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Cardioprotective Effect of Isosorbide Dinitrate Postconditioning Against Rat Myocardial Ischemia-Reperfusion Injury *In Vivo*

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Background: This study investigated the cardioprotective effect of isosorbide dinitrate (ISDN) postconditioning against rat myocardial ischemia/reperfusion injury *in vivo* and provided a theoretical basis for clinical application.

Material/Methods: We randomly divided 32 Wistar rats into 4 groups: sham group, I/R (ischemia/reperfusion) group, I-PostC group (with 3 cycles of 30 s reperfusion and 30 s reocclusion applied at the onset of reperfusion), and P-PostC group (nitrate postconditioning: isosorbide dinitrate (5mg/kg) was given 1 min before reperfusion). The left anterior descending artery (LAD) was occluded for 40 min, followed by a 180-min reperfusion. Relevant indicators were tested. The LAD was occluded again, then we determined the myocardial infarct size. Paraffinized sections were prepared and TUNEL detection was performed.

Results: There were no significant differences in ischemic sizes between different groups. Compared with the I/R group, the levels of cTnI and myocardial infarct size in the I-PostC group and P-PostC group were significantly decreased ($p<0.05$). However, there were no significant difference between the I-PostC group and P-PostC group. Compared with the sham-operated group, the levels of cTnI and MDA in the I/R group, I-PostC group, and P-PostC group were significantly increased ($p<0.05$) and the levels of SOD were significantly decreased ($p<0.05$). Compared with the I/R group, I-PostC and P-PostC decreased the level of MDA and increased the level of SOD (both $P<0.05$).

Conclusions: ISDN postconditioning induces a similar cardioprotective effect as I-PostC. The potential mechanisms of cardioprotection of ISDN postconditioning might be via improvement of myocardial antioxidant capacity and reduced generation of reactive oxygen species.

MeSH Keywords: Cytoprotection • Ischemic Postconditioning • Isosorbide Dinitrate • Myocardial Ischemia

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Background

Acute myocardial infarction (AMI) is the major cause of death and disability worldwide. The infarct size of an AMI has been considered as a prognostic indicator since the early 1970s [1,2] and has been proposed to be a surrogate end-point for short- and long-term outcomes. Therefore, it is crucial to develop therapies to limit final infarct size. Early reperfusion either by thrombolytic therapy or percutaneous coronary intervention (PCI) is the most effective way to salvage ischemic myocytes and improve outcomes of patients with AMI. However, a series of adverse cardiac events occur following reperfusion, including reperfusion arrythmias, myocardial no-reflow, and myocardial stunning [3,4]. This tissue damage is referred to as reperfusion injury and is mainly caused by reactive oxygen species (ROS) and Ca^{2+} overload [5].

It is now clear that the mammalian heart can be conditioned before sustained ischemia and at the start of prolonged reperfusion. Ischemic preconditioning (IPC) consists of brief cycles of ischemia and reperfusion and has been proven to resist to the negative effects of a prolonged ischemic insult [6]. Since IPC must be applied before coronary artery occlusion, it is of limited use in patients with AMI as a therapeutic intervention. In contrast, ischemic postconditioning (I-PostC), consisting of repeated cycles of brief reocclusion and reperfusion before permanent reperfusion [7], can protect vulnerable but still viable myocytes in the ischemic zone. This cardioprotective effect was first confirmed in dogs as reduced infarct size in relation to area at risk by 44%, which was comparable to that induced by IPC. The timing of such a strategy is crucial because the adverse events associated with reperfusion develop within the first minute after restoration of blood flow [8]. Latter studies performed in different species confirmed these findings [9]. I-PostC is a procedure that is clinically feasible and easy to perform in patients undergoing PCI.

Administration of pharmacological agents at the onset of reperfusion to mimic the protective effects of I-PostC is referred to as pharmacological postconditioning (P-PostC). Several agents have been proposed to induce cardioprotection, such as Adenosine [10,11], trimetazidine (TMZ) [12], atrial natriuretic peptide (ANP) [13], erythropoietin (EPO) [14], Cyclosporine A and CsA, and CsA analogs [15,16].

Nitrates are exogenous donors of NO that have been used for more than 130 years history and are among the most widely used anti-myocardial ischemia drugs. Several clinical trials demonstrated that nitrates reduce infarct size in combination with thrombolytic therapy, but most results were negative and even indicated reverse outcomes [16,17]. In addition, there is no published experimental or clinical study focused on nitrate postconditioning. NO donors are usually used as vasodilators in the treatment of AMI, unstable angina, or hypertension. Whether isosorbide dinitrate (ISDN), an exogenous donor of NO, is a potential postconditioning agent still needs to be elucidated.

Therefore, we investigated the cardioprotective effects of ISDN when administered 1 min before opening of the occluded coronary artery in rats, and we compared this effect with that induced by I-PostC.

Material and Methods

Animals

The project was reviewed and approved by Animal Care and Use Committee of Qingdao Municipal Hospital. All experimental animals received humane care in conformance with the Guide for the Care and Use of Laboratory Animals published by the US National Institute of Health (NIH Publication No. 85-23, revised 1996). Male adult Wistar rats (300–350 g) were provided by Jining Medical College. The animals were housed under controlled conditions (25±1°C, relative humidity 55±5%, and 12-h dark and 12-h light) and were allowed free access to standard laboratory food and water.

