

Impact of cold adaptation on cardiac tolerance to ischemia/reperfusion. Role of glucocorticoid and thyroid hormones

Sergey Y. Tsibulnikov¹, Leonid N. Maslov¹, Natalya V. Naryzhnaya¹, Vladimir V. Ivanov², Yuri V. Bushov³, Nikita S. Voronkov¹, Amteshwar S. Jaggi⁴, Yi Zhang⁵ and Peter R. Oelgen⁶

¹ *Laboratory of Experimental Cardiology, Cardiology Research Institute, Tomsk National Research Medical Center, Tomsk, Russia*

² *Laboratory of Experimental Models, Siberian State Medical University, Tomsk, Russia*

³ *Department of Physiology, National Research Tomsk State University, Tomsk, Russia*

⁴ *Department of Pharmaceutical Sciences and Drug Research, Punjabi University, Patiala, India*

⁵ *Department of Physiology, Hebei Medical University, Shijiazhuang, Hebei Province, China*

⁶ *Department of Pathology, University of Kentucky College of Medicine, Lexington, KY, USA*

Abstract. We have established that the continuous cold exposure (CCE, 4°C, 4 weeks) causes cold adaptation, increases systolic blood pressure, exerts infarct-limiting effect during coronary artery occlusion (45 min) and reperfusion (2 h). The CCE increases adrenal weight, heart weight and triiodothyronine (T₃) level but does not change thymus, spleen weight, serum cortisol, corticosterone and thyroxin (T₄) levels. The long-term (4°C, 8 h/day, 4 weeks) intermittent cold exposure (LICE) induces adaptation to the cold and increases T₄ level. The brief (4°C, 1.5 h/day, 4 weeks) intermittent cold exposure (BICE) also evokes adaptation to the cold but had no effect on the blood pressure, the cardiac tolerance to ischemia/reperfusion, and does not change thymus, spleen weight, serum cortisol, corticosterone, T₃ and T₄ levels.

Key words: Cold adaptation — Heart — Ischemia — Reperfusion

Introduction

It is known that prolonged exposure of alien population in the conditions of the Arctic leads to an increase in the incidence of cardiovascular disease (Maslov et al. 2014a). The incidence of hypertension among migrants in the Far North is increased with their length of stay in the Arctic, reaching a level of 61% in people who have lived in this region for over 15 years (Skavronskaya et al. 2005). The rate of acute myocardial infarction (AMI) among the migrants to the Far North increases dramatically after 7–10 years in the Arctic (Turchinskiy 1979). An unexpected AMI statistic is that 24% of AMI cases in the polar city of Norilsk Russia occur in individuals under 44 years of age (Turchinskiy and Sakharova 1979).

Experimental studies have shown that prolonged exposure to the cold can have a negative effect on the functional state

of the cardiovascular system in the experimental animals. As early as 1956, it was shown that the 20-day continuous adaptation of rats to cold (+5°C) led to an increase in their blood pressure (BP) (Adolph 1956). In 1990, Shechtman et al. (1990) found that hypertensive effect of adaptation (+5°C, 39 days) was maintained, at least for 30 days after placing the rats in the room temperature. However, this data applies only to the long-term continuous exposure to the cold. Meanwhile, the people working in the Far North are subject to the periodic exposure to low temperatures, which evokes in them essential hypertension (Skavronskaya et al. 2005). There is no evidence that the continuous or intermittent exposure to the cold modifies the heart resistance to ischemia and reperfusion. Based on epidemiological data it was possible to hypothesize that the adaptation to the cold will reduce cardiac resistance to the pathogenic impact of ischemia and reperfusion.

However, as early as 1946, Selye established (Selye 1946) that a state of resistance occurred after exposure to extreme stress and also after exposure to excessively strong irritants. Selye called this phenomenon cross-resistance. Later studies

Corresponding author: Leonid N. Maslov, Cardiology Research Institute, Tomsk National Research Medical Centre, Russian Academy of Sciences, Kyevsкая 111A, 634012 Tomsk, Russia
E-mail: Maslov@cardio-tomsk.ru

indicated that after the adaptation to various extreme effects, cross-resistance to coronary artery occlusion and reperfusion could appear (Meerson and Malyshev 1989; Meerson et al. 1989; Maslov et al. 2013, 2014b, 2014c). In 1984, Kuroshima et al. (1984) found that the adaptation by means of short-term immobilizations increases the body's tolerance to the cold stress. However, it was unknown whether the adaptation to the cold could have cross effects which increase cardiac tolerance to the damaging effect of coronary artery occlusion and reperfusion.

The aim of this study was to evaluate the effect of the cold adaptation on the cardiac tolerance to the pathogenic impact of ischemia-reperfusion, and to assess the role of glucocorticoid and steroid hormones in the infarction-limiting effect of adaptation to cold.

