THE CARDIOVASCULAR EFFECTS OF MILITARY SERVICE UNDER EXTREME CONDITIONS: A NARRATIVE REVIEW

Wpływ służby wojskowej w warunkach ekstremalnych na układ sercowo-naczyniowy: przegląd narracyjny

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Abstract

Introduction: Military service is associated with exposure to intense physical and mental stress, which affects the cardiovascular system. It remains unclear whether the combination of exertion, operational stress, and extreme environmental conditions can lead to cardiac arrhythmias and hypertension. **Materials and methods:** A review of the scientific literature was conducted, including studies on the effects of exertion, stress, and environmental conditions on the circulatory system in soldiers. Sources included PubMed and Google Scholar. **State of knowledge:** Prolonged exercise leads to cardiac adaptation, whereas excessive exercise may give rise to exercise-induced cardiac fatigue. Mental stress activates the sympathetic nervous system and the hypothalamic–pituitary–adrenal axis, thereby increasing blood pressure and heart rate. High ambient temperature and dehydration increase the risk of arrhythmias and myocardial damage. **Conclusions:** Military service places considerable strain on the circulatory system. Preventive measures, including regular medical screening, risk factor control, and adaptation programmes, are essential. Further research is needed to identify effective strategies for safeguarding the cardiovascular health of military personnel.

Streszczenie

Wstęp: Służba wojskowa wiąże się z ekspozycją na intensywny stres fizyczny i psychiczny, który wpływa na układ sercowo-naczyniowy. Wysiłek fizyczny, stres operacyjny oraz ekstremalne warunki środowiskowe mogą prowadzić do zaburzeń rytmu serca i nadciśnienia. **Materiały i metody:** Przeprowadzono przegląd literatury naukowej, obejmujący badania dotyczące wpływu wysiłku, stresu i warunków środowiskowych na układ sercowo-naczyniowy u żołnierzy. Przeszukano bazy PubMed i Google Scholar. **Stan wiedzy**: Długotrwały wysiłek prowadzi do adaptacji serca, lecz przy nadmiernym obciążeniu może wystąpić przemijające upośledzenie funkcji mięśnia sercowego po wysiłku. Stres psychiczny aktywuje układ współczulny i oś podwzgórze–przysadka–nadnercza, zwiększając ciśnienie tętnicze oraz częstość akcji serca. Wysoka temperatura i odwodnienie nasilają ryzyko zaburzeń rytmu oraz uszkodzenia mięśnia sercowego. **Wnioski:** Służba wojskowa wiąże się ze zwiększonym obciążeniem układu sercowo-naczyniowego. Konieczne jest wdrażanie profilaktyki obejmującej regularne badania, kontrolę czynników ryzyka i programy adaptacyjne. Dalsze badania powinny określić skuteczne strategie ochrony zdrowia sercowo-naczyniowego żołnierzy.

Keywords: cardiovascular system; prevention of cardiovascular diseases; military service; military medicine; extreme conditions

Słowa kluczowe: układ sercowo-naczyniowy; profilaktyka chorób układu krążenia; służba wojskowa; warunki ekstremalne; medycyna wojskowa

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Introduction

Military service entails exposure to extreme physical and mental challenges, compelling the body to mobilize its adaptive reserves [1]. Modern battlefield demands, intensive training regimens, and deployments across diverse climate zones place a substantial physiological burden on the military personnel [1]. The cardiovascular system plays a key role in maintaining homeostasis under these conditions. Exposure to multifactorial stressors (intense exercise, sleep deprivation, extreme temperatures, combat stress) initiates a cascade of neurohormonal responses [2]. These include activation of the hypothalamic–pituitary–adrenal axis (HPA) and the sympathetic nervous system (increased catecholamine and cortisol levels) [2, 3]. While these mechanisms are essential for short-term adaptation, their chronic activation may cause cardiovascular dysregulation [2]. A growing body of evidence points to a link between military service and cardiovascular risk, particularly among veterans [4] and individuals with post-traumatic stress disorder (PTSD) [5]. Clinical observations indicate an increased incidence of acute cardiac events, including sudden cardiac arrest [6], Takotsubo cardiomyopathy [7], and long-term sequelae such as hypertension (HT) [5], coronary artery disease (CAD), and insulin resistance [8]. Understanding these interactions is fundamental for the development of effective preventive strategies in military medicine. This paper reviews the current knowledge on the cardiovascular effects of military service under extreme conditions.