Surgical preparation

Animals were anesthetized with pentobarbital sodium (50 mg/kg i.p.) and anesthesia was maintained by pentobarbital sodium (25 mg/kg i.p.) as needed. Rats were endotracheally intubated and mechanically ventilated with oxygen-enriched room air after anesthesia. An indwelling needle (24 G immersed in heparin) was inserted into the right carotid artery for drug administration. Limb lead II of the electrocardiogram was used to measure the heart rate and record incidence of arrhythmias and ST-segment elevation. Animals with abnormal heart rhythm were excluded before the experiment. Body temperature was maintained at 37–38°C using a heating pad.

Myocardial ischemia/reperfusion and I-postC animal models

The chest was opened by a left lateral thoracotomy through the third or the fourth intercostals space, and the ribs were retracted to expose the heart. Then, the pericardium was sheared gently. A 6-0 Prolene suture was passed through the epicardial layer beneath a major branch of the left anterior descending (LAD) artery (the site about 2 mm of its origin) and the ends of the tie were threaded through a short segment of PE tube (d=2 mm) to form a snare, which made reversible LAD occlusion convenient by gently pulling up on the snare to produce a zone of regional ischemia in the anterior free wall of the left ventricle. The heart was replaced in the chest and the chest

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closed in layers after evacuating air and fluids after surgery to avoid pneumothorax. After a 5-min stabilization period, LAD occlusion was produced by pulling the snare through the tube, and reperfusion was achieved by releasing the snare. The ECG was monitored throughout the experiment. Exact ischemia was confirmed by the occurrence of ST segment elevation of the electrocardiogram. All intravenous applications of saline or drugs were performed through the right carotid artery.

Experimental protocol

All animals were randomly divided into 4 groups: 1) in the sham group (n=8) the ligature was passed, but not tied, and maintained for 220 min; 2) in the I/R (ischemia/reperfusion) group (n=8) the LAD was occluded for 40 min followed by 180 min of prolonged reperfusion without any intervention; 3) in the I-PostC group (n=8), after 40 min of LAD occlusion, 3 cycles of 30 s reperfusion and 30 s reocclusion was applied within the first minute of reperfusion and reperfusion was continued for a total of 180 min; 4) in the P-PostC group (n=8), the LAD was occluded for 40 min and isosorbide dinitrate (5 mg/kg) was administered through the right carotid artery at the last minute of ischemia, followed by 180 min reperfusion.

Determination of cTnI, SOD and MDA

Blood samples were drawn at the end of reperfusion for measuring cTnI (a specific marker of myocardial damage), MDA (an index of lipid peroxidation reflecting oxygen free radicals), and SOD (a free radical scavenger). All samples stood for 30 min at room temperature and then centrifuged (3000 rpm, 15 min). Serum was extracted and saved at –80°C for uniform measurement. The activities of cTnI, SOD, and MDA were determined based on the corresponding detection kit, purchased from Jiancheng Bioengineering Research Agent (Nanjing province, China). A visible spectrophotometer was used to detect optical density at 450 nm of ultraviolet light for cTnI, 550 nm for SOD, and 532 nm for MDA. The final concentrations were calculated according to optical density values.

Determination of area at risk and infarct size

At the end of reperfusion, LAD was relegated again at the original position and 2% Evan's blue dye (Sigma, USA) was injected into the right carotid artery. The heart was excised when the lip of the rat was dyed blue, the left ventricular was saved via cutting off extra tissue, washed out blood, dried by filter paper, weighted, frozen at –20°C for 30 min, and cut into 5–6 slices (2 mm) along the long axis. The normal myocytes were dyed blue, while the ischemic zone was identified as the non-blue region. In each slice, the red-stained area at risk (AAR) was then separated from the non-ischemic zone and incubated in 1% (wt/vol) of 2,3,5-triphenyltetrazolium chloride (TTC) (Sigma, USA) in phosphate buffer (pH 7.4) at 37°C for 15 min to differentiate infarct size (IS) from AAR, followed by fixation for 24 h in 10% formaldehyde. Each slice was divided according to color and weighed. The AAR was expressed as a percentage of the left ventricular mass (AAR/LV), the infarct zone was expressed as a percentage of the AAR (IS/AAR), and the mass of each area was determined gravimetrically.

Determination of myocardial apoptosis index

We used terminal dUTP nick-end labeling (TUNEL) to determine myocardial apoptosis with a TUNEL cell apoptosis detection kit from Roche. Myocardial paraffin sections were prepared and assessed according to the kit instructions, and then we observed cell staining under an optical microscope. The nuclei of normal myocardium were blue and the nuclei of apoptotic cells were brown and yellow. In each slice, 10 high-magnification fields were randomly selected to calculate the percentage of apoptotic cells expressed as the apoptotic index (AI).

Statistical analysis

All data are expressed as means ± standard deviations (SD). The LSD t test was used for comparison between 2 different groups. One-way analysis (ANOVA) of variance was used to evaluate differences among different experimental groups, using SPSS 17.0 statistical software. Differences were considered significant at P<0.05.

Results

Effect on myocardial infarct size

The infarct sizes of the I/R group, I-postC group, and P-postC group were (52.19±1.216)%, (41.015±1.037)%, and (38.129±0.726)%, respectively. Ischemic postconditioning and isosorbide dinitrate postconditioning significantly reduced the infarct size compared with the I/R group (all P<0.05), but the P-postC group had no significant change compared with the I-postC group (P>0.05). Although there were no significant differences, infarct size tended to be smaller in the P-PostC group (p=0.057) (Table 1, Figure 1).