Materials and Methods

Animals and protocols

The experimental protocol was approved by the Ethical Committee of the Cardiology Research Institute and it was conformed to the European Union Directive 2010/63/EU. Male Wistar rats weighing 230–260 g were housed at $24 \pm 1^\circ\text{C}$ with a relative humidity of 60–70% and a light and dark cycle of 12 h with free access to water and standard rat chow. We used three research protocols. Rats were exposed to continuous normoxic conditioning for four weeks (28 days) in a cold chamber equipped with a generator Bio-Nova-204G4R1 (NTO Bio-Nova Company, Moscow, Russia). Concentrations of O_2 and CO_2 in the chamber were continuously measured by TCO_D-IR and OLC 20 sensors, and maintained at 20.95% and 0.03%, respectively, by a MX32 controller (Oldham, France). The first protocol (protocol 1) included animals with continuous cold exposures (CCE), they resided inside the refrigerator chamber (23 m^3) at $+4^\circ\text{C}$ two rats in a cage for four weeks (Kvetnansky et al. 2012). The second protocol (protocol 2) included rats with long intermittent cold exposures (LICE) which were exposed at $+4^\circ\text{C}$ for 8 h daily for 4 weeks (van Bergen et al. 1992). The third protocol (protocol 3) included animals which were subjected to brief intermittent cold exposures (BICE), which were in a cold chamber at $+4^\circ\text{C}$ for 1.5 h daily for 28 days (4 weeks) (Bozhko and Gorodetskaya 1994). The control group consisted of rats which were at a temperature of 24°C in vivarium of Laboratory Experimental Cardiology. All rats were included in the experiment 24 h after termination of the cold exposure.

Cold tolerance test

Cold tolerance was assessed after 24 h after finish of cold adaptation. Animals were placed in a cooler at -18°C for

4 h. The temperature was measured using an electronic thermometer DT-501 (A&D company Ltd, Japan) at every hour after initiation of exposure to the cold. The number of animals in the experimental groups was 32. There were 8 rats in each group.

Myocardial ischemia/reperfusion

The rats were anesthetized with α -chloralose (50 mg/kg, i.p.; Sigma-Aldrich, St. Louis, USA). A tracheotomy was performed, and the lungs were ventilated by a rodent ventilator model SAR-830 Series (Central Wisconsin Engineers Inc., Schofield, USA) with room air. Atelectasis was prevented by maintaining a positive end-expiratory pressure of 5–10 mmH₂O. Arterial blood pH, PCO₂, and PO₂ were determined throughout the experiment by a gas analyzer model Stat Profile M (Nova Biomedical Corporation, Waltham, MA, USA) and maintained within a normal physiological range by adjusting the respiratory rate and tidal volume. The rectal temperature was maintained between 36.5 and 37.5°C during the experiment by using a non-invasive PhysioSuite heating pad (Kent Scientific Corporation, Torrington, USA) during the experiment. The left descending coronary artery was occluded 1–2 mm below the atrial appendage and reperfused as described previously Schultz et al. (1997). The right carotid artery was cannulated for the measurement of blood pressure (BP), which was detected by a pressure transducer model SS13L (Biopac System Inc., Goleta, California, USA) coupled with the device for electrophysiological studies MP35 (Biopac System Inc., Goleta, USA). The same device was used to record the ECG. After 45 minutes of ischemia the ligature was loosen and reestablished blood flow was confirmed by the epicardial hyperemic response. The duration of reperfusion was 2 h. ECG recording was performed during the period of ischemia and 10 min after the resumption of the coronary circulation with an apparatus for electrophysiological studies MP35. Arrhythmias were quantified during the first 10 min of ischemia (phase 1a), following 35 min of ischemia (phase 1b), and the first 10 min of reperfusion. According to Russell (Russell et al. 1984), arrhythmogenesis of heart rhythm disturbance in the first 10 min of coronary artery occlusion is different from the mechanism of arrhythmia development after 10 min of ischemia. Therefore, in this study, we analyzed the incidence of arrhythmias during phase 1a and phase 1b and following reperfusion. Recording and processing of the data was performed using the software INSTBSL-W company Biopac System Inc. (Goleta, USA). In assessing cardiac arrhythmias, only the ventricular arrhythmias were taken into account: single premature ventricular beats (sPVC), multiple PVCs, ventricular tachycardia, ventricular fibrillation.

