The cardioprotection of the late phase of ischemic preconditioning is enhanced by postconditioning via a COX-2-mediated mechanism in conscious rats

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The phenomenon of ischemic preconditioning (PC) has been well documented to be a powerful endogenous mechanism of cardioprotection. PC is a biphasic phenomenon, with an early (or classic) phase that develops within minutes from the initial ischemic insult and lasts 2–3 h (11, 28) and a late (or delayed) phase that becomes apparent 12–24 h later and lasts 3–4 days (5). Despite extensive studies, the actual mechanism of protection remains unclear. The current consensus is that early PC is mediated by the activation of preexisting signaling kinases (such as PKC, phosphatidylinositol 3-kinase/Akt, etc.), whereas the cardioprotection of late PC is conferred by the induction of new proteins [such as inducible nitric oxide (NO) synthase (7, 33), cyclooxygenase-2 (COX-2) (31), Mn superoxide dismutase (17), and aldose reductase (29)].

More recently, Vinten-Johansen and colleagues (44) have described a cardioprotective phenomenon, termed ischemic postconditioning, in which brief intermittent episodes of myocardial ischemia applied at the onset of reperfusion result in a significant reduction in infarct size. Postconditioning has been subsequently confirmed to be cardioprotective by several groups in various experimental models (2, 8, 9, 13, 16, 18, 21, 37, 41–43). Despite these reports, our recent study (35) in conscious rats found that the protection afforded by postconditioning is modest relative to that afforded by early and late PC, being observed only when the index ischemic insult is <45 min. Because postconditioning is thought to be more clinically relevant than PC (38), exploring interventions that enhance the cardioprotective effect of postconditioning may be useful.

As postconditioning has been suggested to share many of the signaling mechanisms of early PC (14, 15), it is possible that there may be redundancy between these two forms of protection, which would limit potential synergy if both were performed to protect the heart from ischemia-reperfusion injury. Indeed, previous studies (13, 37) have found that the infarct-sparing effect of postconditioning is not enhanced by early PC.

Given that late PC provides cardioprotection via the induction of new proteins (5), we hypothesized that postconditioning may lead to additive cardioprotection. COX-2 has been implicated as a mediator of the cardioprotection of late PC induced by ischemia (31), heat stress (3), and pharmacological stimuli such as opioids (19, 25), nicorandil (36), atorvastatin (4), and anesthetics (34). Therefore, the present study sought to determine whether combining late PC and postconditioning enhances the infarct-sparing effect and, if so, whether this additive effect is mediated by a COX-2-related mechanism.

MATERIALS AND METHODS

The present study was performed in accordance with the guidelines of the Animal Care and Use Committee of the University of Louisville School of Medicine and with the National Institutes of Health Guide for the Care and Use of Laboratory Animals (NIH Pub. No. 86-23).

The conscious rat model of myocardial ischemia and reperfusion has been described in detail previously (35). Briefly, Fischer-344 male rats (Harlan Sprague Dawley, 9–12 wk of age) were anesthetized and instrumented under sterile conditions with a balloon occluder around the left anterior descending coronary artery and with bipolar leads anchored to the chest. Rats were allowed to recover for a minimum of 7 days after surgery.