Effect on ischemia infarct size

In the I/R group, I-postC group, and P-postC group the ischemia size was (47.11±1.821)%, (45.388±6.758)%, and (43.498±4.327)%, respectively. The ischemia sizes in the I-postC group and P-postC group decreased significantly compared with the I/R group(P<0.05) and the t value was 4.39 for the P-postC group. The ischemia size of the I-postC group decreased significantly compared with the P-postC group (P<0.05) (Table 2, Figure 2).

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Table 1. The comparison between groups in the area of ischemia and infarct.

Group	LV (g)	AAR/LV (%)	IS/AAR (%)
I/R	0.815±0.022	47.117±1.821	52.190±1.216
I-PostC	0.794±0.061	45.388±6.758*	41.015±1.037*
P-PostC	0.814±0.011	43.498±4.327*@	38.129±0.726*#

Data are means ±SD. * $P<0.05$ *vs.* I/R; # $P>0.05$ *vs.* I-PostC; ; @ $P<0.05$ *vs.* I-PostC

Table 2. Level of SOD, MDA and cTnI in the serum of rats.

Group	SOD (U/L)	MDA (nmol/L)	cTnI (ng/L)
Sham	1.816±0.02754	1.31±0.0404	1.992558±0.0002501
I/R	1.794±0.01918	1.81±0.0309	1.996793±0.0001419
I-PostC	1.811±0.00122*	1.62±0.0294#	1.995089±0.0001021#
P-PostC	1.813±0.01382*@	1.59±0.0348#	1.995252±0.0001434#

Data are means ±SD.* $P<0.05$ *vs.* I/R: # $P<0.01$ *vs.* I/R; @ $P<0.01$ *vs.* I-Post.

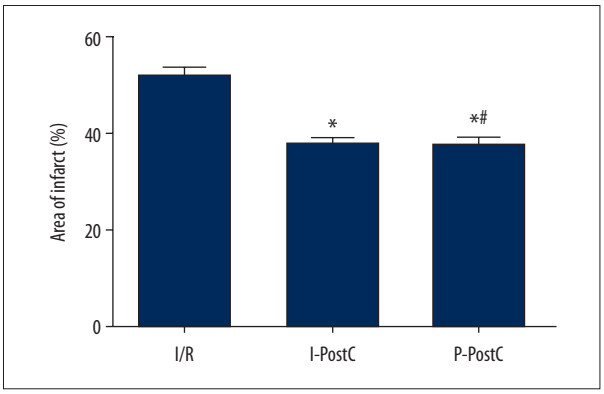

Figure 1. Detection of the area of infarct. * In comparison to I/R, they indicate $P<0.05$. # In comparison to I-PostC, it indicates $P>0.05$

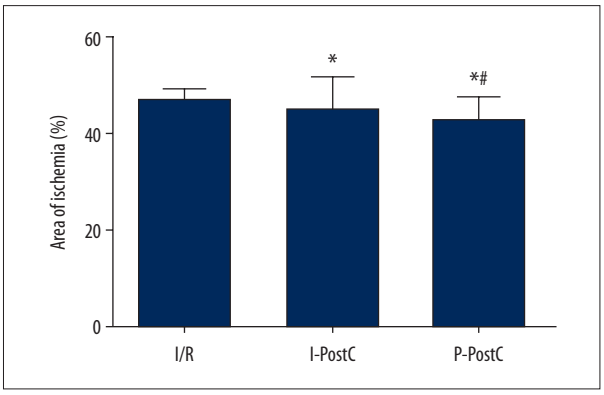

Figure 2. Detection of the area of ischemia. * In comparison to I/R, they indicate $P<0.05$. # In comparison to I-PostC, it indicates $P<0.05$.

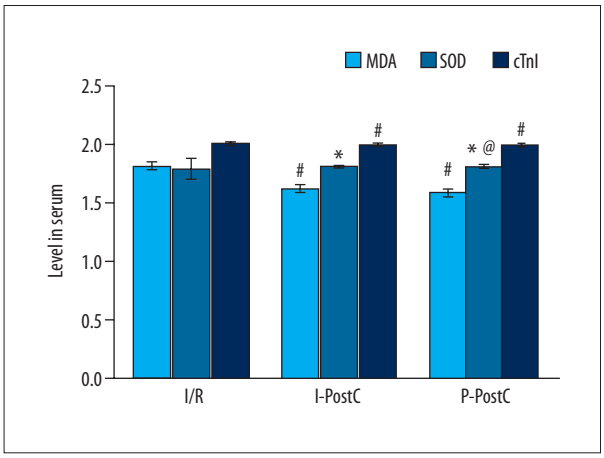

Figure 3. Detection of MDA, SOD and cTnI level in the serum of Rats. * In comparison to I/R, they indicate $P<0.05$. # In comparison to I/R, they indicate $P<0.01$. @ In comparison to I-PostC, it indicates $P<0.01$.

Effect on concentrations of SOD, MDA, and cTnI

The concentrations of MDA and c-TnI in the I-PostC group and P-PostC group were significantly lower than in the I/R group ($P<0.01$). In contrast, SOD concentration was significantly increased in the I-PostC group and P-PostC group ($P<0.05$) and SOD concentration in the P-PostC group was higher than in the I-PostC group ($P<0.01$), as shown in Table 2 and Figure 3.

Result of HE staining

The rat myocardial cells from the sham-operated group were normal, and a few lymphocytes could be seen between

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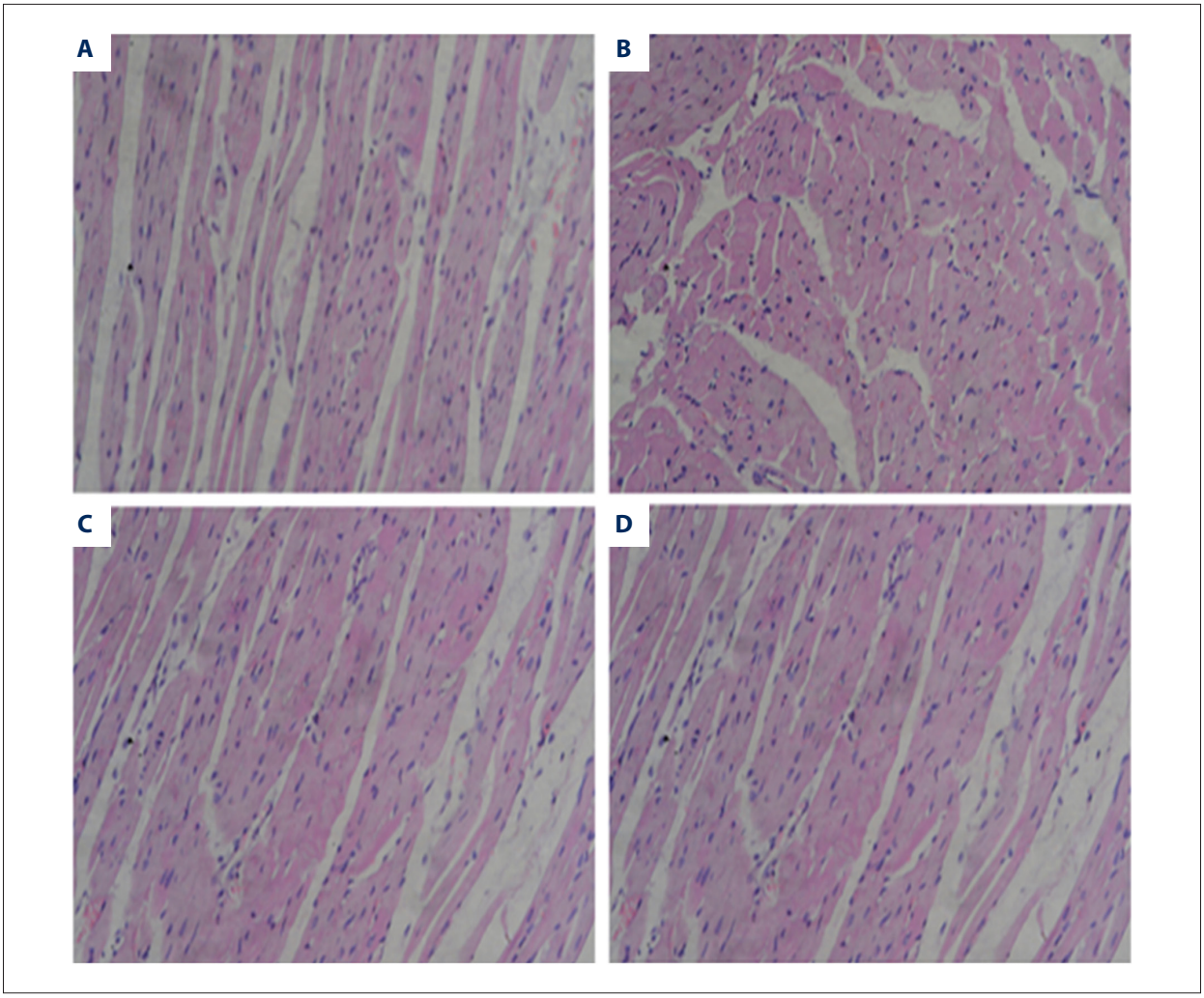

Figure 4. HE staining. (**A**) Sham group, (**B**) I/R group, (**C**) I-Post group, (**D**) P-Post group.

myocardial cells and around blood vessels. The infarct myocardial cells in the I/R group showed bigger cell nuclei and partial cell necrosis, and invasion of inflammatory cells could be seen between myocardial cells, of which the majority were lymphocytes and neutrophil granulocytes. The I-postC group and P-postC group had similar results to the I/R group, but with minimized invasion of inflammatory cells and necrosis of myocardial cells (Figure 4).

Effect on myocardial apoptosis index

The myocardial apoptosis index in the I-PostC group and P-PostC group were significantly lower than in the I/R group ($P<0.05$), and there were no significant differences between the I-PostC group and P-PostC group ($P>0.05$).

The color of normal myocardial cell nuclei was blue-green under optical microscopy, and apoptotics nuclei were brown or clay-colored. In the infarct zone, many myocardial cells had clay bank nuclei, and many shrunken, broken, and apoptotic cells were seen there, while there were fewer clay-colored cells in the non-infarct zone. The apoptotic index of the I/R group, I-postC group, and P-postC group were (26.92±1.91)%, (20.54±3.05)%, and (19.49±2.41)%, respectively (Figure 5).