Identification of area of necrosis and area at risk (AAR) was performed by the method of Neckar et al. (2003). AAR

is the myocardium subject to ischemia-reperfusion. After reperfusion hearts were removed from the chest and washed with a syringe through the aorta cannulated with saline containing 125 IU/ml heparin and then the ligature was tightened again and myocardium was stained through aorta with 5% potassium permanganate to determine the AAR. After washing heart sections were made of 1 mm thick perpendicular to the longitudinal axis with slicer SHARA001-1 (Zivic Instruments, Pittsburgh, USA). The area at risk was not stained with potassium permanganate. Infarct size (IS) was determined by staining with 1% solution of 2,3,5-triphenyl tetrazolium chloride for 30 min at 37°C. Necrotic myocardium does not stain because the dead cardiomyocytes do not contain dehydrogenases. After completing, coloring slices were placed in 10% formaldehyde solution for 1 day. The next day, after staining, the right ventricle was removed and slices were scanned on both sides with the scanner HP Scanjet G4050. The AAR and IS was determined by a computerized planimetric method. The infarct size was expressed as a percentage of the area at risk as the IS/AAR. The number of animals in the experimental groups was 48. In each group there were 12 rats.

Evaluation of cold adaptation

In a separate series of experiments, the rats were used to determine the level of hormones, adrenal weight, spleen, thymus, heart and brown fat. We did not perform coronary artery occlusion in these rats. One index of cold adaptation of animals is a relative increase in brown fat weight (Lim et al. 2012) therefore interscapular brown fat was weighed in rats. The number of animals in the experimental groups was 51.

Evaluation of the stress response to cold exposure

Rats were decapitated 24 h after completion of exposure to the cold. Blood was centrifuged during 10 min at $3000 \times g$ and at a temperature 4°C. The obtained blood serum was frozen and stored at -18°C for not more than 2 weeks. Evaluation of stress damage to the stomach was determined by the number of gastric ulcers and their total area (Scoto

and Parenti 1993; Yigiter et al. 2010). The number of animals in the experimental groups was 51.

Determination of hormones

The determination of corticosterone content in blood serum was carried out with EIA (Enzyme immunoassay kit) «Corticosterone (Human, Rat, Mouse) ELISA» RE52211 (IBL International GmbH, Hamburg, Germany) using Microplate Reader Infinite 200 PRO (Tecan Austria GmbH, Grodig, Austria). The content of cortisol, triiodothyronine (T_3) and thyroxin (T_4) in blood serum was performed with radioimmunoassay kit "Cortisol RIA KIT" IM1841, " T_3 RIA KIT" IM1669 and " T_4 RIA KIT" IM1447 (Beckman Coulter, Immunotech, Prague, Czech Republic). The radioactivity of samples was measured with a multichannel radiometer RIG-12 Progress-RIA (NTC Amplitude Company, Moscow, Russia). The number of animals in the experimental groups was 51.

Statistical analysis

Results were expressed as means \pm SEM. One-way analysis of variance with Newman-Keuls post hoc test was used to detect differences in parametric variables among adapted and control rats. The Chi squared test was used to detect differences in the incidence of ventricular arrhythmias among groups. Differences were considered significant at $p < 0.05$.

Results

Our studies indicate that continuous exposure to the cold (4°C, 4 weeks) causes a two-fold increase in brown fat weight in comparison with the intact animals (Table 1). We have also found that LICE (4°C, 8 h/day, 4 weeks) causes a 50% increase in weight of the interscapular brown fat in comparison with the intact animals. We found that BICE (4°C, 1.5 h/day, 4 weeks) does not cause a change in the weight of brown fat. It has been documented that brown fat plays an important role in the thermogenesis and cold acclimatization and that

Table 1. Body, organ and tissue weight of rats after exposure to cold

	<i>n</i>	Body weight (g)	Thymus (mg)	Adrenal glands (mg)	Spleen (mg)	Heart weight (mg)	LV weight (mg)	RV weight (mg)	LV mass index (%)	Brown fat (mg)
Control	15	282.6 \pm 9.3	240.5 \pm 13.2	35.6 \pm 2.1	1059.5 \pm 96.1	956.2 \pm 31.4	808.6 \pm 36.2	148.5 \pm 11.4	0.31 \pm 0.013	300.4 \pm 38.2
CCE	12	264.8 \pm 3.56	217.0 \pm 12.9	49.7 \pm 2*	933.8 \pm 45.2	1123.3 \pm 46.7*	957.8 \pm 41.7*	166.3 \pm 14.7	0.36 \pm 0.015	764.6 \pm 30.5*
LICE	12	266.7 \pm 28.9	272.5 \pm 13.7	33.1 \pm 1.1	1052.8 \pm 58.6	984.2 \pm 31.7	846.3 \pm 17.7	138.7 \pm 13.5	0.32 \pm 0.006	566.66 \pm 28.9*
BICE	12	271.7 \pm 21.1	244.5 \pm 15.2	34.2 \pm 1.9	1060.2 \pm 64.3	1003.4 \pm 58.7	869.6 \pm 21.5	134.5 \pm 15.1	0.32 \pm 0.007	311.7 \pm 21.02

Data is expressed as mean \pm SEM. * $p < 0.01$ versus control; *n*, number of rats in group; CCE, continuous cold exposure (+4°C, 4 weeks); LICE, long-term intermittent cold exposure (+4°C, 8 h/day, 4 weeks); BICE, brief intermittent cold exposure (+4°C, 1.5 h/day, 4 weeks); LV, left ventricle; RV, right ventricle.