Aim

The primary aim of this paper is to synthesize and critically analyse the available literature on the cardiovascular effects of military service under extreme conditions. The article is a narrative review. Specific objectives include:

- Analysis of key pathophysiological mechanisms underlying the cardiovascular response to physical and psychological stressors;
- Characterization of acute clinical manifestations and cardiac events during exposure to extreme conditions;
- Assessment of the long-term cardiovascular consequences of military service, including the risk of chronic diseases;
- Review of available prevention, monitoring, and intervention strategies aimed at protecting the cardiovascular health of military personnel.

Materials and methods

This literature review used PubMed and Google Scholar databases to investigate the cardiovascular effects of military service. Publications were selected and analyzed with respect to physiological and pathological cardiovascular changes arising from stress, environmental conditions, adaptive mechanisms, and preventive interventions.

State of knowledge

Mechanisms underlying the cardiovascular effects of extreme environmental conditions

Autonomic response and the role of stress and hormones

The autonomic nervous system (ANS) maintains homeostasis through the interaction between the sympathetic nervous system (SNS) and parasympathetic nervous system (PNS) [9, 10]. In military service, the balance shifts towards SNS (responsible for elevated heart rate and blood pressure) with simultaneous PNS inhibition. This is manifested by reduced heart rate variability (HRV), confirming the predominance of sympathetic activation and reduced adaptive capacity [9, 10]. The ANS response is linked to stress hormones (cortisol, catecholamines) [11]. During prolonged stress associated with military service, their elevated levels increase blood pressure and heart rate. Field studies have shown a correlation between elevated cortisol and impaired physical performance and decreased HRV, particularly in the context of sleep deprivation. These levels normalise following recovery [11].

Haemodynamic and metabolic changes and oxidative stress

Under extreme conditions, haemodynamic changes are observed, such as reduced circulating blood volume and diminished venous return (reduction of preload) [12]. High physical loads increase heart rate and blood pressure, thereby elevating the cardiac workload [12]. These changes are associated with metabolic disturbances and oxidative stress (increased lipolysis and fatty acid oxidation) [13]. Oxidative stress, resulting from the imbalance between free radicals and defence mechanisms, can lead to cellular damage and cardiovascular deterioration [13]. Dehydration, sleep deprivation, and caloric deficit further exacerbate chronic sympathetic activation and haemodynamic and metabolic disturbances [12, 13]. Adaptation involves upregulation of metabolic efficiency and antioxidant mechanisms. Monitoring haemodynamic and metabolic parameters is crucial, as uncompensated changes may progress to myocardial dysfunction. Training and nutritional interventions may contribute to improved performance and health in military personnel [13].

Inflammation and immune response

Exposure to extreme conditions (hypoxia, hyperthermia, oxidative stress, physical exercise) triggers robust activation of the immune system and inflammatory pathways. This leads to increased production of proinflammatory cytokines (IL-6, TNF-α), activation of NF-κB, and migration of immune cells to the vascular endothelium [14]. This sterile inflammatory response promotes endothelial dysfunction, increases oxidative stress, and may lower the threshold for myocardial and vascular damage [14].

Coagulation disorders and the risk of thrombosis

Extreme conditions shift haemostatic balance in a prothrombotic direction. Hyperthermia (heat stroke) activates

the coagulation cascade (tissue factor release, platelet aggregation, inhibition of fibrinolysis), which increases the risk of microthrombosis and disseminated intravascular coagulation (DIC) [15]. Dehydration and haemoconcentration increase blood viscosity, promoting turbulent flow, endothelial injury, and blood stasis, shifting haemostasis toward a prothrombotic state [16].

