Loss of Myocardial Ischemic Postconditioning in Adenosine A₁ and Bradykinin B₂ Receptors Gene Knockout Mice

Lei Xi, MD; Anindita Das, PhD; Zhi-Qing Zhao, MD, PhD; Vanessa F. Merino, PhD; Michael Bader, PhD; Rakesh C. Kukreja, PhD

Background—Ischemic postconditioning (PostC) is a recently described cardioprotective modality against reperfusion injury, through series of brief reflow interruptions applied at the very onset of reperfusion. It is proposed that PostC can activate a complex cellular signaling cascade, in which cell membrane receptors could serve as the upstream triggers of PostC. However, the exact subtypes of such receptors remain controversial or uninvestigated. To this context, the purpose of present study was to determine the definitive role of adenosine A₁ and bradykinin B₁ and B₂ receptors in PostC.

Methods and Results—The hearts isolated from adult male C57BL/6J wild-type mice or the mice lacking adenosine A₁, or bradykinin B₁ or B₂ receptors subjected to zero-flow global ischemia and reperfusion in a Langendorff model. PostC, consisting of 6 cycles of 10 seconds of reperfusion and 10 seconds of ischemia, demonstrated significantly reduced myocardial infarct size (22.8±3.1%, mean±SEM) as compared with the non-PostC wild-type controls (35.1±2.8%, P<0.05). The infarct-limiting protection of PostC was absent in adenosine A₁ receptor knockout mice (34.9±2.7%) or bradykinin B₂ receptor knockout mice (33.3±1.7%) and was partially attenuated in bradykinin B₁ receptor–deficient mice (25.6±2.9%; P>0.05). On the other hand, PostC did not significantly alter postischemic cardiac contractile function and coronary flow.

Conclusions—With the use of three distinctive strains of gene knockout mice, the current study has provided the first conclusive evidence showing PostC-induced infarct-limiting cardioprotection could be triggered by activation of multiple types of cell membrane receptors, which include adenosine A₁ and bradykinin B₂ receptors. (Circulation. 2008;118[suppl 1]:S32–S37.)

Key Words: adenosine ■ bradykinin ■ infarction ■ receptors ■ reperfusion

Ischemic postconditioning (PostC) is a series of brief mechanical interruptions of reperfusion applied at the very onset of reperfusion. Since the original description of PostC in an in vivo dog model in 2003, this cardioprotective phenomenon has been confirmed by a number of research groups in several mammalian species including rat, mouse, rabbit, dog, and human. This novel cardioprotective strategy has received considerable interests, mainly because of its potential clinical applicability as a postischemic cardiac contractile function and coronary flow. However, the exact subtypes of adenosine and bradykinin receptors involved in triggering PostC remain controversial or unknown. To resolve this issue, the present study was undertaken to determine the efficacy of PostC in reducing myocardial infarct size in strains of mice lacking adenosine A₁ and bradykinin B₁ and B₂ receptors.

Materials and Methods

Animals
Adult male C57BL/6J wild-type (C57-WT) mice and homozygous (+/−) bradykinin B₂ receptor knockout (B2-KO) mice were purchased from The Jackson Laboratory (Bar Harbor, Me). Adult male adenosine A₁ receptor knockout (A1-KO) mice were bred in the Virginia Commonwealth University (VCU) animal facility using the
breeding pairs of homozygous (−/−) A1-KO mice, a generous gift from Dr. Jurgen Schnerrmann (NIDDK, Bethesda, Md). Adult male homozygous (−/−) bradykinin B1 receptor knockout (B1-KO) mice were generated at the Max-Delbrück-Center for Molecular Medicine, Berlin-Buch, Germany according to the published methods. The B1-KO mice at age of 6 weeks were transferred to VCU animal facility. Because all of the gene-knockout mice used in this study were generated from C57BL/6J background, C57-WT mice were used as the common control group for A1-KO, B1-KO, and B2-KO groups. The animal care and experiments were conducted in conformance with the guidelines on humane use and care of laboratory animals for biomedical research published by NIH (No. 85-23, revised 1996), and the rodent experiment protocol was approved by the Institutional Animal Care and Use Committee of VCU.