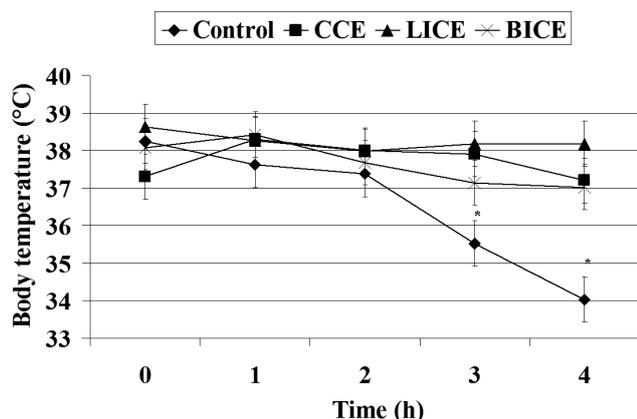


Figure 1. Cold tolerance test ($n = 32$). * $p < 0.05$ versus all cold exposure groups. On time 0, the animal was placed in a cooling chamber. CCE, continuous cold exposure ($+4^{\circ}\text{C}$, 4 weeks); LICE, long-term intermittent cold exposure ($+4^{\circ}\text{C}$, 8 h/day, 4 weeks); BICE, brief intermittent cold exposure ($+4^{\circ}\text{C}$, 1.5 h/day, 4 weeks).

an increase in the weight of brown adipose tissue is an indicator of exposure to cold adaptation (Cannon and Nedergaard 2004). Therefore it is a reasonable hypothesis that resistance to cold would occur after both continuous exposure to the cold and intermittent prolonged exposure to the cold.

Table 2. Hormonal indices of stress response in rats

	n	Corticosterone (nmol/l)	Cortisol (nmol/l)	T_3 (nmol/l)	T_4 (nmol/l)
Control	15	2568.5 ± 93.3	58.3 ± 12.2	1.04 ± 0.17	45.6 ± 4.6
CCE	12	2587.3 ± 91.4	47.1 ± 6.1	$1.55 \pm 0.1^*$	49.9 ± 2.4
LICE	12	2571.5 ± 98.5	49.7 ± 5.5	0.84 ± 0.08	$71.1 \pm 5.9^*$
BICE	12	2589.7 ± 99.8	41.9 ± 6.1	0.71 ± 0.09	64.2 ± 4.1

Data is expressed as mean \pm SEM. * $p < 0.01$ versus control; n , number of rats in group; T_3 , triiodothyronine; T_4 , thyroxine. (For other abbreviations, see Table 1).

Table 3. The incidence of ventricular arrhythmias

n	Ischemia								Reperfusion (10 min)			
	Phase 1a (1–10 min)				Phase 1b (10–20 min)							
	sPVC (%)	PVCs (%)	VT (%)	VF (%)	sPVC (%)	PVCs (%)	VT (%)	VF (%)	sPVC (%)	PVCs (%)	VT (%)	VF (%)
Control	2 (13)	13 (87)	10 (67)	6 (40)	6 (40)	9 (60)	6 (40)	2 (13)	13 (77)	2 (13)	0 (0)	0 (0)
CCE	2 (17)	10 (83)	9 (75)	5 (42)	5 (42)	7 (58)	5 (42)	1 (8)	11 (92)	1 (8)	0 (0)	0 (0)
LICE	1 (8)	11 (92)	8 (67)	4 (33)	4 (33)	8 (67)	6 (50)	1 (8)	10 (83)	2 (17)	0 (0)	0 (0)
BICE	0 (0)	12 (100)	8 (67)	5 (42)	5 (42)	7 (58)	6 (50)	1 (8)	9 (75)	3 (25)	0 (0)	0 (0)

Data is expressed as mean \pm SEM. n , number of rats in group. sPVC, single premature ventricular complexes; PVCs, premature ventricular complexes; VT, ventricular tachycardia; VF, ventricular fibrillation. (For other abbreviations, see Table 1).

Indeed, further experiments showed that a 2 h exposure to cold (-18°C) causes a decrease in the body temperature in the non-adapted rats to 37.4°C after 4 h temperature drops to 34°C (Fig. 1). Cold tolerance occurs in animals subjected to brief (4°C , 8 h/day, 4 weeks) intermittent exposure to the cold (Fig. 1).