The impact of individual factors: age, chronic conditions, and lifestyle

Advancing age is associated with a lower cardiovascular adaptive reserve and impaired thermoregulation, increasing susceptibility to circulatory failure under heat stress. Population studies have shown that each 1°C rise in ambient temperature above the optimal value is associated with an approximately 2.1% increase in the risk of cardiovascular death (RR = 1.021; 95% CI: 1.020–1.023), while in individuals over 65 years of age, a short-term 1°C temperature increment may elevate the risk of a cardiovascular event by up to 33% [17]. Individuals with pre-existing chronic conditions (e.g., hypertension, diabetes) already exhibit chronic inflammation, and therefore are particularly vulnerable to decompensation under additional environmental stress. Studies involving military exposure to toxic environments (e.g., smoke from oil well fires) showed that the risk of coronary artery disease was nearly three times higher (OR = 2.95; CI: 1.40–6.19) compared to unexposed individuals [14]. Lifestyle factors, including chronic sleep deprivation and smoking, further promote a pro-inflammatory and pro-thrombotic profile, thereby compromising adaptive capacity. Cohort studies have shown that individuals consuming ≥5 glasses of water daily had more than a two-fold lower risk of CAD mortality compared to those consuming ≤2 glasses [18]. The individual profile thus constitutes the basis for risk stratification

Acute clinical sequelae

Serving under extreme conditions is associated with complex physical, mental, and environmental stress, giving rise to dynamic cardiovascular disturbances, including arrhythmias, coronary events, and cardiomyopathy. Overactivation of the HPA axis and the sympathetic nervous system constitutes a key mechanism [2].

Arrhythmias and sudden cardiac arrest

Arrhythmias and sudden cardiac death (SCD) represent serious acute consequences of military service. A 25-year study among military recruits found SCD to be the most common non-traumatic cause of death accounting for 42% of fatalities, with hypertrophic cardiomyopathy and myocarditis accounting for 33% and 20%, respectively [6]. Intense physical exertion and mental stress upregulate sympathetic activity and catecholamine levels, thereby increasing the risk of ventricular arrhythmias [2]. Neuroendocrine studies have demonstrated alterations in cortisol and DHEA-S levels that correlate with stress response and may modulate susceptibility to arrhythmias [3]. Continuous monitoring of physiological parameters has confirmed that extreme conditions (temperature, dehydration) give rise to clinically significant fluctuations in heart rate [1].

Acute coronary events (including myocardial infarction)

Stress and physical overload can trigger acute coronary events. A meta-analysis by Padhi et al. showed that PTSD increases the risk of myocardial infarction (MI) by approximately 30% [5]. Veterans with PTSD are more likely to meet the diagnostic criteria for metabolic syndrome, including obesity, dyslipidaemia, and HT, which further increases the cardiovascular risk [8]. Acute stress can also lead to transient coronary vasoconstriction and an imbalance between myocardial oxygen supply and demand (type II MI) [2].

Acute heart failure and stress-induced cardiomyopathy (Takotsubo syndrome)

Takotsubo syndrome represents a common complication of acute stress. Kahili et al., who enrolled 3,248 patients in their study, showed a 38% increase in the incidence of this syndrome during periods of increased social stress, such as armed conflicts [7]. The mechanism underlying Takotsubo syndrome involves a rapid release of catecholamines, leading to transient left ventricular systolic dysfunction, with a clinical presentation mimicking MI, yet without significant coronary artery stenosis [2].

Blood pressure disorders in extreme situations

Blood pressure fluctuations are common among military personnel. Data from the Veterans Health Administration indicate that hypertension (HT) is one of the most common chronic conditions in this population (71%) [4]. Field studies have documented episodes of both transient HT (sympathetic activation) and hypotension (dehydration, hyperthermia). Continuous physiological monitoring allows for early detection of cardiovascular overload [1].

Extreme environmental conditions

Military personnel are exposed to dynamic fluctuations in temperature, atmospheric pressure, and oxygen levels. Adaptation to such conditions requires intense activation of regulatory systems (HPA axis, SNS), which may contribute to chronic circulatory dysregulation [2].

High ambient temperature and dehydration

Elevated ambient temperatures prompt blood redistribution to the skin and increase fluid loss, leading to hypovolemia and increased cardiac workload [1]. Dehydration further exacerbates tachycardia and can ultimately lead to circulatory collapse. Activation of the HPA axis in response to heat stress (elevated cortisol and catecholamines) may promote arrhythmia [2]. Chronic exposure carries the risk of heat overload syndromes [1]. A 25-year review of military recruit autopsy findings identified 126 non-traumatic sudden deaths, with structural cardiac abnormalities present in 51% of cases. These were most commonly coronary artery anomalies (61%), myocarditis (20%), and hypertrophic cardiomyopathy (13%) [6]. Hyperthermia and dehydration are both factors contributing to sudden cardiac death in individuals with previously undiagnosed cardiac defects [6].