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Myocardial infarct size. Chronically instrumented rats were assigned to two subsets (Fig. 1); myocardial infarction was induced in conscious rats by performing a 45-min (subset 1) or 60-min (subset 2) coronary occlusion (as the index ischemia) followed by 24 h of reperfusion. In each subset, rats were further divided into 5 groups as follows: no further intervention [controls (groups I and VI)], PC with 12 cycles of 2-min occlusion/2-min reperfusion 24 h before the index ischemia [PC (groups II and VII)], postconditioning with 20 cycles of 10-s occlusion/10-s reperfusion at the onset of reperfusion following the index ischemia [postconditioning (groups III and VIII)], or both PC and postconditioning plus vehicle [PC + postconditioning (groups IV and IX)] or the COX-2 inhibitor celecoxib [PC + postconditioning + celecoxib (groups V and X)]. Celecoxib (Searle) was dissolved in 20% DMSO in normal saline and administered intraperitoneally 10 min prior to the end of the index ischemia at a dose of 3 mg/kg (Fig. 1). All rats received diazepam (4 mg/kg ip) 10 min before the index ischemia to relieve the stress caused by the sustained coronary occlusion. No antiarrhythmic agents were given at any time. At the conclusion of the study, rats were killed. The occluded/reperfused vascular bed and the infarct were identified by postmortem perfusion using rabbit polyclonal anti-COX-2 antibody (Cayman Chemical) and normalized to the corresponding Ponceau S signal determined by densitometric analysis of the Ponceau S stain record, as previously described (31). To assess the enzymatic activity of COX-2, myocardial PGE2 content was measured. PGE2 was extracted from tissue samples, purified by using the PGE2 affinity sorbent, and measured using an enzyme immunoassay kit (Cayman Chemical) as previously described (31).

Statistical analysis. Data were analyzed by a one-way ANOVA followed by Student’s t-tests with the Bonferroni correction using SigmaStat 2.0 for Windows. The relationship between infarct size and risk region size was compared among groups with analysis of covariance (ANCOVA) using the size of the risk region as the covariate (27, 33, 35) and was assessed by linear regression analysis using the least-squares method. ANCOVA was performed using SPSS 8.0 for Windows. P < 0.05 was considered significant. Results are reported as means ± SE.

RESULTS

A total of 102 conscious rats were used (40, 39, and 23 rats, respectively, for the experiments of subsets I, II, and III). Table 1 summarizes the initial assignments and exclusions. Rats that developed ventricular fibrillation but cardioverted spontaneously were included in the final analysis. There were no significant differences in heart rate throughout the experimental protocol among groups (Table 2). In addition, body weight, total LV weight, and the size of the region at risk did not differ among the groups (Table 3).

Myocardial infarct size. In subset I (rats subjected to a 45-min coronary occlusion), the myocardial infarct size was 64.5 ± 2.9% of the risk region in the control group (group I) and was reduced significantly in the PC group (group II: 43.0 ± 5.0%, P < 0.05 vs. group I) but not in the postconditioning group (group III: 57.0 ± 2.4%, P = not significant)
confirming our previous observation that the cardioprotection of postconditioning is weaker than that of PC (35). The infarct size was 32.8 ± 6.4% in the PC + postconditioning group (group IV; P < 0.05 vs. groups I and III) (Figs. 3 and 4). The infarct size in group IV was ~25% smaller compared with group II, although the difference was not statistically significant, suggesting that the combined interventions produced a more robust infarct-sparing effect.

In rats subjected to a 60-min coronary occlusion (subset 2), the myocardial infarct size was 73.6 ± 3.0% of the risk region in the control group (group VI) (Figs. 5 and 6). Neither late PC alone (group VII: 66.4 ± 2.7%) nor postconditioning alone (group VIII: 71.7 ± 4.5%) reduced the infarct size significantly compared with group VI. However, the infarct size was significantly reduced by combining late PC and postconditioning (group IX: 54.5 ± 1.7%, P < 0.05 vs. groups VI, VII, and VIII, respectively) (Figs. 5 and 6), indicating that the two interventions exerted additive cardioprotection. The COX-2 inhibitor celecoxib effectively abrogated the additive infarct-sparing effect of late PC plus postconditioning in both subsets [group V (Figs. 3 and 4) and group X (Figs. 5 and 6)].

Expression of COX-2 protein. As shown in Fig. 7, a weak COX-2 signal was detected in control rats (group I). COX-2 expression in the ischemic-reperfused region was upregulated by PC (group XII) but, as expected, not by postconditioning (group XIII). COX-2 protein levels in the nonischemic region

Table 1. Exclusions from the study

<table>
<thead>
<tr>
<th>Subset 1: 45-min occlusion</th>
<th>Initial Assignment</th>
<th>Died of VF During Occlusion</th>
<th>Technical Failure</th>
<th>Final Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group I (control)</td>
<td>8</td>
<td>1</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>Group II (PC)</td>
<td>8</td>
<td>1</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>Group III (PostC)</td>
<td>8</td>
<td>1</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>Group IV (PC + PostC)</td>
<td>8</td>
<td>1</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>Group V (PC + PostC + celecoxib)</td>
<td>8</td>
<td>1</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Subset 2: 60-min occlusion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group VI (control)</td>
<td>8</td>
<td>2</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Group VII (PC)</td>
<td>8</td>
<td>1</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Group VIII (PostC)</td>
<td>8</td>
<td>1</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Group IX (PC + PostC)</td>
<td>8</td>
<td>2</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Group X (PC + PostC + celecoxib)</td>
<td>7</td>
<td>1</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Subset 3: myocardial levels of COX-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group XI (control)</td>
<td>5</td>
<td></td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Group XII (PC)</td>
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<td></td>
<td></td>
<td>4</td>
</tr>
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<td>Group XIII (PostC)</td>
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<td></td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Group XIV (PC + PostC)</td>
<td>5</td>
<td></td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Group XV (PC + PostC + celecoxib)</td>
<td>4</td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>102</td>
<td>13</td>
<td>5</td>
<td>84</td>
</tr>
</tbody>
</table>

Values are numbers of rats excluded per group. VF, ventricular fibrillation; PC, late preconditioning (12 cycles of 2-min ischemia/2-min reperfusion applied 24 h prior to occlusion); PostC, postconditioning (20 cycles of 10-s ischemia/10-s reperfusion at the onset of reperfusion following occlusion); COX-2, cyclooxygenase-2.
were not elevated and were similar among groups (data not shown).

**Myocardial PGE2 content.** To determine whether the increase in COX-2 protein expression was associated with increased COX-2 enzymatic activity, myocardial PGE2 content was measured using enzyme immunoassay. As shown in Fig. 8, PGE2 content in the nonischemic region was similar among groups. PC (group XII) resulted in a significant increase in PGE2 content in the ischemic-reperfused region (+143 ± 38% vs. group XI, P < 0.05). Postconditioning (group XIII), on the other hand, slightly increased PGE2 content (+35 ± 48% vs. group XI), and the change was not significant (P = 0.49). Interestingly, the combination of PC and postconditioning (group XIV) resulted in a further increase in PGE2 content vis-à-vis PC alone (+48 ± 10% vs. group XII, P < 0.05). The increased PGE2 content was completely abrogated by celecoxib (group XV) (Fig. 8). The fact that in group XIV there was a further increase in PGE2 content (Fig. 8) without additional COX-2 protein expression (Fig. 7) suggests that postconditioning enhances the enzymatic activity of PC-induced COX-2.

**DISCUSSION**

The salient findings of this study can be summarized as follows: 1) late PC alone reduced the infarct size induced by a 45-min coronary occlusion but not by a 60-min coronary occlusion, whereas postconditioning alone had no significant infarct-sparing effect after either a 45- or 60-min occlusion; 2) the combination of late PC and postconditioning resulted in a robust infarct-sparing effect in rats subjected to either a 45- or 60-min occlusion, demonstrating an additive protective effect of the two interventions; 3) celecoxib completely abrogated the infarct-sparing actions of the combined interventions, suggesting that COX-2 plays a critical role in this additive effect; 4)
late PC resulted in increased myocardial COX-2 protein expression with a concomitant increase in the myocardial content of COX-2-derived PGE2; and 5) the combination of late PC and postconditioning further increased the myocardial PGE2 content without a concomitant increase in COX-2 protein expression, implying that postconditioning enhances the enzymatic activity of the COX-2 induced by late PC. Taken together, these results demonstrate that the combination of late PC and postconditioning produces an additive cardioprotective effect via a COX-2-mediated mechanism.

Ischemic postconditioning is a newly described cardioprotective strategy (44) thought to be clinically more feasible than other therapies because it can be implemented during reperfusion (38). A number of investigations have found that postconditioning shares many signaling mechanisms with early PC (15) and exhibits similar physiological and cellular aspects of protection (39). Although one study (42) reported that combining early PC with postconditioning induced additive protection in rabbits, two other studies found no such effect in rats (37) or dogs (13), implying potentially overlapping mechanisms. Unlike early PC, late PC provides cardioprotection via the synthesis of new proteins (5, 6). Therefore, if postconditioning is preceded by the intervention of late PC, in principle there should be an additive protective effect.

In this study, we sought to rigorously determine whether the combination of late PC and postconditioning exerts an additive protection (38). A number of investigations have found that postconditioning shares many signaling mechanisms with early PC (15) and exhibits similar physiological and cellular aspects of protection (39). Although one study (42) reported that combining early PC with postconditioning induced additive protection in rabbits, two other studies found no such effect in rats (37) or dogs (13), implying potentially overlapping mechanisms. Unlike early PC, late PC provides cardioprotection via the synthesis of new proteins (5, 6). Therefore, if postconditioning is preceded by the intervention of late PC, in principle there should be an additive protective effect.

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Fig. 3. Infarct size after a 45-min coronary occlusion and 24 h of reperfusion. ○, Individual hearts; ⋄, group means ± SE.

Fig. 4. Relationship between the size of the region at risk and size of myocardial infarction in rats exposed to a 45-min coronary occlusion. Both individual values and the regression lines obtained by linear regression analysis are shown for groups I–V. In all groups, infarct size was positively and linearly related to the size of region at risk. Analysis of covariance (ANCOVA) demonstrated that the regression lines for groups II and IV were significantly shifted downward and to the right compared with that for group I (P < 0.05 for each comparison), indicating that for any given size of the region at risk, infarct size was smaller in rats that received either late PC alone or late PC + PostC. In group V, the line was similar to that for group I, indicating that COX-2 inhibition abrogated the additive protective effect of the combined interventions.

Fig. 5. Infarct size after a 60-min coronary occlusion and 24 h of reperfusion. ○, Individual hearts; ⋄, group means ± SE.

Fig. 6. Relationship between the size of the region at risk and size of myocardial infarction in rats exposed to a 60-min coronary occlusion. Both individual values and the regression lines obtained by linear regression analysis are shown for groups VI–X. In all groups, infarct size was positively and linearly related to the size of region at risk. ANCOVA demonstrated that the regression line for group IX was significantly shifted downward and to the right compared with that for groups VI–VIII (P < 0.05 for each comparison), indicating that for any given size of region at risk, infarct size was smaller in rats that received the combined interventions of late PC and PostC. In group X, the line was significantly different from that in group IX, indicating that COX-2 inhibition abrogated the additive protective effect of the combined interventions.
additive protection effect. To this end, we used the same conscious rat model used in our previous study (35). Although conscious animal models are more expensive, time consuming, and technically demanding than open-chest models, we reasoned that they yield results that are less prone to the influence of spurious factors associated with anesthesia and surgery and, therefore, are more clinically relevant (35). We confirmed our previous finding (35) that postconditioning alone fails to reduce infarct size after a 45-min ischemic period.

Using this model, we first examined the additive effects of late PC and postconditioning in rats subjected to a 45-min index ischemia (subset 1). We found that the combined interventions resulted in a robust limitation of infarct size, which did not differ significantly from that induced by late PC alone (Fig. 3). It is possible, however, that an additive effect may have been masked by the robust protection afforded by late PC after a 45-min ischemic insult.

Evidence that COX-2 plays an essential role in conferring the cardioprotection afforded by late PC was provided by studies in rabbits (31) and mice (10, 12, 23, 40) in the setting of ischemia-induced PC. Subsequent studies have shown that COX-2 mediates the delayed infarct-sparing effects of a panoply of pathophysiological stimuli and pharmacological agents, such as opioid receptor agonists (20, 22, 25), nicorandil (36), heat stress (3), anesthetics (1, 34), diazoxide (1), and atorvastatin (4). In the present study, we found that ischemic PC dramatically increased COX-2 protein expression (over 6-fold above control) 24 h later (Fig. 7), corroborating our previous findings in conscious rabbits (31). To assess COX enzymatic activity, we measured the myocardial content of PGE2, which is the main product of COX-2 activity in PC myocardium, as shown by our previous study (31). We found that late PC was associated with a 2.4-fold increase in myocardial PGE2 content compared with controls (Fig. 8), indicating a significant increase in COX activity, consistent with our prior results (31). A novel finding of this study is that postconditioning further increased COX enzymatic activity, as evidenced from a 3.6-fold increase in PGE2 content under conditions in which there was no further increase in COX-2

![Fig. 7. Expression of COX-2 protein in rat myocardium. A: representative immunoblots of COX-2 expression in the ischemic-reperfused region. The Ponceau S staining reflects equal protein loading. B: densitometric analysis of COX-2 signals. In all samples, densitometric measurements of COX-2 immunoreactivity were expressed as percentages of the average value measured in control rats. PC, 12 cycles of 2-min ischemia/2-min reperfusion applied 24 h prior to occlusion (late PC); PostC, 20 cycles of 10-s ischemia/10-s reperfusion at the onset of reperfusion following occlusion; Celecoxib, 3 mg/kg ip celecoxib administered 10 min before reperfusion. Data were normalized to the Ponceau S signals and are expressed as means ± SE.](http://ajpheart.physiology.org/content/293/10/AJP-HeartCircPhysiol.full)

![Fig. 8. Content of PGE2 in rat myocardium. PGE2 was extracted from the ischemic-reperfused and nonischemic regions and expressed as picograms per milligram of protein. Groups were as described in Fig. 7. Data are means ± SE.](http://ajpheart.physiology.org/content/293/10/AJP-HeartCircPhysiol.full)
protein expression (Fig. 7). Because this increase in PGE$_2$ content was associated with enhanced cardioprotection and because COX-2 inhibition completely abrogated this additive effect (Figs. 3 and 5), the present study suggests that the enzymatic activity of the COX-2 protein induced by late PC is further increased by postconditioning to provide additional cardioprotection. To our knowledge, this is the first evidence that postconditioning enhances COX-2 activity. The mechanism remains unclear but may involve increased NO availability. Previous studies have shown that postconditioning is associated with the activation of NO synthase (37, 42) and that NO activates COX-2 protein induced by late PC (32).

Because postconditioning appears to enhance the protective effects of late PC by enhancing COX-2 activity, our findings raise the possibility that the benefits of this additive cardioprotection may be lost in patients who take the COX inhibitor acetylsalicylic acid (aspirin) (26). However, since aspirin is a relatively weak inhibitor of COX-2 activity (24), it appears that the doses used for prophylaxis of acute myocardial infarction and stroke would be unlikely to affect the additive cardioprotection of postconditioning. In this regard, we (30) have previously shown that the administration of aspirin either at an antithrombotic dose (5 mg/kg) or at an analgesic/antiplatelet dose (10 mg/kg) does not interfere with the cardioprotective effects of late PC against myocardial stunning. Further studies will be necessary to definitely address this issue.

In conclusion, in conscious rats subjected to a relatively severe ischemic insult (45-min coronary occlusion), the ability of postconditioning to confer protection appears to be COX-2 dependent. That is, postconditioning does not afford protection if COX-2 is expressed at low levels (i.e., at constitutively expressed COX-2 levels), but it does confer additional protection (above and beyond that of late PC alone) when COX-2 protein is upregulated (e.g., during the late phase of PC). Thus, the combination of late PC and postconditioning produces additive protection, likely due to a postconditioning-induced enhancement of COX-2 activity. These findings have conceptual and mechanistic implications for the pathophysiology of postconditioning. Furthermore, they may facilitate the development of strategies that enhance the cardioprotection of postconditioning. For example, if patients at risk are pharmacologically preconditioned to induce expression of COX-2, they could be further protected by postconditioning.

GRANTS
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