifuge test of +Gz tolerance was performed in 38 fighter pilots. Repeated +Gz exposure in medium intensity seems not to influence the cardiac systolic function of pilots, but may have a slight and temporary harmful effect on cardiac diastolic function, implying that attention should be paid to protect the cardiac function of pilots after a repeated +Gz exposure. The study by Ji *et al.* [13] showed that the cardiac arrhythmias under +Gz acceleration could be taken as an index of evaluating cardiovascular compensatory function and warning against acceleration induced loss of consciousness. The study by Tripp *et al.* [14] reported the use of two-dimensional echocardiography in normal men during +Gz acceleration. The heart's position in relation to the chest did not change during acceleration up to +7 Gz. End-diastolic volumes (EDV) and stroke volumes (SV) decreased during a +Gz acceleration ramp that increased until the subject experienced peripheral light loss (PLL) ($P < 0.05$). An inflated G-suit partially counteracted this effect. By 30 seconds of a +3 Gz acceleration plateau, the protective effects of the inflated G-suit to maintain EDV is lost and the EDV of the inflated G-suit was lower than the EDV of the uninflated G-suit ($P < 0.05$).

4.3. Cardiac Structure in Acceleration Exposure-Induced Cardiovascular Injuries

The study by Li *et al.* [15] aimed to study the effect of +Gz on myocardial microstructure of iniature swine with coronary stenosis. The ventricular microstructure does not change significantly in miniature swine with mild coronary stenosis but changes significantly in those with moderate and severe stenosis at the maximum +Gz tolerance. The study by Carter *et al.* [16] showed that exposure to acceleration forces (+Gz) and anti-G protective manoeuvres causes changes in cardiac preload and afterload. These changes can result in cardiac hypertrophy or enlargement.

The study by Öztürk *et al.* [17] aimed to reveal the negative or positive cardiac responses to this occupational high +Gz exposure. The study design was cross-sectional and observational. They have evaluated 21 echocardiographic parameters of 63 pilots who applied for aircrew periodic medical examination. They conclude that according to the results of their study, long term +Gz exposure has no effects on cardiac morphologic and systolic functions but has effects on right ventricular diastolic functions.

4.4. Myocardial Injuries in Acceleration Exposure-Induced Cardiovascular Injuries

The study by Liu *et al.* [18] showed that the −Gx exposures has a significant influence on the levels of inflammatory factors in the myocardium of rabbits, which could be involved in the mechanism of myocardium injure induced by −Gx. It may lead to ultrastructural damage of myocardial tissue. The study by Zhang *et al.* [19] suggested that repeated exposures to high +Gz could increase the expression of ICAM-1 in cardiovascular endothelium of rats, indicating that cell adhesion moleecules (CAMs) induced 1eucocyte diapedesis played a role in producing myocardial injuries due to high +Gz stress. The study by Jamshidi *et al.* [20] investigated the effect of body acceleration on human cardiac function. Finite element analysis is conducted to simulate geometrical and mechanical properties of human heart. Based on the finite element analysis, ventricular volume change, stress and deformation of heart model are evaluated. It is revealed that when the body is subjected to high accelerations, structural changes in the heart reduce blood supply to body up to 7.2% at +6G.

4.5. Myocardial Enzymes in Acceleration Exposure-Induced Cardiovascular Injuries

The study by Guo *et al.* [21] aimed to investigate the injury degree on heart of pure alternated +8Gz and alternated +8Gz and −8Gz (±Gz) exposures on rats. The changes of plasma levels of myocardium enzymes in rats of ±Gz group were more prominent than that of +Gz group. It is suggested that the harmful effect of alternated ±Gz exposures on heart is more prominent than that excerted by +Gz exposures only. The study by Li *et al.* [22] aimed to observe the changes of serum myocardial enzymes in rats after acute and chronic +Gz exposures. Two +Gz stress profiles can induce the increase of serum myocadial enzyme in rats, and the injury effect of acute +Gz stress is more remarkable.

4.6. Protective Measures for Acceleration Exposure-Induced Cardiovascular Injuries

The study by Chen *et al.* [23] showed that Rhodiola crenulata compound preconditioning could regulate the concentration of corticosterone in the serum of the rats exposed +10 Gz, which may be related with its protective effect on high sustained +Gz-induced injury of myocardium. The study by Ye *et al.* [24] showed that hypobaric hypoxia preconditioning (HHP) can reduce oxidative damage of myocardial tissue caused by acceleration and has myocardial protective effect, the mechanism is related to enhancing the activity of antioxidant enzymes and reducing oxidative stress on the activation of NOS and then inhibiting the release of NO in rats. The study by Sun *et al.* [25] showed that hyperbaric oxygen preconditioning (HBOP) can improve myocardial function and vascular endothelial function in pilots with poor acceleration tolerance, thereby improving their lower body negative pressure (LBNP) tolerance.

5. Limitations and Shortcomings

Our research may have some potential limitations including a small number of included studies and the heterogeneity of the studies. Due to the included studies are too heterogeneous for quantitative synthesis, our research narratively described the results.

6. Conclusion

With the improvement of the performance of fighter aircraft, the problem of continuous acceleration is becoming more and more serious for pilots. Therefore, it is important to explore the compensatory response of cardiovascular system under the effect of ±Gz or ±Gx and clarify the mechanism of injury occurrence for flight safety. This paper analyzes the research progress in the cardiovascular compensatory response. It is expected to provide reference for subsequent exploration of the mechanism of sustained ±Gz or ±Gx acceleration and the selection of ways to protect against anti-G.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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