Low ambient temperatures

Cold exposure triggers cutaneous vasoconstriction and increased peripheral vascular resistance, raising blood pressure and left ventricular workload, which is particularly dangerous for hypertensive individuals [4]. Cold is a potent stressor that stimulates the SNS and may, similarly to emotional stress, give rise to Takotsubo syndrome [7]. Extremely low temperatures can reduce coronary blood flow and impair myocardial repolarization, thereby promoting arrhythmias and endothelial dysfunction [5].

Altitude and hypoxia

Hypobaric conditions induce tissue hypoxia, with early responses including increased heart rate and cardiac output. Prolonged exposure results in increased haematocrit and blood viscosity (risk of thrombosis and pulmonary hypertension). Hypoxic stress further activates the HPA axis (increased cortisol) [2] and affects DHEA-S levels, which may serve an adaptive function [3]. Morgan et al. showed that exposure to severe military survival stress was associated with an increase in DHEA-S from 27.8 µg/dL (± 11.1) to 60.1 µg/dL (± 26.2) and cortisol from 8.6 µg/dL (± 3.8) to 31.1 µg/dL (± 5.8). A higher DHEA-S to cortisol ratio under these conditions correlated with better task performance (r = 0.61) and lower dissociation (r = –0.63) [3]. Real-time monitoring of physiological parameters enables early detection of maladaptive responses under hypoxic conditions [1].

Long-term consequences of military service

Hypertension, coronary artery disease, heart failure

Prolonged exposure to stress leads to activation of the HPA axis and SNS, resulting in stress hyperactivation and disruption of homeostasis. Persistently elevated cortisol and catecholamine levels contribute to raised blood pressure and vascular remodelling [2]. Combat veterans exhibit a higher incidence of HT compared to the general population [4], and exposure to combat trauma increases the risk of CAD and HF. A meta-analysis of over 335,000 participants showed that PTSD was associated with a significantly increased risk of cardiovascular disease (HR = 1.417; 95% CI: 1.313–1.522), including MI (HR = 1.415; 95% CI: 1.331–1.500) and stroke (HR = 2.074; 95% CI: 1.165–2.982) [5].

Cardiac remodelling

The long-term impact of military service on cardiac remodelling remains the subject of intensive research. Structural changes, such as left ventricular hypertrophy, are observed in response to haemodynamic and neurohormonal stress [19]. A 2021 study by Charton et al. enrolled 20 soldiers from special forces units and 38 cadets from a non-elite military unit. In special forces soldiers, intense physical exertion was associated with significant morphological and functional changes in all four heart chambers, including transient impairment of both ventricular and atrial systolic function, as assessed by the 2D-strain method – an advanced echocardiographic technique that quantifies systolic and diastolic myocardial deformation based on 2D image analysis.

Chronic exposure to stress factors, including sleep deprivation, may result in both systolic and diastolic dysfunction [19].

Insulin resistance as a mediator in the relationship between PTSD and metabolic conditions

Metabolic dysregulation, including insulin resistance, is a key mediating mechanism. Chronic activation of the HPA axis leads to increased cortisol and glucose levels and visceral fat accumulation. Veterans with PTSD are more likely to meet the diagnostic criteria for metabolic syndrome [8]. An analysis of 253 veterans (women and men) assessed five key diagnostic factors for metabolic syndrome, including blood pressure, waist-to-hip ratio, as well as fasting HDL, triglyceride, and glucose levels. Metabolic syndrome criteria were met by 40% of subjects, including 43% in the PTSD group. Logistic regression analysis showed a significant correlation between PTSD severity and the prevalence of metabolic syndrome (p = 0.03), suggesting that chronic activation of stress-related pathways may play a central role in the development of metabolic disorders in this population [8]. Insulin resistance is a mediator between neurohormonal dysregulation and endothelial injury and CAD progression [20]. Changes in DHEA-S and cortisol levels in individuals exposed to combat stress have been shown to correlate with impaired glucose metabolism [3], further increasing long-term cardiovascular risk.