We have found that after the CCE adrenal weight increased by 40% as compared to the intact animals (Table 1). The heart weight after the CCE has increased by 17%. The weight of the left ventricle increased by 18% while the weight of the right ventricle did not change. The left ventricle mass index was increased by 16% in CCE group (Table 1). We have found no changes in the weight of thymus and spleen in these rats. We found that after the CCE the T_3 level in rat serum increased by 49% as compared to the intact animals (Table 2). Cortisol, corticosterone and T_4 levels in rat serum after CCE were unchanged (Table 2). We have found that intermittent exposure to the cold (4°C , 8 h/day, 4 weeks) increased T_4 level in rat serum increased by 56% as compared to intact animals (Table 2) but did not affect the weight of the heart, thymus, spleen, adrenal glands (Table 1). Cortisol, corticosterone and T_3 levels in rat serum after cold adaptation were unchanged (Table 2). We have found that brief intermittent exposure to the cold ($+4^{\circ}\text{C}$, 1.5 h/day, 4 weeks) did not affect the weight of the heart, thymus, spleen, adrenal glands (Table 1). Cortisol, corticosterone, triiodothyronine (T_3) and thyroxine (T_4) levels in rat serum after cold adaptation were unchanged (Table 2). We also could not detect gastric ulcers after continuous and intermittent exposures to the cold.

We have demonstrated that the cold adaptation had no effect on the incidence of ischemic and reperfusion of ventricular arrhythmias (Table 3).

We have found an increase in systolic blood pressure from 127 mmHg in the intact rats up to 146 mmHg in rats exposed to continuous cold (Table 4). At the same time, the diastolic blood pressure and heart rate did not change. After the intermittent exposure to the cold we were not able to detect changes in blood pressure and heart rate.

Table 4. Effect of cold exposure (or adaptation) on systolic blood pressure during ischemia and reperfusion

	<i>n</i>	Systolic blood pressure (mmHg)					
		before ischemia	ischemia	start of reperfusion	5 minutes of reperfusion	15 minutes of reperfusion	45 minutes of reperfusion
Control	15	127 ± 6	127 ± 8	125 ± 6	124 ± 6	119 ± 7	110 ± 7
CCE	12	146 ± 5*	145 ± 7*	142 ± 6*	140 ± 7*	136 ± 6*	135 ± 6*
LICE	12	126 ± 5	123 ± 5	126 ± 7	125 ± 7	123 ± 6	120 ± 7
BICE	12	123 ± 5	125 ± 7	122 ± 6	120 ± 7	115 ± 6	113 ± 6

Data is expressed as mean ± SEM. * $p < 0.01$ versus control; *n*, number of rats in group. (For abbreviations, see Table 1).

As shown in Figure 2, in rats which were subjected to continuous exposure to the cold, the IS/AAR ratio was significantly lower by 33% than that of the control group. We found no reduction of myocardial infarct size in rats after LICE and BICE.

Discussion

Our data indicates that after CCE and LICE in rats actually formed adaptation to the cold as evident by the increase in brown fat weight and increased resistance to the effects of low temperature (-18°C). In animals after BICE we found no change of brown fat weight but increased tolerance to the impact of low temperature (-18°C). Our studies indicate that there are different degrees of cold adaptation in the three groups. Despite finding no change in brown fat weight in BICE, there could have been changes in the mitochondrial components of the brown fat, leading to the cold tolerance seen in this group (Ricquier et al. 1979; Kuroshima et al. 1984).

We have shown that continuous exposure to the cold causes cardiac hypertrophy, the left ventricle mass index was increased by 16% in CCE group. The cold induced hypertrophy of the myocardium has been demonstrated by other authors (Hamilton and Ferguson 1972; Harri et al. 1984; van Bergen et al. 1992). Apparently this hypertrophy in the heart is the result of an increase in blood pressure.

Continuous exposure to the cold promoted an increase in adrenal weight but had no effect on the weight of the thymus and spleen. Increased adrenal weight in our view indicates an increase in the adaptive capacity of the organism. After LICE and BICE we found no weight change of these organs. The presented data demonstrates the exposure to the cold used in these studies is not a chronic stress.

We found an increase of the levels in rat blood serum of the hormone T_3 after CCE and an increase in T_4 after LICE.

The increase in thyroid hormone levels in rat blood serum is consistent with earlier findings of other investigators (McAllister et al. 2000; Vezyraki et al. 2000; Bojko et al. 2008).

We have found an increase in systolic blood pressure after CCE. This data is in agreement with the experimental results of other researchers who have found an increase in blood pressure in conscious rats after acclimatization to the cold ($+6^{\circ}\text{C}$, 4 weeks) (Fregly et al. 1989). Blood pressure was measured 1 h after exposure to cold in rats at room temperature (25°C) (Fregly et al. 1989). Intermittent exposure to cold had no effect on blood pressure.