Model of Global Ischemia-Reperfusion in Langendorff Isolated Mouse Heart

The methodology of Langendorff isolated buffer-perfused mouse heart preparation was previously described in detail. In brief, the mouse was anesthetized with pentobarbital sodium (100 mg/kg, 33 IU heparin; i.p.) and the heart was quickly removed from the mouse. The heart was cannulated (time delay <3 minutes) and tied on a 20-gauge blunt needle connected to Langendorff perfusion system. The heart was retrogradely perfused at constant pressure of 55 mm Hg with modified Krebs-Henseleit buffer containing (in mmol/L): 118 NaCl, 24 NaHCO3, 2.5 CaCl2, 4.7 KCl, 1.2 KH2PO4, 1.2 MgSO4, 11 glucose, and 0.5 EDTA. The buffer was continuously gassed with 95% O2 + 5% CO2 (pH ~7.4) and warmed by a heating bath/circulator. The heart temperature was continuously monitored and maintained at 37±0.5°C. Ventricular function was measured by a force-displacement transducer (model FT03, Grass) attached to the apex with surgical thread and metal hook. The resting tension was adjusted to ~0.30 g. The contractile force was continuously recorded with a PowerLab 8SP computerized data acquisition system connected to the force transducer. Coronary flow rate was calculated by timed collection of the outflow perfusate. No electric pacing was applied to the heart.

Experiment Groups and Protocol

As illustrated in Figure 1, C57-WT control mice and the three strains of receptor-deficient mice (ie, A1-KO, B1-KO, B2-KO) were randomized into the following 8 experiment groups. Group 1: C57-WT (n=8), C57-WT subjected to ischemia and postC intervention (6 cycles of 10 seconds of reperfusion and 10 seconds of ischemia) during the initial 2 minutes of reperfusion; Group 3: A1-KO (n=8), A1-KO subjected to ischemia and reperfusion; Group 4: A1-KO+postC (n=7), A1-KO subjected to ischemia and postC; Group 5: B1-KO (n=9), B1-KO subjected to ischemia and reperfusion; Group 6: B1-KO+postC (n=9), B1-KO subjected to ischemia and postC; Group 7: B2-KO (n=7), B2-KO subjected to ischemia and reperfusion; and Group 8: B2-KO+postC (n=7), B2-KO subjected to ischemia and postC.

Measurement of Infarct Size

At the end of experiment, the heart was immediately removed from Langendorff apparatus, weighed, and frozen at −20°C. The frozen heart was manually cut into 7 to 8 transverse slices (~1 mm thickness), which were incubated in 10% TTC for 30 minutes at room temperature. TTC was then replaced with 10% formaldehyde for 3 to 4 hours of fixation before infarct size was measured using a computerized morphometry system (Biosquant 98). The risk area was calculated as total ventricular area minus cavities. Infarct size was calculated as % of risk area.

Data Analysis and Statistics

The experimental data were presented as the group means and standard errors (SEM). The difference among experimental groups was analyzed with 2-way ANOVA followed by Bonferroni post hoc test for pair-wise comparison. This analysis examines the effects of two variables (ie, Factor 1: PostC intervention and Factor 2: animal genetic background), both individually and together, on the experimental response. P<0.05 was considered as statistically significant.

The authors had full access to and take full responsibility for the integrity of the data. All authors have read and agree to the manuscript as written.

Results

Animal Exclusion Record and Morphometric Characteristics

Of 66 mice originally used in the present study, 3 mice (ie, 4.5% of the total) were excluded because of persistent arrhythmia or poor preischemic function. The body weight and heart weight were significantly higher in A1-KO and B1-KO mice as compared with the non-PostC C57-WT mice, indicating a genetic background related variation in body/heart mass (Table 1).

Myocardial Infarct Size

As shown in Figures 2 and 3, PostC resulted in reduction of infarct size following ischemia-reperfusion in C57-WT mice (22.8±3.1%), as compared with the wild-type control mice without PostC (35.1±2.8%; P<0.05). Infarct size in the non-PostC A1-KO and B2-KO was not different from the C57-WT controls (P>0.05). However, the infarct-limiting protection of PostC was completely abolished in mice lacking either adenosine A1 receptors or bradykinin B2 receptors (Figure 3; P>0.05 versus the corresponding non-PostC A1-KO or B2-KO). Genetic deletion of bradykinin B1 receptors also did not alter myocardial infarct size (ie, 30.9±3.6% in B1-KO versus 35.1±2.8% in C57-WT; P>0.05). PostC was able to marginally reduce infarct size to 25.6±2.9% in B1-KO (Figure 3; P>0.05 versus non-PostC B1-KO group), indicating PostC was partially attenuated in the mice deficient of bradykinin B1 receptors.
Table 1. Morphometric Characteristics and Baseline Cardiac Function of the Mice

<table>
<thead>
<tr>
<th></th>
<th>C57-WT (n=8)</th>
<th>C57-WT + PostC (n=8)</th>
<th>A1-KO (n=8)</th>
<th>A1-KO + PostC (n=9)</th>
<th>B1-KO (n=9)</th>
<th>B1-KO + PostC (n=9)</th>
<th>B2-KO (n=7)</th>
<th>B2-KO + PostC (n=7)</th>
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</thead>
<tbody>
<tr>
<td>Body weight, g</td>
<td>28.1±2.3</td>
<td>31.1±0.6</td>
<td>35.9±2.5*</td>
<td>35.4±1.4</td>
<td>35.2±1.2*</td>
<td>36.3±2.2</td>
<td>30.1±2.8</td>
<td>30.8±2.5</td>
</tr>
<tr>
<td>Heart wet weight, mg</td>
<td>205±9</td>
<td>215±6</td>
<td>259±13*</td>
<td>266±7*</td>
<td>261±18*</td>
<td>249±13</td>
<td>218±20</td>
<td>213±18</td>
</tr>
<tr>
<td>Coronary flow, ml/min</td>
<td>1.6±0.2</td>
<td>1.8±0.2</td>
<td>1.8±0.2</td>
<td>2.3±0.2</td>
<td>1.6±0.2</td>
<td>2.0±0.2</td>
<td>2.0±0.3</td>
<td>1.8±0.1</td>
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<tr>
<td>Heart rate, bpm</td>
<td>345±22</td>
<td>351±16</td>
<td>316±29</td>
<td>343±20</td>
<td>317±23</td>
<td>301±22</td>
<td>349±30</td>
<td>351±23</td>
</tr>
<tr>
<td>Developed force, g</td>
<td>0.81±0.11</td>
<td>0.96±0.18</td>
<td>1.03±0.21</td>
<td>0.84±0.19</td>
<td>0.76±0.15</td>
<td>1.00±0.20</td>
<td>0.59±0.14</td>
<td>0.59±0.12</td>
</tr>
<tr>
<td>Rate-force product, g×bpm</td>
<td>284±46</td>
<td>339±67</td>
<td>306±55</td>
<td>285±63</td>
<td>234±46</td>
<td>290±63</td>
<td>188±30</td>
<td>217±56</td>
</tr>
</tbody>
</table>

Values are mean±SEM. bpm indicates beats per minute. *P<0.05 vs C57-WT group; †P<0.05 vs C57-WT + PostC group (2-way ANOVA with Bonferroni post-hoc test).

Baseline and Postischemic Cardiac Contractile Function

There was no significant difference in the preischemia baseline levels of ventricular developed force and rate-force product among the eight experimental groups (Table 1; P>0.05), despite the baseline contractile function tended to be lower in B2-KO groups. After the global ischemia-reperfusion, the developed force and rate-force product were remarkably depressed in all of the 8 experimental groups, whereas heart rate remained at a constant level similar to the preischemic values at both early (5 minutes) and late (30 minutes) time points of reperfusion (Tables 1 and 2; Figure 4). Interestingly, PostC did not improve the postischemic cardiac contractile function at either 5 minutes or 30 minutes of reperfusion in any strain of the wild-type and gene knockout mice (Table 2 and Figure 4; P>0.05). It is notable that the early postischemic functional recovery was remarkably improved in B1-KO group (ie, 89.8±10.6% of preischemic baseline for rate-force product versus 58.9±12.6% in C57-WT group; see Figure 4B), although it failed to reach the statistical significance mainly because of the high intragroup variability for the contractile function parameters (P>0.05 with 2-way ANOVA). Furthermore, this trend of functional improvement in B1-KO mice disappeared at the end of 30 minutes reperfusion (Figure 4D).

Baseline and Postischemic Coronary Flow

Genetic deletion of adenosine A1, or bradykinin B1 or B2 receptors did not alter the preischemic and postischemic coronary flow rate (P>0.05; