Ischemic preconditioning prevents in vivo hyperoxygenation in postischemic myocardium with preservation of mitochondrial oxygen consumption

Xuehai Zhu,1,2 Bin Liu,1 Shaotang Zhou,1 Yeong-Renn Chen,1 Yuanmu Deng,1 Jay L. Zweier,1 and Guanglong He1
1The Center for Biomedical Electron Paramagnetic Resonance Spectroscopy and Imaging, Davis Heart and Lung Research Institute, and the Division of Cardiovascular Medicine, Department of Internal Medicine, The Ohio State University College of Medicine, Columbus, Ohio; and 2Key Laboratory of Organ Transplantation, Ministry of Education Institute of Organ Transplantation, Tongji Hospital, Tongji Medical College, Huazhong University of Science and Technology, Wuhan, China

Submitted 1 March 2007; accepted in final form 17 May 2007

Zhu X, Liu B, Zhou S, Chen Y-R, Deng Y, Zweier JL, He G. Ischemic preconditioning prevents in vivo hyperoxygenation in postischemic myocardium with preservation of mitochondrial oxygen consumption. Am J Physiol Heart Circ Physiol 293: H1442–H1450, 2007. First published May 18, 2007; doi:10.1152/ajpheart.00256.2007.—Ischemic preconditioning (IPC) strongly protects against ischemia-reperfusion injury; however, its effect on subsequent myocardial oxygenation is unknown. Therefore, we determined in an in vivo mouse model of regional ischemia and reperfusion (I/R) if IPC attenuates postischemic myocardial hyperoxygenation and decreases formation of reactive oxygen/nitrogen species (ROS/RNS), with preservation of mitochondrial function. The following five groups of mice were studied: sham, control (I/R), ischemic preconditioning (IPC + I/R, 3 cycles of 5 min coronary occlusion/5 min reperfusion) and IPC + I/R Nω-nitro-L-arginine methyl ester treated, and IPC + I/R eNOS knockout mice. I/R and IPC + I/R mice were subjected to 30 min regional ischemia followed by 60 min reperfusion. Myocardial PO2 and redox state were monitored by electron paramagnetic resonance spectroscopy. In the IPC + I/R, but not the I/R group, regional blood flow was increased after reperfusion. PO2 upon reperfusion increased significantly above preischemic values in I/R but not in IPC + I/R mice. Tissue redox state was measured from the reduction rate of a spin probe, and this rate was 60% higher in IPC than in non-IPC hearts. Activities of NADH dehydrogenase (NADH-DH) and cytchrome c oxidase (CcO) were reduced in I/R groups compared with sham. There were no differences in NADH-DH and CcO expression in I/R and IPC + I/R groups compared with sham. After 60 min reperfusion, strong nitrotyrosine formation was observed in I/R mice, but only weak staining was observed in IPC + I/R mice. Thus IPC markedly attenuates postischemic myocardial hyperoxygenation with less ROS/RNS generation and preservation of mitochondrial O2 metabolism because of conserved NADH-DH and CcO activities.

ischemia reperfusion; reactive oxygen species; free radicals; nitric oxide; peroxynitrite; redox; mitochondria

ISCHEMIC HEART DISEASE HAS been a leading cause of morbidity and mortality. Ischemia is characterized by insufficient oxygen and nutrient supply to the area at risk and leads to tissue infarction. Prompt return of blood to the area at risk reduces mortality by 50% (15). Never the less, reperfusion injury introduces further complications to the reperfused myocardium, including cardiac arrhythmias and diminished contractile function (8). Rapid entry of calcium ions in cardiac myocytes produces contraction bands, mitochondrial granules, and a loss of vascular integrity, resulting in hemorrhage in the infarct. In addition, reactive oxygen/nitrogen species (ROS/RNS) generated upon reperfusion play an important role in the process of cellular damage with oxidation and denaturation of a number of critical proteins and peroxidation of membrane lipids. Nitration of functional proteins occurs, and this further contributes to cellular injury (7, 28). Reperfusion injury is associated with loss of contractile function, cell death, and reperfusion arrhythmias, including ventricular tachycardia and fibrillation, which also has been reported to induce ROS formation (14).

In 1986, Murry et al. (32) reported a profound myocardial protective mechanism induced by mild ischemic stress that conferred resistance to a subsequent ischemic stress, namely ischemic preconditioning (IPC). Since then, IPC has been shown to reduce infarction in pigs, dogs, rabbits, rats, and mice (16, 24, 26, 47, 53). Several mechanisms have been identified to result in IPC. These include G protein-coupled receptor-mediated processes, including those agonized by adenosine (11), bradykinin (49), and opioids (38), and free radical-mediated processes, including those initiated by nitric oxide (NO), superoxide (O2•−), and their reaction product peroxynitrite (ONOO−; see Refs. 13, 51, and 60). So far, the downstream signal transduction pathways have included a key role for activation of protein kinase C (30, 34), with subsequent activation of tyrosine kinases (3, 20), mitogen-activated protein kinases (29, 35), and the mitochondrial ATP-sensitive K+ channel (mitoKATP; see Refs. 17 and 48). To date, the exact cellular mechanism(s) responsible for IPC are still debated; however, the production of free radicals, including NO, O2•−, and ONOO−, are believed to play an important role in ischemia-induced reperfusion injury, and IPC is thought to diminish their subsequent formation (4, 6, 39, 58, 59).

NO and ONOO− have been reported to interact with NADH dehydrogenase (NADH-DH) and cytchrome c oxidase (CcO) on the mitochondrial respiratory chain, thereby regulating mitochondrial oxygen consumption (27). Recently, we and others have demonstrated that NO, O2•−, and their derivative ONOO− suppress myocardial tissue oxygen consumption by regulating mitochondrial respiration on NADH-DH and CcO after ischemia-reperfusion (I/R; see Refs. 9, 40, 52, 54, 55). We have also demonstrated in an in vivo mouse heart model that there is a hyperoxygenation status after regional I/R because of...
the suppression of mitochondrial oxygen consumption (55). IPC was reported to reduce the generation of ROS/RNS after both the acute and late phase of postischemic reperfusion (12, 23). Therefore, we hypothesize that IPC attenuates in vivo postischemic myocardial hyperoxygenation through attenuating ROS/RNS formation, thereby upregulating tissue oxygen consumption and therefore preserving mitochondrial respiration that in turn contributes to postischemic myocardial protection.

However, in vivo assessment of myocardial tissue oxygenation and redox status has been challenging. The standard oxygen electrode techniques suffer from motion artifacts and nonrepeatability if the electrode is inserted in the myocardium of a beating heart, although this technique can be applied to measure tissue oxygen consumption by monitoring coronary oxygenation in the effluent/affluent in large animals (2, 43). The development of electron paramagnetic resonance (EPR) techniques using oxygen-sensitive probes such as lithium phthalocyanine (LiPc) or redox-sensitive probes such as 2,2,5,5-tetramethyl-1-carboxylopyrrolidine-N-oxyl (PCA) has provided fast and accurate methods for monitoring tissue PO2 or redox status in various organs and tissues in vivo (19, 41, 56). Doppler blood flow measurement, in conjunction with in vivo EPR measurement of tissue oxygenation, has enabled in vivo assessment of myocardial oxygen consumption and mitochondrial function.

There are two phases of protection afforded by IPC, e.g., the early phase and the late phase (5). Both share some common signaling pathways and some distinct mechanisms. The current study focuses on the early phase of IPC. In untreated or preconditioned mice, EPR spectroscopy was applied to monitor cardiac tissue PO2 and along with laser Doppler flow measurements of tissue perfusion. The effects of early phase IPC on oxygen consumption and redox status were determined. We show that, in the early phase, IPC attenuates postischemic myocardial hyperoxygenation and prevents oxidative stress and preserves tissue oxygen consumption and mitochondrial function through protection of the mitochondrial respiratory chain, and this is associated with infarct size reduction in the postischemic heart.

MATERIALS AND METHODS

Animals and materials. Male wild-type C57BL/6 and eNOS knockout (eNOS−/−) mice were purchased from Jackson Laboratory (Bar Harbor, ME). Wild-type mice were randomly selected to be administered 1 mg/ml X2-nitro-l-arginine methyl ester (l-NAME; Sigma Chemical) in drinking water for 3 days before experiment (l-NAME-treated group). Redox probe PCA (Sigma Chemical) was prepared in PBS and kept frozen until use. All procedures were performed with the approval of the Institutional Animal Care and Use Committee at The Ohio State University, Columbus, Ohio, and conformed to the Guide for the Care and Use of Laboratory Animals (NIH publication no. 85-23, revised 1996).

Myocardial I/R model and IPC protocol. The I/R model and the surgical protocol were similar to methods described previously (18, 21, 55). Mice were anesthetized with ketamine (55 mg/kg) plus xylazine (15 mg/kg). Atropine (0.05 mg sc) was administered to reduce airway secretions. Animals were orally intubated with PE-90 tubing and connected to a mouse mini-ventilator (model 845; Harvard Apparatus). Core body temperature was maintained at 37°C with a thermo heating pad and monitored with the rectal thermometer. In all groups of mice, similar basal heart rates were observed, with values of 300–350 beats/min, typical for anesthetized mice.

A median sternotomy was performed, and the left anterior descending coronary artery (LAD) was visualized and completely ligated for 30 min in I/R mice by tightening an 8-0 silk suture after passing it over a length of PE-10 tubing beneath the LAD at points 1–2 mm inferior to the left auricle. The 8-0 suture was similarly placed in the sham group but without LAD occlusion. The PE-10 tubing was ligated with the LAD to achieve easier ligature release and better reperfusion. Ischemia was confirmed visually by the appearance of pale and bulging myocardium in the area at risk (AAR). The ligature was removed, and reperfusion was visually confirmed after 30 min of LAD occlusion. Reperfusion was maintained for 60 min to obtain oximetry measurements and 24 h for the measurement of infarct size.

IPC was introduced by three cycles of 5 min ischemia, followed by 5 min reperfusion. The final reperfusion period of the IPC protocol was extended to 15 min to ensure the stabilization of tissue PO2. The IPC + I/R mice were then subjected to 30 min LAD occlusion followed by either 60 min of reperfusion (for EPR oximetry measurements) or 24 h of reperfusion (for measurements of infarct size) similar to I/R mice.

Regional blood flow measurement. An optical surface suction probe with a diameter of 2 mm (P10d; Moor Instruments) was placed on the surface of the heart at the AAR; therefore, it was able to move with the beating heart. The probe was connected to a laser Doppler tissue perfusion monitor (Moor Instruments) after thoracotomy and exposure of the heart. Blood flow was monitored during preischemic, IPC, 30 min ischemia, and 60 min reperfusion periods. Blood flow in the preischemic state was taken as 100%.

EPR oximetry. Approximately 10 μg of LiPc (the oxygen-sensing probe) was loaded in a 27-gauge needle and implanted in the mid-myocardium of the AAR after the heart was exposed. The location of the LiPc was confirmed by histology. Then the mouse was moved to a home-built in vivo EPR spectrometer (as shown in Fig. 1A), and EPR oximetry was performed after a 30-min equilibration period with the following parameters: frequency 1.1 GHz, microwave power 16 mW, modulation field 0.045 G. The EPR line-width of LiPc linearly responds to tissue PO2 in the range of 0–150 mmHg with a sensitivity of 5.9 mG/mmHg (as shown in Fig. 1B and Ref. 19).

In vivo EPR measurement of tissue redox status. In vivo EPR measurements of tissue redox status were performed using PCA as the spin probe, which has a characteristic three-line EPR spectrum. Five microliters of 10 mM PCA solution in PBS was intramuscularly injected as a bolus in the AAR. Then EPR spectra were acquired before, during, and after ischemia in the preconditioned and nonpreconditioned mice with a surface loop resonator placed above the heart. The lower field peak height was monitored with time. Next, the decay of EPR signal intensity was fitted with a single exponential curve to determine the rate of reduction.

Hemodynamic measurements. The right common carotid artery was cannulated with PE-50 tubing tipped with PE-10 tubing. The cannula was attached to a transducer and monitor (PowerLab/400 ADInstruments) for analysis of mean arterial blood pressure (MABP) and heart rate (HR). The MABP was determined as: end diastolic arterial pressure/systolic arterial pressure (systolic arterial pressure + diastolic arterial pressure)/3. The rate pressure product (RPP) was determined from the following equation: RPP = MABP × HR (mmHg/min).

Activities of NADH-DH and CoQ. Frozen myocardial tissue, obtained from the infarct region, was homogenized in ice-cold HEPES buffer (3 mM, pH 7.2) containing sucrose (0.25 mol/l), EGTA (0.5 mmol/l), and protease-inhibitor cocktail (1:40; Roche). NADH-DH activity was measured in the presence of Triton-X-1HN buffer (20 mMol/l, pH 8.0), NADH (150 mmol/l; Sigma), and coenzyme Q1 (100 mmol/l; Sigma). CoQ activity was measured in the presence of phosphate buffer (50 mMol/l, pH 7.4) and reduced cytochrome c (60 mol/l; Sigma). The extinction coefficients, ε340 nm = 6.22 mmol/l·cm for NADH and ε550 nm = 18.5 mmol/l·cm for cytochrome c were used for
ISCHEMIC PRECONDITIONING ATTENUATES IN VIVO MYOCARDIAL HYPEROXYGENATION

activity calculation (10). Protein concentration of the tissue homogenate was measured by the Lowry method, and the activities were normalized to protein concentrations as micromoles per minute per milligram protein.

Western blot analysis of protein expression of NADH-DH and CcO. Proteins of the homogenate were subjected to electrophoresis on 4–20% Tris-glycine polyacrylamide gradient gels. Anti-OxPhos Complex I subunit 39 kDa and Anti-OxPhos Complex IV subunit VIb (Invitrogen, Carlsbad, CA) and anti-GAPDH were used to confirm equal loading (Santa Cruz Biotechnology, Santa Cruz, CA). The secondary antibodies were conjugated with horseradish peroxidase, and the protein was detected by use of enhanced chemiluminescence secondary antibodies were conjugated with horseradish peroxidase, and the protein was detected by use of enhanced chemiluminescence. Before addition of the primary antibody, slides were blocked with serum-free, protein block (Dako X0909) for 15 min at room temperature. Rabbit polyclonal nitrotyrosine (Upstate, Charlotteville, VA) was used as the primary antibody at a dilution of 1:50 and incubated for 1 h at room temperature. Slides were next biotin blocked for endogenous biotin. Biotinylated goat anti-rabbit antibody (Vector, Burlingame, CA) was used as the secondary antibody at a dilution of 1:200 and incubated for 30 min at room temperature. Vectastain Alkaline Phosphatase (Vector) was used as the detection system for 30 min. Permanent Red (Dako) was used as the substrate chromogen. The slides were then counterstained with hematoxylin, dehydrated through graded ethanol solutions, and cover slipped.

Infarct size. Hearts were excised and cannulated through the ascending aorta after 30 min ischemia and 24 h reperfusion with a 23-gauge needle for perfusion with 3–4 ml of 1.0% triphenyl tetrazolium chloride (TTC) in phosphate buffer (pH 7.4, 37°C). The LAD was reocluded by tightening the suture left in the myocardium after I/R and TTC staining. The hearts were then perfused with 2–3 ml of 10% Phthal Blue (Heubach) to delineate nonischemic myocardium. The hearts were weighed, frozen, and cut into five transverse slices, each with ~1 mm thickness. Each slice was photographed from both sides with a high-resolution digital camera on a dissecting microscope. The sections were photographed and contoured with a planimeter (Adobe PhotoShop 5.0) to delineate the borders of the entire heart, the nonischemic area, and the infarcted area. The sizes of the nonischemic area, AAR, and infarct area (INF) were calculated as percentages of the total left ventricle (LV) area multiplied by the total weight of that slice. The infarct size was measured by an independent, blinded observer using the above-mentioned computer planimetry.

Statistical analysis. A two-way ANOVA was used for data analysis of PO2, arterial pressure, mean arterial pressure, and RPP. A 1-way ANOVA was used for analysis of enzyme activity; these were followed by Newman-Keuls multiple-comparison test among the groups. A t-test was used for data analysis of AAR and INF size. Data were represented as means ± SE. A value of $P < 0.05$ was considered significant.

**Fig. 1.** Instrument setup for in vivo electron paramagnetic resonance (EPR) spectroscopy with lithium phthalocyanine (LiPc) as the O2 probe and 2, 2, 5, 5-tetramethyl-3-carboxylpyrrolidine-N-oxyl (PCA) as the redox probe. A: photograph showing the anesthetized mouse in the EPR spectrometer with the positioning of the loop resonator on top of the chest. B: O2 response of LiPc showed a good linearity in the range of 0–150 mmHg with a sensitivity of 5.9 mG/mmHg.

**Fig. 2.** Regional blood flow measurement. Blood flow in the area at risk was measured before ischemia, during 30 min ischemia and 60 min reperfusion in control (I/R), and also during IPC in ischemic preconditioned (IPC + I/R) mice. Regional blood flow was improved in the preconditioned mice after reperfusion compared with that in the preischemic state ($+P < 0.05$) and I/R mice ($+P < 0.05$); $n = 7$ mice/group.
RESULTS

Regional blood flow measurement. Regional blood flow was measured before ischemia in both I/R and IPC/H11001 I/R mice with basal values defined as 100% (Fig. 2). During the IPC episodes, regional coronary blood flow measured within the risk region decreased by just over 60% during the 5-min period of ischemia and rebounded to just over 100% of basal values after the 5-min reperfusion period. In both groups, when hearts were subjected to 30 min ischemia with coronary ligation, blood flow decreased rapidly with values of 15.0 ± 6.9 and 14.0 ± 6.8% in the AAR after 30 min ischemia in I/R and IPC + I/R mice, respectively. Upon reperfusion, blood flow was rapidly restored to 95.9 ± 6.0 or 102.6 ± 8.9% of basal values in the first 5 min in I/R and IPC + I/R mice, respectively. In I/R mice, reperfusion blood flow remained constant, with 93.8 ± 7.9% of the basal value seen at 60 min reperfusion. However, in IPC + I/R mice, reperfusion blood flow increased significantly above basal values (P < 0.05) and was higher than the values seen in I/R mice (P < 0.05).

Fig. 3. In vivo measurement of myocardial tissue PO2 with EPR oximetry on wild-type control and preconditioned mice. Wild-type C57BL/6 mice were subjected to 30 min left anterior descending coronary artery (LAD) occlusion followed by 60 min reperfusion (I/R) or 3 cycles of 5 min LAD occlusion followed by 5 min reperfusion (the last reperfusion was prolonged to 15 min), and 30 min ischemia and 60 min reperfusion (IPC + I/R). Tissue PO2 overshot the baseline values in the I/R group, but this was attenuated in the IPC + I/R group. *I/R vs. IPC + I/R at the end of 60 min reperfusion; n = 7/group.

Fig. 4. In vivo measurement of myocardial tissue PO2 with EPR oximetry on preconditioned eNOS knockout (eNOS−/−) and NO-nitro-L-arginine methyl ester (L-NAME)-treated mice. eNOS−/− and L-NAME-treated mice were subjected to 30 min LAD occlusion followed by 60 min reperfusion (I/R) or 3 cycles of 5 min LAD occlusion followed by 5 min reperfusion (the last reperfusion was prolonged to 15 min), and 30 min ischemia and 60 min reperfusion (IPC + I/R). There was no overshoot of tissue PO2 in both groups in the postischemic hearts compared with that in the wild-type control group as shown in Fig. 3; n = 7/group.

Fig. 5. In vivo EPR measurement of tissue redox status using the 2,2,5,5-tetramethyl-3-carboxylpyrrolidine-N-oxyl (PCA) redox probe. After thoracotomy and exposure of the heart, 5 μl of 10 mM PCA in PBS was injected in the area at risk, and EPR spectroscopy was performed. A: representative decay profiles of the EPR signal intensity after reperfusion, shown as open circles for the I/R group and triangles for the IPC + I/R group. Fitting curves are shown as the lines, with solid line for I/R group and dashed line for IPC + I/R group. *I/R-ischemia vs. normal, P < 0.01. **I/R-reperfusion vs. normal, P < 0.01. ***IPC + I/R-ischemia vs. normal, P < 0.01. ****IPC + I/R-reperfusion vs. normal, P = not significant; n = 7/group.
Regional myocardial tissue Po2 in the AAR. The baseline values of tissue Po2 in the preischemic state were 16.3 ± 0.7 and 15.1 ± 0.8 mmHg in wild-type I/R and IPC I/R mice, respectively (Fig. 3). Decreases of tissue Po2 were clearly observed during each 5-min ischemic period followed by increases with each reperfusion phase. In both groups, tissue Po2 values dropped rapidly following the onset of ischemia to <2 mmHg within 10 min and then gradually decreased to values of 0.7 ± 0.2 and 1.2 ± 0.3 mmHg in I/R and IPC + I/R mice, respectively. Upon reperfusion, the values of Po2 increased rapidly in both groups. In wild-type I/R mice, tissue Po2 increased and overshot basal values, with 26.2 ± 0.8 mmHg seen at the end of the 60 min reperfusion period. In wild-type IPC + I/R mice, the Po2 increased back to preischemic values, reaching 15.6 ± 1.5 mmHg at 60 min reperfusion. In contrast to the I/R mice, no overshoot in myocardial oxygenation was seen. In eNOS−/− and L-NAME-treated preconditioned mice, there was no overshoot of tissue Po2 after reperfusion in both groups, as shown in Fig. 4.

In vivo myocardial tissue redox status. After injection of PCA in the AAR, EPR spectra before, during, and after ischemia were collected every 60 s for up to 1 h in both the preconditioned and nonpreconditioned mice. Representative time-dependent profiles of the EPR signal intensity in the reperfused hearts are shown in Fig. 5A. Figure 5B shows the reduction rate constants of PCA in wild-type I/R and IPC + I/R mice in the preischemic state (0.042 ± 0.003 vs. 0.041 ± 0.003/min), ischemic state (0.084 ± 0.015 vs. 0.079 ± 0.005/min), and postischemic state (0.028 ± 0.004 vs. 0.044 ± 0.003/min). A 60% faster decay of the EPR signal was observed upon reperfusion in the preconditioned than in the nonpreconditioned hearts. Potassium ferricyanide, a known

Fig. 6. Measurement of the rate pressure product (RPP) of heart rate (HR) and mean arterial blood pressure (MABP). MABP was calculated as: MABP = end diastolic ABP + (systolic ABP – end diastolic ABP)/3, where ABP is arterial blood pressure. RPP was calculated as: RPP = HR × MABP. RPP in IPC + I/R group was slightly higher than that in I/R group at the end of 60 min reperfusion; n = 7/group.

Fig. 7. Activities of mitochondrial enzymes NADH dehydrogenase (NADH-DH) and cytochrome c oxidase (CcO) in sham, I/R, and IPC + I/R mice. The activities of NADH-DH and CcO were significantly lower in I/R mice than that in sham mice (*P < 0.05). However, activities in IPC + I/R mice were restored to the values comparable to that of sham group; n = 7/group.

Fig. 8. Protein expressions with Western blot. Protein expressions of NADH-DH (A) and CcO (B) were measured with basal levels of NADH-DH and CcO expression set as 100%. The blots were imaged and quantified. There were no differences among the sham, I/R, and IPC + I/R groups; n = 7/group.
standard oxidant that oxidizes reduced PCA back to its paramagnetic form, was injected to the same spot 10 min after the injection of PCA, and the signal was restored, confirming that PCA was reduced in the tissue as previously described (56).

**RPP.** Basal values of RPP in I/R and IPC + I/R mice were measured as 20.0 ± 2.3 × 10^3 and 20.9 ± 2.7 × 10^3 mmHg/min, respectively (Fig. 6). RPP values were 16.2 ± 2.1 and 18.5 ± 1.5 × 10^3 mmHg/min at the end of 60 min reperfusion in I/R and IPC + I/R mice. The RPP values at the end of reperfusion were slightly higher in IPC mice than that in I/R mice; however, the difference was not significant.

**Mitochondrial NADH-DH and CcO activity.** To investigate the mechanism(s) by which ROS/RNS regulate mitochondrial O_2 consumption, the activities of NADH-DH and CcO were measured. Baseline values of the activities of NADH-DH and CcO in the sham group were measured as 0.23 ± 0.01 and 0.44 ± 0.03 μmol·min^{-1}·mg protein^{-1}, respectively (Fig. 7). The activities of NADH-DH and CcO at the end of 60 min reperfusion were 0.17 ± 0.01 and 0.35 ± 0.03 μmol·min^{-1}·mg protein^{-1} in the I/R group, respectively, and 0.21 ± 0.01 and 0.41 ± 0.02 μmol·min^{-1}·mg protein^{-1} in IPC + I/R mice, respectively. Compared with the sham group, the activities of NADH-DH and CcO were significantly lower in the I/R group (P < 0.05) but not in the IPC + I/R group.

**Protein expression of NADH-DH and CcO.** Protein expressions of NADH-DH and CcO were measured by Western blotting to determine if the expression of these key mitochondrial electron transport proteins is altered by I/R and IPC. The NADH-DH and CcO protein levels after I/R were 95.5 ± 6.3 and 103.8 ± 11.8%, respectively, of basal preischemic values, in I/R mice and 94.0 ± 11.7 and 97.8 ± 10.5% in IPC + I/R mice (Fig. 8). There was no significant difference among the groups.

**Formation of nitrotyrosine.** Nitrotyrosine staining showed very prominent red coloration in the vascular beds in the positive control group that was infused with ONOO^- (see Fig. 9). There was no observable nitrotyrosine staining in the negative control group. Only very weak red staining for nitro-

---

Fig. 9. Immunohistochemical staining of nitrotyrosine, a biomarker of peroxynitrite formation. Sections were fixed and prepared as described in MATERIALS AND METHODS, and photomicrographs are obtained at ×400 magnification. A: positive control with direct injection of peroxynitrite; strong diffuse nitrotyrosine staining in the vascular beds was present (red color, arrows). B: negative control; no nitrotyrosine staining (red) was present. Only weak staining in hearts of sham group was seen (C), whereas strong red staining was present in the I/R heart (D; arrows). E: in the IPC + I/R heart only weak staining was seen.
tyrosine was seen in the sham group. In contrast, strong nitrotyrosine staining was observed with a homogeneous distribution throughout the myocytes in the I/R group, however, staining was much weaker in the IPC + I/R group.

**AAR and INF.** Data of AAR as a percentage of LV area in I/R and IPC + I/R mice (Fig. 10, A and B) were 61.3 ± 3.2 and 55.0 ± 4.1%, respectively, and with no significant difference between the groups. Infarct size (INF) as a percentage of AAR in I/R and IPC + I/R mice were 32.2 ± 3.4% and 12.8 ± 1.9%, respectively, and the difference was significant (*P* < 0.01).

**DISCUSSION**

It has been clearly established that IPC imparts profound myocardial protection against subsequent ischemia (5). A number of mechanisms have been shown to mediate IPC, and these include alterations in oxygen radical and NO production. Of note, it has been reported that IPC-associated protection is diminished in the disease states with preexisting oxidant stress such as diabetes or hypercholesterolemia (22, 45, 46). Oxygen is critical for myocardial function and aerobic metabolism, with oxygen reduction by the mitochondria providing 90% of the energy in the heart (36). During global myocardial ischemia, tissue oxygen levels fall to near zero and on reperfusion a rapid rise occurs (57, 58). Al-Obaidi et al. (1) measured myocardial tissue oxygen supply and utilization during coronary artery bypass surgery using an electrode and observed an overshoot of tissue oxygenation. However, there were no data showing the mechanisms leading to this hyperoxygenation status. Tanoue et al. (43) measured the unloaded myocardial oxygen consumption using an electrode in an in vivo sheep model and observed an increase in tissue oxygen consumption; however, there were no data showing the myocardial tissue oxygenation. We have previously measured in vivo myocardial tissue PO2 using EPR oximetry and observed a hyperoxygenation status after I/R. The hyperoxygenation status was caused by endothelium-induced NO and its derivatives (55). However, questions still remain regarding the alterations in myocardial oxygenation during IPC and the effects of IPC on in vivo oxygenation during subsequent regional I/R.

Recently, we have developed methods suitable for noninvasive measurement of myocardial oxygenation and redox status in living mice utilizing in vivo EPR spectroscopy with oxygen-sensitive microcrystals and redox probes such as PCA (55, 56). The EPR oximetry technique has been applied to measure tissue oxygenation in a broad range of disease applications. In the current work, EPR oximetry was performed using a highly characterized oxygen-sensitive spin probe (LiPc) that has been demonstrated to be a very powerful in vivo probe for measuring tissue PO2 (19, 25, 41, 55). Once LiPc is implanted, the technique is noninvasive, and tissue PO2 can be measured repeatedly for hours or even days. This technique in conjunction with Doppler determination of blood flow can be used to assess alterations in tissue oxygenation and oxygen consumption in vivo (55).

In the current study, we investigated the effects of IPC on myocardial oxygenation, perfusion, redox status, and mitochondrial function in the postischemic heart. After I/R in IPC hearts, regional blood flow was increased compared with that in non-IPC hearts. The increased blood flow after reperfusion in the preconditioned hearts could be because of adenosine-mediated vasodilation, since it is known that IPC stimulates adenosine formation (5). The enhanced flow could also be because of decreased cellular swelling with prevention of microvascular occlusion and no-reflow in IPC hearts. Measurements of the in vivo redox status in the preconditioned and non preconditioned hearts demonstrated that IPC maintains the redox status of the reperfused heart at preischemic levels. This prevention of the shift to a more oxidized state confirms that IPC attenuates oxidant stress. Tissue PO2 overshoot preischemic baseline values in non-IPC hearts, but this overshoot was not seen with IPC. This overshoot with higher levels of myocardial oxygenation in postischemic myocardium suggested that oxygen consumption is decreased by the process of I/R injury. These observations are consistent with prior reports that ROS/RNS formed upon postischemic reperfusion inhibit mitochondrial oxygen consumption and electron transport (40, 55). When NO formation was diminished as in the eNOS−/− or l-NAME-treated preconditioned groups, the overshoot of tissue PO2 diminished after reperfusion as reported previously (55). These data confirmed that the postischemic hyperoxygenation in the wild-type control heart was induced by endothelium-derived NO and its derivatives. Furthermore, we observe that inhibition of NO formation by eNOS−/− or inhibition of the enzyme did not further alter myocardial oxygenation in IPC.
ISCHEMIC PRECONDITIONING ATTENUATES IN VIVO MYOCARDIAL HYPEROXYGENATION

H1449

hearts, and similar levels of reoxygenation were observed. This is consistent with prior reports that IPC results in inhibition of NO formation from NOS (15, 51).

In our current study, we have observed for the first time in the regional I/R mouse heart model that IPC attenuates in vivo myocardial hyperoxygenation status in the postischemic myocardium. The attenuation of the hyperoxygenation after regional I/R may have profound effect on postischemic cardiac remodeling, since oxygenation is a key mediator of the development and maturation of cardiac myocytes (37). Furthermore, the higher blood flow and lower P02 with IPC indicates that IPC attenuates postischemic myocardial hyperoxygenation and preserves higher levels of O2 consumption in postischemic myocardium. We also observed that IPC prevented the loss of the activities of the critical mitochondrial electron transport enzymes NADH-DH and CcO.

It has been previously demonstrated that ONOO− is formed in postischemic myocardium from the reaction of NO and O2− and results in tyrosine nitration (44, 50). We observed in our studies with the regional I/R mouse heart model that nitrosyrosine formation in postischemic myocardium is increased and that this is greatly diminished in ischemic preconditioned hearts after I/R. Thus our data suggest that IPC attenuates ROS/RNS formation, and this may contribute to the preservation of myocardial oxygen consumption and mitochondrial function leading to the attenuation of hyperoxygenation after I/R. This regional improvement of tissue oxygen consumption in IPC hearts was seen on histopathology to be associated with markedly decreased myocardial infarction.

It was observed that, while the levels of expression of NADH-DH and CcO were unchanged after I/R, their activities were significantly decreased. This I/R-induced downregulation of the function of these mitochondrial enzymes is consistent with a prior report and the fact that these have been shown to be sensitive to oxidant-induced modification and denaturation (42, 55). IPC abolished this loss of mitochondrial function. Therefore, our results suggest that IPC decreased formation of NO and O2− during subsequent postischemic reperfusion, and this protected the myocardium at risk and preserved mitochondrial function.

There are redundant signaling pathways for the protection afforded by IPC; some are linear and some are branching and converging (31). The mechanisms demonstrated in our study, possibly together with other aforementioned receptor-mediated protective mechanism(s), led to a decrease in the infarct size after I/R as demonstrated by the decreased infarct size seen on TTC staining in IPC + I/R vs. I/R mice. The attenuation of pathological ROS/RNS production with preconditioning after I/R is one of the mechanisms by which mitoKATP channel openers seem to be acting to protect against myocardial injury (31, 33). Thus there may be one or more interconnections between the processes of altered ROS/RNS or oxygen metabolism and other critical molecular pathways of IPC-induced protection.

Conclusions. In conclusion, our study suggests that IPC attenuates in vivo postischemic myocardial hyperoxygenation by improving myocardial oxygen consumption and decreasing ROS/RNS generation after regional I/R, which in turn preserves mitochondrial function and electron transport enzyme activity. This preservation of mitochondrial function and oxygen consumption contributes to myocardial protection. Further studies of the detailed mechanisms by which IPC induces suppression of pathological ROS/RNS formation and how this process relates to other pathways of protection are warranted.

ACKNOWLEDGMENTS

We thank Dr. Ilangoan Govindasamy for help with electron paramagnetic resonance oxymetry and Dr. William Muir and Dr. Arthur Strauch for helpful discussions.

GRANTS

This work was supported by American Heart Association Grant 0435299N and National Heart, Lung, and Blood Institute Grants HL-081630, and partially HL-073087 (G. He), and HL-38324, HL-63744, and HL-65608 (J. L. Zweier).

REFERENCES

H1450

ISCHEMIC PRECONDITIONING ATTENUATES IN VIVO MYOCARDIAL HYPEROXYGENATION