We have found that only CCE causes a decrease in the IS/AAR ratio. The mechanism of cardioprotective effect of cold adaptation remains unknown, we hypothesize that it can be associated with an increase in the density of β_3 adrenergic receptor (β_3 AR) in the myocardium in response to long-term continuous exposure to cold (Benes et al. 2012). Indeed, there is evidence that the administration of adrenomimetics in animals prior to the coronary occlusion may be the cause of the infarct-limiting effect (Khaliulin et al. 2011; Salie et al. 2012). It has also been shown that pretreatment with β_3 AR agonist BRL37344 can increase cardiac tolerance to ischemia and reperfusion (Aragon et al. 2011; García-Prieto et al. 2014). Thyroid hormones also can be involved in the regulation cardiac resistance to ischemia and reperfusion. It has also been demonstrated that the thyroid receptor agonist DITPA can ameliorate ischemic/reperfusion heart injury

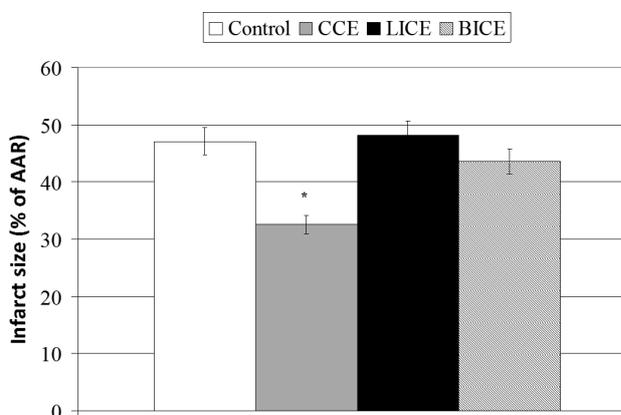


Figure 2. Infarct-limiting effect of cold exposure. * $p < 0.01$ versus control. AAR, area at risk. (For other abbreviations, see Fig. 1).

(Abohashem-Aly et al. 2011). The long-term administration of T_4 also enhanced cardiac resistance to ischemia and reperfusion (Kumar et al. 2012).

It has been shown that migrants living long-term in the Far North have a greater frequency of myocardial infarction than in the population of Russians living in the mid-latitudes (Turchinskiy 1979; Turchinskiy and Sakharova 1979). It is now apparent to us that our findings contradict the results of epidemiological studies. In this regard, it should be noted that the increase in the incidence of cardiovascular diseases in the alien population occurs only after living a few years in the Arctic Circle (Turchinskiy 1979). Perhaps after a few years of living in the conditions of the cold and the polar night, a person develops disadaptation. We hypothesize that after a few months in the refrigerator chamber, the phenomena of disadaptation will develop in rats and a high tolerance to cardiac ischemia and reperfusion will be replaced by low tolerance.

Thus, we have established that the continuous exposure to the cold (4°C, 4 weeks) causes cold adaptation, increases systolic blood pressure, exerts infarct-limiting effect, but does not induce a chronic stress. The intermittent exposure to the cold had no effect on cardiac tolerance to ischemia/reperfusion and is not a chronic stress. The continuous exposure to the cold promotes an increase of T_3 level in serum but intermittent exposure to the cold (8 h/day, 4 weeks) contributes to an elevation of serum T_4 levels. The continuous and intermittent exposure to the cold had no effect on the glucocorticoid levels. We believe that the study of the molecular mechanisms of the cardioprotective effect of adaptation to cold will not only expand the horizons of our knowledge of heart tolerance to the action of ischemia/reperfusion, but also in the future will contribute to the development of new approaches to the prevention of human ischemic and reperfusion injuries.

Acknowledgment. This research was carried out within the framework of the state assignment AAAA-A15-115120910024-0. This study was supported by Russian Science Foundation grant 16-15-10001.

Conflict of interest. There is no conflict of interest.

References

- Abohashem-Aly AA, Meng X, Li J, Sadaria MR, Ao L, Wennergren J, Fullerton DA, Raeburn CD (2011): DITPA, a thyroid hormone analog, reduces infarct size and attenuates the inflammatory response following myocardial ischemia. *J. Surg. Res.* **171**, 379–385
<https://doi.org/10.1016/j.jss.2011.04.009>
- Adolph EF (1956): General and specific characteristics of physiological adaptations. *Am. J. Physiol.* **184**, 18–28
<https://doi.org/10.1152/ajplegacy.1955.184.1.18>
- Aragon JP, Condit ME, Bhushan S, Predmore BL, Patel SS, Grinsfelder DB, Gundewar S, Jha S, Calvert JW, Barouch LA, et al. (2011): Beta3-adrenoreceptor stimulation ameliorates myocardial ischemia-reperfusion injury via endothelial nitric oxide synthase and neuronal nitric oxide synthase activation. *J. Am. Coll. Cardiol.* **58**, 2683–2691
<https://doi.org/10.1016/j.jacc.2011.09.033>
- Benes J, Novakova M, Rotkova J, Farar V, Kvetnansky R, Riljak V, Myslivecek J (2012): Beta3 adrenoreceptors substitute the role of M2 muscarinic receptor in coping with cold stress in the heart: evidence from M2KO mice. *Cell. Mol. Neurobiol.* **32**, 859–869
<https://doi.org/10.1007/s10571-011-9781-3>
- Bojko ER, Evdokimov VG, Potolitsyna NN, Kaneva AM, Varlamova NG, Kochan TI, Vakhnina NA, Shadrina VD, Solonin IuG, Loginova TP, et al. (2008): The pituitary-thyroid axis and oxygen consumption parameters under the conditions of chronic cold exposure in the North. *Human Physiol.* **34**, 215–220
<https://doi.org/10.1134/S0362119708020126>
- Bozhko AP, Gorodetskaya IV (1994): Meaning of thyroid hormones in the implementation of the protective effects of cold adaptation. *Pat. Fiziol. Eksper. Terap.* **4**, 29–32 (in Russian)
- Cannon B, Nedergaard J (2004): Brown adipose tissue: function and physiological significance. *Physiol. Rev.* **84**, 277–359
<https://doi.org/10.1152/physrev.00015.2003>
- Fregly MJ, Kikta DC, Threatte RM, Torres JL, Barney CC (1989): Development of hypertension in rats during chronic exposure to cold. *J. Appl. Physiol.* **66**, 741–749
<https://doi.org/10.1152/jappl.1989.66.2.741>
- García-Prieto J, García-Ruiz JM, Sanz-Rosa D, Pun A, García-Alvarez A, Davidson SM, Fernández-Friera L, Nuno-Ayala M, Fernández-Jiménez R, Bernal JA, et al. (2014): β_3 Adrenergic receptor selective stimulation during ischemia/reperfusion improves cardiac function in translational models through inhibition of mPTP opening in cardiomyocytes. *Basic Res. Cardiol.* **109**, 422
<https://doi.org/10.1007/s00395-014-0422-0>
- Hamilton MJ, Ferguson JH (1972): Effects of exercise and cold acclimation on the ventricular and skeletal muscles of white mice (*Mus musculus*). I. Succinic dehydrogenase activity. *Comp. Biochem. Physiol. A Comp. Physiol.* **43**, 815–824
- Harri M, Dannenberg T, Oksanen-Rossi R, Hohtola E, Sundin U (1984): Related and unrelated changes in response to exercise and cold in rats: a reevaluation. *J. Appl. Physiol.* **57**, 1489–1497
<https://doi.org/10.1152/jappl.1984.57.5.1489>
- Khaliulin I, Halestrap AP, Suleiman MS (2011): Temperature preconditioning is optimal at 26° C and confers additional protection to hypothermic cardioplegic ischemic arrest. *Exp. Biol. Med.* **236**, 736–745
<https://doi.org/10.1258/ebm.2011.010357>
- Kumar A, Taliyan R, Sharma PL (2012): Evaluation of thyroid hormone induced pharmacological preconditioning on cardiomyocyte protection against ischemic-reperfusion injury. *Indian J. Pharmacol.* **44**, 68–72
<https://doi.org/10.4103/0253-7613.91870>
- Kuroshima A, Habara Y, Uehara A, Murazumi K, Yahata T, Ohno T (1984): Cross adaptation between stress and cold in rats. *Pflugers Arch.* **402**, 402–408
<https://doi.org/10.1007/BF00583941>