Changes in risk factors associated with military service

Alterations in metabolic and cardiac risk factors have been observed during military service. Low dietary fibre intake correlated with higher total and LDL cholesterol levels, as evidenced by a significant positive correlation between changes in fibre intake and variations in total (r = –0.36, p = 0.033) and LDL cholesterol (r = –0.39, p = 0.019).

The study further demonstrated that body fat percentage (BF%) and fat mass were positively correlated with total (r = 0.51; p = 0.002) and LDL cholesterol (r = 0.53; p = 0.001). Mean total cholesterol ranged from 4.64 to 4.71 mmol/L, while LDL cholesterol ranged from 2.27 to 2.87 mmol/L over the six-month follow-up, with body fat percentage remaining stable at approximately 13.5%. These findings highlight the role of diet and body composition in shaping cardiovascular risk profile during military service [21].

Cardiovascular prevention and monitoring among military personnel

Selection and screening

Prior to deploying military personnel to extreme environments, screening tests, encompassing medical history and physical examination, are essential. Soldiers assigned to high-altitude, desert, or polar operations require extensive diagnostic screening, including electrocardiography (ECG). Modern ECG interpretation standards, such as the Seattle Criteria, were developed to improve diagnostic accuracy in highly active individuals, including soldiers [22]. These criteria enable clinicians

to distinguish physiological changes typical of training adaptations that require no further diagnosis, such as sinus bradycardia ≥30/min, first-degree atrioventricular block (PR ≤400 ms), or incomplete right bundle branch block (QRS <120 ms), from actual pathologies that may lead to sudden cardiac arrest, including ST segment depression ≥0.5 mm, pathological Q waves (>40 ms or ≥3 mm), T wave inversion in at least two adjacent leads, or QTc prolongation ≥470/480 ms [23]. The use of the Seattle criteria and automated ECG analysis algorithms based on them significantly reduced the false positive rate (to 3.7%) while maintaining 100% sensitivity in detecting life-threatening conditions [22]. This approach is of particular importance in the military population, where rapid and reliable cardiac assessment is crucial for personnel safety. Extended diagnosis (echocardiography, cardiac stress test) is essential for military personnel at risk (positive family history, syncope, HT, diabetes, etc.) [22]. Soldiers aged 35 years or older and those returning to active duty following a prolonged absence also require special attention due to their increased risk of asymptomatic CAD. Exposure to extreme conditions may reveal previously undiagnosed cardiovascular disorders.

Adaptive training and acclimatization — heat and altitude

Heat acclimatization represents a fundamental strategy for reducing cardiac risk. A two-week programme of progressive high-temperature training (conducted in accordance with NATO guidelines) reduces the need for compensatory increases in cardiac output [24]. Isothermal conditioning has been shown to produce more pronounced cardiac adaptations (average heart rate reduction of 11 beats/min) than traditional training (reduction of 4 beats/min) [25]. Altitude acclimatization (above 1,500 m) is an adaptative response to hypobaric hypoxia. Exposure to low partial pressure of oxygen (PO_2) initiates sympathetic nervous system activation (increased heart rate) [26]. Acute mountain sickness (AMS) represents the primary threat (38% incidence at 3,500 m). Preventive strategies include gradual ascent (altitude limit <305 m per day) and staging (acclimatization at intermediate altitudes) [26].

Risk management: hydration, supplementation

Dehydration-related body weight loss exceeding 2% leads to a 5–10% decline in physical performance, underscoring the critical importance of adequate hydration [24]. Guidelines recommend intake of beverages containing 20–30 mEq/L sodium, 2–5 mEq/L potassium, and 5–10% carbohydrate to prevent fluid, electrolyte, and glycogen depletion. Sodium plays a key role in water absorption and compensation for sweat losses [27].

Post-exposure procedures (rehabilitation, post-event monitoring)

Return to duty following a cardiac event requires an individualized assessment, including cardiac stress test and haemodynamic parameters, conducted under cardiological supervision. Comprehensive cardiac rehabilitation has been shown to reduce mortality by 20–30% and improve exercise tolerance by 25–35% [28].

Psychological interventions to reduce stress and PTSD severity

Meta-analyses indicate that psychological interventions, including trauma-focused cognitive behavioural therapy (TF-CBT) and eye movement desensitization and reprocessing therapy (EMDR), effectively reduce PTSD symptoms in veterans, though the effect is smaller and less durable than that observed in the general population [29].