Discussion

In this study, I-PostC and P-PostC both reduced serum concentrations of MDA, infarct size, and myocardial apoptosis index, which was corroborated by the reduction of cTnI, and there were no significant differences between the 2 groups. In contrast, concentrations of SOD were increased. We confirmed that 3 cycles of 30 s/30 a perfusion/ischemia postconditioning applied within the first minute of reperfusion conferred a cardioprotective effect against reperfusion injury. P-PostC with isosorbide dinitrate exerted the same beneficial effect on post-ischemic rat hearts *in vivo*. Associated with reintroduction of oxygen at the

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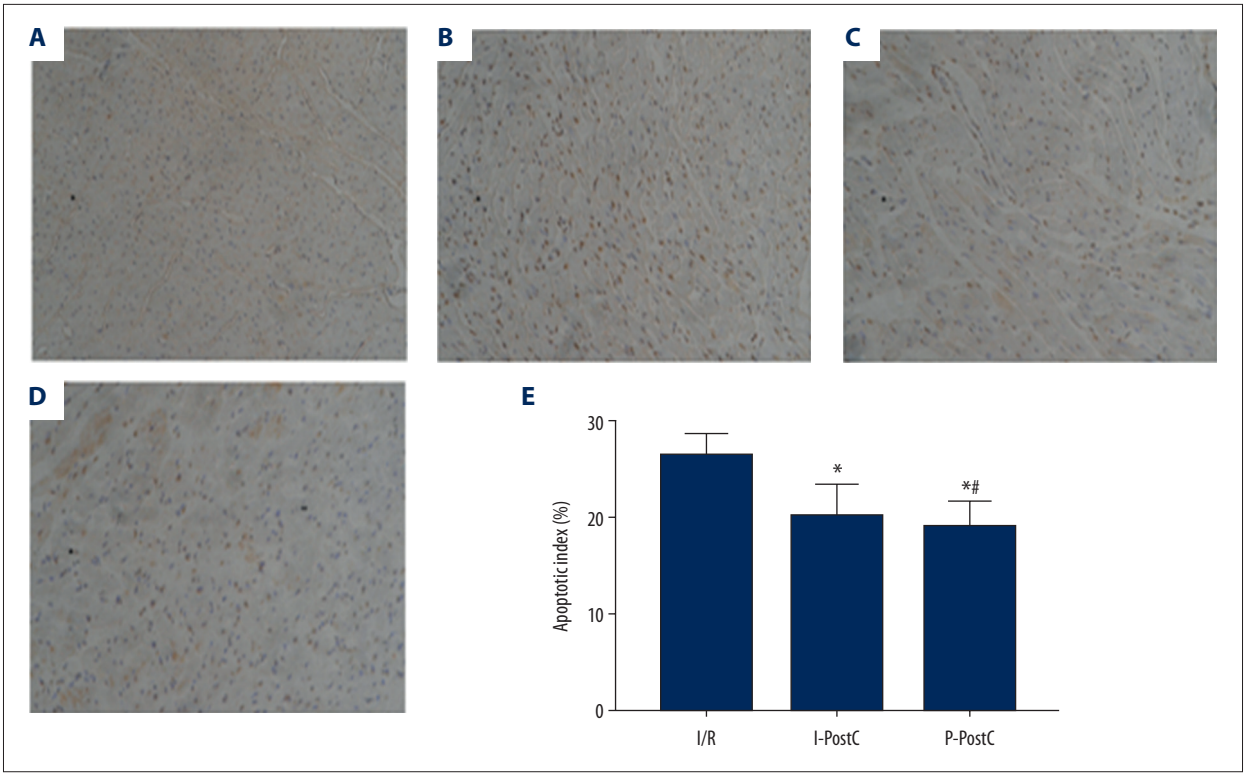

Figure 5. Apoptosis detection between groups. (**A**) Sham group, (**B**) I/R group, (**C**) I-Post group, (**D**) P-Post group. (**E**) Statistical analysis between groups. * In comparison to I/R, they indicate $P<0.05$. # In comparison to I-PostC, it indicates $P>0.05$.

start of reperfusion, several metabolic and biochemical changes occurred in the ischemic myocardium, including a massive production of ROS, which, if exceeding the defensive capacity of the cell, would cause widespread injury. Yang et al. [18] indicated that ROS burst into production in the first minute of reperfusion and reached a maximum at 4–5 min. ROS interacted with lipids, caused lipid peroxidation, produced lipid peroxides (LPO), and then exerted a series of changes in the cell structure and function, eventually leading to myocardium damage [19,20]. One of the most important LPO metabolites is MDA, a presumptive marker of oxidant-mediated lipid peroxidation, which is quantified to estimate the extent of lipid peroxidation in the AAR myocardium [21]. SOD is a ROS scavenger and represents the degree of neutrophil infiltration [22,23]. Generally, the activity of MDA and SOD has a close relationship with myocardium injury. The present study showed that the levels of MDA in the I-PostC and P-PostC groups were significantly lower than that in the I/R group, and SOD levels were correspondingly higher, indicating that reducing the generation of oxygen free radicals and improving antioxidant capacity of myocardium might be an important mechanism of the cardioprotective effect induced by ISDN postconditioning.

Organic nitrates, which are exogenous NO donors, have been used for the prevention and treatment of ischemic heart diseases for more than 130 years [24,25]. The ability of nitrates to induce cardioprotection in live rats and the underlying mechanisms by which nitrates afford protection against ischemia-reperfusion injury are unknown. Filice [26] reported that NO plays a crucial role in the protective transduction pathway of I-PostC. NO is thought to exert its cardioprotective properties by antiapoptotic, antioxidant, and anti-inflammatory effects (cGMP-dependent) [27–30]. It is known that NO is a basic substance of endothelial origin, which triggers effects via cGMP. The signaling cascade NO→cG→cGMP inhibits artery proliferation and prevents aggregation and inflammatory effects, which indicates the potential suitability of this pathway, and the opportunity for the use of drugs administered, in circulatory diseases [31]. In addition, NO can inhibit GSK-3β and mitochondrial permeability transition pore (mPTP) opening via the activation of KATP channels, which are cGMP-independent effects [32]. As a result, mitochondria can be preserved to maintain energy metabolism and survive during ischemia and reperfusion.

However, NO and ROS are generated within the same mitochondria sites. Under some conditions, it could increase ROS, and cause mitochondrial uncoupling and energy wasting [29]. Low concentration is associated with cytoprotective effects and high concentration with cytotoxicity. This dichotomy of effector function is a “double-edged sword”. High concentrations of NO interact with ROS and produce peroxynitrite, which is

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toxic to myocardium [33]. The amount of peroxynitrite production therefore depends on the ratio of superoxide to NO. However, low concentration of ROS is also involved in cardioprotection. Therefore, instead of eliminating ROS, it is more important to balance the production of ROS and NO.

Endogenous NO production depends on the normal function of endothelia cells. However, most coronary heart diseases are due to coronary atherosclerosis, in which function of endothelia cells is damaged. One of the first events occurring during "unprotected" reperfusion is the development of endothelial dysfunction [34] due to the loss of capacity of endothelial cells to release NO [8]. Thus, the concentration of NO *in vivo* during reperfusion is decreased, and administration of nitrate to supplement NO *in vivo* during reperfusion may afford cardioprotection. We also compared the cardioprotective effect of nitrate to I-PostC to see whether nitrate could induce the same effect.

In this work, the research on mechanism of MIRI showed that ischemia postconditioning promotes the synthesis of NO, and the inhibitors of nitric oxide synthase were able to erase the myocardial-protective effect of ischemia postconditioning. NO might be a trigger of protection mechanism through inhibiting the mitochondrial permeability transition pore (mPTP), stabilizing the mitochondrial membrane potential, and decreasing the myocardial apoptosis [35,36]. NO can inhibit cell apoptosis through many mechanisms, but it is still unknown which is the major one. By immunoblotting, Maejima et al. [37] demonstrated that exogenous NO could inhibit apoptosis of myocardial cell through S-nitrosylation. Investigating *in vitro* perfusion of rat cardiac MIRI, Weiland et al. [38] found that inhibition of endogenous NO synthesis activated the caspase cascade system, resulting in increased myocardial cell apoptosis. Other researchers found that inhibition of nitric oxide synthase could increase cardiac cell apoptosis through activation of Bax and decreasing the synthesis of Cox [39,40]. Kunapuli et al. [41] revealed that ischemia postconditioning decreases myocardial enzyme release and reduces myocardial cell apoptosis through activation of the mitochondrial pathway and cell receptor pathways. A recent Chinese study reported that NO inhibits ischemia induced cardiac cell apoptosis [42]. The experiment result of XiangYing Jiao et al. [43] showed that the myocardial cell apoptosis caused by ischemia/reperfusion could be decreased by increasing the generation of endogenous NO by giving extra L-Arg, which reveals that endogenous NO has an antiapoptotic effect. All the research above proves that NO reduces ischemia reperfusion damage through regulating myocardial cell apoptosis. The reason why nitrates minimize cell apoptosis caused by MIRI and protect myocardial cells can be easily deduced theoretically from the NO providers themselves. Research also shows that NO released from nitrates can relieve aortic systolic pressure and pulmonary capillary wedge pressure, increase cardiac output, and improve cardiac function [44]. The results of the present study show that the apoptosis index in the I-postC group and P-postC group were both lower than in the I/R group($P<0.05$), which suggests that ischemia the postconditioning group and nitrate ester drugs postprocessing group both could reduce the apoptosis of ischemia cell and alleviate the damage of ischemia reperfusion. No difference was observed between the I-postC group and P-postC group, which shows that nitrates postprocessing and ischemia postconditioning can decrease apoptosis of ischemic myocardial cells.

Conclusions

Taken together, our data show that ISDN postconditioning limits myocardial infarction and reduces myocardial injury and reactive response. The results of the present study reveal that ISDN postconditioning can ameliorate myocardial IR injury in rats and induce a similar cardioprotective effect as with I-PostC. In addition to Adenosine, TMZ, and ANP, the use of ISDN postconditioning may help to reduce IR injury. However, there are several limitations to the present study. According to previous studies, low concentrations of NO confer cellular protection, and high concentrations of NO can cause damage cells via oxidative stress, and the maximum protective effect of the concentrations of NO in the body is not clear. In future studies, it is essential to test different doses to identify the optimal dose. Second, rats used in this study were healthy adults, and whether age and other accompanying diseases will weaken or counteract the protective effect of drug postprocessing need further study with different age groups and different disease groups. This is clinically relevant because most AMI patients are elderly and have many co-commodities. Third, the long-term effects of nitrate postconditioning need to be clarified. To translate these experiments to clinical practice, different ischemic times, collateral factors, age, sex, and co-existing diseases should also be taken into considerations. Finally, the small sample size of animals involved in this study limits generalizability of our experimental results.