- Kvetnansky R, Ukropec J, Laukova M, Manz B, Pacak K Vargovic P (2012): Stress stimulates production of catecholamines in rat adipocytes. *Cell. Mol. Neurobiol.* **32**, 801–813
<https://doi.org/10.1007/s10571-012-9822-6>
- Lim S, Honek J, Xue Y, Seki T, Cao Z, Andersson P, Yang X, Hosaka K, Cao Y (2012): Cold-induced activation of brown adipose tissue and adipose angiogenesis in mice. *Nat. Protoc.* **7**, 606–615
<https://doi.org/10.1038/nprot.2012.013>
- Maslov LN, Vychuzhanova EA, Gorbunov AS, Tsibul'nikov SYu (2014a): The role of dyslipidemia in the pathogenesis of vascular events among Arctic populations. *Vestnik RAMN.* 7–8, 133–136 (in Russian)
- Maslov LN, Naryzhnaya NV, Tsibulnikov SYu, Kolar F, Zhang Y, Wang H, Gusakova AM, Lishmanov YuB (2013): Role of endogenous opioid peptides in the infarct size-limiting effect of adaptation to chronic continuous hypoxia. *Life Sci.* **93**, 373–379
<https://doi.org/10.1016/j.lfs.2013.07.018>
- Maslov LN, Vychuzhanova YeA, Gorbunov AS, Tsibul'nikov SYu, Khaliulin IG, Chauski YE (2014c): The role of the thyroid system in adaptation to cold. *Russ. Fiziol. Zh. Im. I. M. Sechenova* **100**, 670–683 (in Russian)
- McAllister TA, Thompson JR, Samuels SE (2000): Skeletal and cardiac muscle protein turnover during cold acclimation in young rats. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* **278**, R705–R711
<https://doi.org/10.1152/ajpregu.2000.278.3.R705>
- Meerson FZ, Malyshev IYu (1989): Adaptation to stress increases the heart resistance to ischemic and reperfusion arrhythmias. *J. Mol. Cell. Cardiol.* **21**, 299–303
[https://doi.org/10.1016/0022-2828\(89\)90745-1](https://doi.org/10.1016/0022-2828(89)90745-1)
- Meerson FZ, Ustinova EE, Manukhina EB (1989): Prevention of cardiac arrhythmias by adaptation to hypoxia: regulatory mechanisms and cardiotropic effect. *Biomed. Biochim. Acta* **48**, 583–588
- Neckar J, Szarszoi O, Herget J, Ostádal B, Kolár F (2003): Cardioprotective effect of chronic hypoxia is blunted by concomitant hypercapnia. *Physiol. Res.* **52**, 171–175
- Ricquier D, Mory G, Hemon P (1979): Changes induced by cold adaptation in the brown adipose tissue from several species of rodents, with special reference to the mitochondrial components. *Can. J. Biochem.* **57**, 1262–1266
<https://doi.org/10.1139/o79-167>
- Russell DC, Lawrie JS, Riemersma RA, Oliver MF (1984): Mechanisms of phase 1a and 1b early ventricular arrhythmias during acute myocardial ischemia in the dog. *Am. J. Cardiol.* **53**, 307–312
[https://doi.org/10.1016/0002-9149\(84\)90444-2](https://doi.org/10.1016/0002-9149(84)90444-2)
- Salie R, Moolman JA, Lochner A (2012): The mechanism of beta-adrenergic preconditioning: roles for adenosine and ROS during triggering and mediation. *Basic. Res. Cardiol.* **107**, 281
<https://doi.org/10.1007/s00395-012-0281-5>
- Schultz JE, Hsu AK, Gross GJ (1997): Ischemic preconditioning is mediated by a peripheral opioid receptor mechanism in the intact rat heart. *J. Mol. Cell. Cardiol.* **29**, 1355–1362
<https://doi.org/10.1006/jmcc.1996.0369>
- Scoto GM, Parenti C (1993): Prevention of stress-induced gastric ulcers by mu- and delta-opioid agonists in the rat. *J. Physiol. Paris* **87**, 385–388
- Selye H (1946): The general adaptation syndrome and the diseases of adaptation. *J. Clin. Endocrinol. Metab.* **6**, 117–230
<https://doi.org/10.1210/jcem-6-2-117>
- Shechtman O, Papanek PE, Fregly MJ (1990): Reversibility of cold-induced hypertension after removal of rats from cold. *Can. J. Physiol. Pharmacol.* **68**, 830–835
<https://doi.org/10.1139/y90-126>
- Skavronskaya TV, Leus AI, Fedoseeva LA, Kumanovskaya TA, Preobrazhenskiy DV (2005): Prevalence of hypertension among gas industry employees in Far North. *Kardiologiya* **45**, 84 (in Russian)
- Turchinskiy VI (1979): Cardiac aspects of human adaptation in the Far North. *Vestnik AMN USS.* **6**, 23–32 (in Russian)
- Turchinskiy VI, Sakharova SI (1979): The clinical course of myocardial infarction in young people under the conditions of the industrial city of the Far North. *Kardiologiya* **19**, 39–45 (in Russian)
- van Bergen P, Fregly MJ, Papanek PE (1992): Effect of a reduction in sodium intake on cold-induced elevation of blood pressure in the rat. *Proc. Soc. Exp. Biol. Med.* **200**, 472–479
<https://doi.org/10.3181/00379727-200-43456>
- Van Bergen P, Fregly MJ, Papanek PE (1992): Effect of a reduction in sodium intake on cold-induced elevation of blood pressure in the rat. *Proc. Soc. Exp. Biol. Med.* **200**, 472–479
<https://doi.org/10.3181/00379727-200-43456>
- Vezyraki P, Kalfakakou V, Evangelou A (2000): Atrial natriuretic peptide and thyroid hormones relation to plasma and heart calcium and magnesium concentrations of Wistar rats exposed to cold and hot ambients. *Biol. Trace Elem. Res.* **73**, 163–173
<https://doi.org/10.1385/BTER:73:2:163>
- Yigiter M, Albayrak Y, Polat B, Suleyman B, Salman AB, Suleyman H (2010): Influence of adrenal hormones in the occurrence and prevention of stress ulcers. *J. Pediatr. Surg.* **45**, 2154–2159
<https://doi.org/10.1016/j.jpedsurg.2010.07.027>

Received: April 5, 2018

Final version accepted: January 7, 2019