Special aspects

Gender differences

Female military personnel, female recruits in particular, are exposed to greater cardiovascular strain than their male counterparts during intense physical exercise, as evidenced by higher heart rates and blood pressure during load-bearing marches [30]. Field studies have shown that these differences are particularly visible during long marches (over 8 km), highlighting the need for individualized training programmes, gradually increased load, and continuous physiological monitoring in female recruits [30].

In a cohort of 60 recruits (30 women and 30 men, mean age 20 ± 2 years), women exhibited heart rate higher by a mean of 12–15 beats/min and systolic blood pressure higher by 6–8 mmHg during 8–10 km load-bearing marches, confirming the greater cardiovascular burden experienced by female personnel [30].

Age: young recruits vs older veterans

The MIL-SCORE study, which enrolled 6,487 Polish professional soldiers (mean age 38 ± 9 years, women accounting for 7.8%), identified age as one of the key factors differentiating the health profile of military personnel [31]. Older veterans (>50 years of age) exhibited significantly higher rates of HT (45.2%) and obesity (58.7%) compared to young recruits (<35 years of age), in whom the prevalence of these disorders was 18.9% and 21.4%, respectively [31]. These findings underscore the need to implement cardiometabolic preventive measures already in the early stages of military service [31].

The specificity of international missions compared to national exercises

Soldiers deployed on foreign missions are exposed to significantly greater environmental and psychophysical stress than during domestic exercises [32]. The most frequently mentioned contributing factors include operational stress, prolonged exposure to extreme temperatures, sleep deprivation, and limited capacity for physical recovery [32].

Studies among Polish soldiers have shown that a high prevalence of cardiovascular risk factors, including HT, obesity, and hypercholesterolaemia, may increase susceptibility to the adverse effects of these conditions [31]. Analyses involving 82,341 US soldiers (mean age 27 ± 6 years) demonstrated a 27% higher incidence of new-onset HT and a 19% higher incidence of new-onset hy-

percholesterolaemia among those serving on overseas deployments compared with those participating in domestic exercises [32]. Therefore, it is recommended to implement preventive and monitoring programmes tailored to the specific mission and the climate of the operational area [32].

The perspective of the Polish Armed Forces

Polish epidemiological studies confirm the growing burden of cardiovascular risk among both recruits and veterans [31]. Analyses of military populations have identified HT, overweight, and dyslipidaemia as the most prevalent risk factors [31]. At the same time, international studies have shown that similar trends are also observed in the armed forces of other NATO member states, confirming the global nature of the cardiovascular health problem among professional soldiers [32].

Data from national and international programmes indicate that over 40% of professional soldiers across the surveyed armed forces meet the criteria for at least one major cardiovascular risk factor (HT, obesity, or dyslipidaemia) [31, 32]. These findings highlight the need for regular screening, health education, and the implementation of comprehensive preventive measures, particularly among individuals returning from overseas deployments [31, 32].

Conclusions

Military service imposes substantial physiological and psychosocial demands. Multifactorial stress, including combat exposure, physical exertion, thermal stress, and sleep deprivation, activates the HPA axis and sympathetic nervous system. These responses, while adaptive in the short term, may lead to haemodynamic dysregulation, arrhythmias, and increased risk of cardiovascular disease when chronically activated. Excessive neurohormonal stimulation, oxidative stress, and inflammatory processes contribute to endothelial damage, vascular dysfunction, and cardiac remodelling. Extreme environmental conditions, including temperature, hypoxia, and dehydration, exacerbate this process, increasing the risk of acute cardiovascular events, including sudden cardiac death. In the military population, both acute manifestations (cardiac arrhythmias, left ventricular systolic dysfunction) and long-term consequences (HT, coronary artery disease, metabolic disorders) have been observed. The intensity of these changes depends on individual factors, such as genetic predisposition, training level, and the body's adaptive capacity, which modulate individual resistance to stress. Early risk identification and comprehensive prevention, encompassing cardiac screening, monitoring of exercise capacity, metabolic control, thermal adaptation, hydration, and recovery, are crucial. Further research is needed to develop personalized diagnostic and preventive models for populations exposed to extreme stress.

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