Conflict of interest

None.

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References:

1. Page DL, Caulfield JB, Kastor JA et al: Myocardial changes associated with cardiogenic shock. N Engl J Med, 1971; 285(3): 133–37
2. Sobel BE, Bresnahan GF, Shell WE, Yoder RD: Estimation of infarct size in man and its relation to prognosis. Circulation, 1972; 46(4): 640–48
3. Ferrari R, Balla C, Malagù M et al: Reperfusion damage-a story of success, failure, and hope. Circ J, 2017; 81: 131–41
4. Ibáñez B, Heusch G, Ovize M et al: Evolving therapies for myocardial ischemia/reperfusion injury. J Am Col Cardiol, 2015; 65(14): 1454–71
5. Tajeddine N: How do reactive oxygen species and calcium trigger mitochondrial membrane permeabilisation? Biochim Biophys Acta, 2016; 1860(6): 1079–88
6. Khalaf A, Babiker F: Discrepancy in calcium release from the sarcoplasmic re-ticulum and intracellular acidic stores for the protection of the heart against ischemia/reperfusion injury. J Physiol Biochem, 2016; 72(3): 1–14
7. Araszkiewicz A, Grygier M, Lesiak M et al: The impact of ischemia-reperfusi-on injury on the effectiveness of primary angioplasty in ST-segment elevation myocardial infarction. Postepy Kardiol Interwencyjnej, 2013; 9(3): 275–81
8. Lefer AM, Lefer DJ: The role of nitric oxide and cell adhesion molecules on the microcirculation in ischemia-reperfusion. Cardiovasc Res, 1996; 32(4): 743–51
9. Hausenloy DJ, Barrabes JA, Bøtker HE et al: Ischaemic conditioning and targeting reperfusion injury: A 30 year voyage of discovery. Basic Res Cardiol, 2016; 111(6): 70
10. Maslov LN, Mrochek AG, Khaliulin IG et al: Perspective of use of agonists of adenosine and opioid receptors for prevention of reperfusion damages of heart. Analysis of experimental and clinical data. Vestn Ross Akad Med Nauk, 2014; (5–6): 5–13
11. Ihara M, Asanuma H, Yamazaki S et al: An interaction between glucagon-like peptide-1 and adenosine contributes to cardioprotection of a dipeptidyl peptidase 4 inhibitor from myocardial ischemia-reperfusion injury. Am J Physiol Heart Circ Physiol, 2015; 308(10): H1287–97
12. Şentürk T, Çavun S, Avcı B et al: Effective inhibition of cardiomyocyte apoptosis through the combination of trimetazidine and N-acetylcysteine in a rat model of myocardial ischemia and reperfusion injury. Atherosclerosis, 2014; 237(2): 760–66
13. Suzuki T, Saiki Y, Horii A et al: Atrial natriuretic peptide induces peroxisome proliferator activated receptor γ during cardiac ischemia – reperfusion in swine heart. Gen Thorac Cardiovasc Surg, 2017; 65(2): 85–95
14. Rong R, Xijun X: Erythropoietin pretreatment suppresses inflammation by activating the PI3K/Akt signaling pathway in myocardial ischemia-reperfusion injury. Exp Ther Med, 2015; 10(2): 413–18
15. Wu N, Li WN, Shu WQ et al: Blocking the mitochondrial permeability transition pore with cyclosporine-A can restore cardioprotection of ischemic postconditioning in hypercholesterolemic rat heart. Eur Rev Med Pharmacol Sci, 2015; 19(3): 446–54
16. Dongworth RK, Hall AR, Burke N et al: Targeting mitochondria for cardioprotection: Examining the benefit for patients. Future Cardiol, 2014; 10(2): 255–72
17. De Alencar Neto JN: Morphine, oxygen, nitrates, and mortality reducing pharmacological treatment for acute coronary syndrome: An evidence-based review. Cureus, 2018; 10(1): e2114
18. McCarthy CP, Donnellan E, Wasfy JH et al: Time-honored treatments for the initial management of acute coronary syndromes: Challenging the status quo. Trends Cardiovasc Med, 2017; 27(7): 483–91
19. Yang XM, Proctor JB, Cui L et al: Multiple, brief coronary occlusions during early reperfusion protect rabbit hearts by targeting cell signaling pathways. J Am Coll Cardiol, 2004; 44(5): 1103–10
20. Maslov LN, Naryzhnaia NV, Iuk P et al: [Reactive oxygen species are triggers and mediators of an increase in cardiac tolerance to impact of ischemia-reperfusion]. Ross Fiziol Zh Im I M Sechenova, 2015; 101(1): 3–24 [in Russian]
21. Granger DN, Kvietys PR: Reperfusion injury and reactive oxygen species: The evolution of a concept. Redox Biol, 2015; 6: 524–51
22. Xiang YC, Xiao YG, Qin G et al: Effects of dexmedetomidine postconditioning on myocardial ischemia and the role of the PI3K/Akt-dependent signaling pathway in reperfusion injury. Mol Med Rep, 2016; 14(1): 797–803
22. Andrienko TN, Pasdois P, Pereira GC et al: The role of succinate and ROS in reperfusion injury – A critical appraisal. J Mol Cell Cardiol, 2017; 110: 1–14
23. Egea J, Fabregat I, Frapart YM et al: European contribution to the study of ROS: A summary of the findings and prospects for the future from the COST action BM1203 (EU-ROS). Redox Biol, 2017; 13: 94–162
24. Münzel T, Steven S, Daiber A: Organic nitrates: Update on mechanisms underlying vasodilation, tolerance and endothelial dysfunction. Vascul Pharmacol, 2014; 63(3): 105–13
25. Nossaman VE, Nossaman BD, Kadowitz PJ: Nitrates and nitrites in the treatment of ischemic cardiac disease. Cardiol Rev, 2010; 18(4): 190–97
26. Filice E, Pasqua T, Quintieri AM et al: Chromofungin, CgA47-66-derived peptide, produces basal cardiac effects and postconditioning cardioprotective action during ischemia/reperfusion injury. Peptides, 2015; 71: 40–48
27. Korkmaz-Icöz S, Radovits T, Szabó G: Targeting phosphodiesterase 5 as a therapeutic option against myocardial ischaemia/reperfusion injury and for treating heart failure. Br J Pharmacol, 2018; 175(2): 223–31
28. Andreadou I, Iliodromitis EK, Rassaf T et al: The role of gasotransmitters NO, H2S and CO in myocardial ischaemia/reperfusion injury and cardioprotection by preconditioning, postconditioning and remote conditioning. Br J Pharmacol, 2015; 172(6): 1587–606
29. Chen Z, Qi Y, Gao C: Cardiac myocyte-protective effect of microRNA-22 during ischemia and reperfusion through disrupting the caveolin-3/eNOS signaling. Int J Clin Exp Pathol, 2015; 8(5): 4614–26
30. Chai Y, Zhang DM, Lin YF: Activation of cGMP-dependent protein k-inase stimulates cardiac ATP-sensitive potassium channels via a ROS/calmodulin/CaMKII signaling cascade. PLoS One, 2011; 6(3): e18191
31. Szadujkis-Szadurska K, Grzesk G, Szadujkis-Szadurski L et al: Role of nitric oxide and cGMP in the modulation of vascular contraction induced by angiotensin II and Bay K8644 during ischemia/reperfusion. Exp Ther Med, 2013; 5(2): 616–20
32. Ong SB, Samangouei P, Kalkhoran SB et al: The mitochondrial permeability transition pore and its role in myocardial ischemia reperfusion injury. J Mol Cell Cardiol, 2015; 78: 23–34
33. Kalogeris T, Baines CP, Krenz M, Korthuis RJ: Ischemia/reperfusion. Compr Physiol, 2016; 7(1): 113–70
34. Lu S, Zhang Y, Zhong S et al: Nn-butyl haloperidol iodide protects against hypoxia/reoxygenation injury in cardiac microvascular endothelial cells by regulating the ROS/MAPK/Egr-1 pathway. Front Pharmacol, 2017; 7: 520
35. Strutyns'kyĭ RB, Kotsiuruba AV, Neshcheret OP et al: [The changes of metabolism in myocardium at ischemia-reperfusion and activating of the ATP-sensitive potassium channels]. Fiziol Zh, 2012; 58(1): 13–26
36. Borutaite V, Morkuniene R, Arandarcikaite O et al: Nitric oxide protects the heart from ischemia-induced apoptosis and mitochondrial damage via protein kinase G mediated blockage of permeability transition and cytochrome C, release. J Biomed Sci, 2009; 16(1): 70
37. Maejima Y, Adachi S, Ito H et al: Nitric oxide inhibits ischemia/reperfusion-induced myocardial apoptosis by modulating cyclin A-associated kinase activity. Cardiovasc Res, 2003; 59(2): 308–20
38. Weiland U, Haendeler J, Ihling C et al: Inhibition of endogenous nitric oxide synthase potentiates ischemia-reperfusion-induced myocardial apoptosis via a caspase-3 dependent pathway. Cardiovasc Res, 2000; 45(3): 671–78
39. Wu N, Li W, Shu W et al: Protective effect of picroside II on myocardial ischemia reperfusion injury in rats. Drug Des Devel Ther, 2014; 8: 545–54
40. Liu AH, Cao YN, Liu HT et al: DIDS attenuates staurosporine-induced cardiomyocyte apoptosis by PI3K/Akt signaling pathway: Activation of eNOS/NO and inhibition of Bax translocation. Cell Physiol Biochem, 2007; 22(1–4): 177–86
41. Kunapuli S, Rosanio S, Schwarz ER: "How do cardio-myocytes die?" apoptosis and autophagic cell death in cardiac-myocytes. J Card Fail, 2006; 12(5): 381–91
42. Cao J, Xie H, Sun Y et al: Sevoflurane post-conditioning reduces rat myocardial ischemia reperfusion injury through an increase in NOS and a decrease in phopshorylated NHE1 levels. Int J Mol Med, 2015; 36(6): 1529–37
43. Li S, Tao L, Jiao X et al: TNFα-initiated oxidative/nitrative stress mediates c-ardiomyocyte apoptosis in traumatic animals. Apoptosis, 2007; 12(10): 1795–802
44. Doganci S, Yildirim V, Bolcal C et al: Sodium nitrite and cardioprotective effect in pig regional myocardial ischemia-reperfusion injury model. Adv Clin Exp Med, 2012; 21(6): 713–26

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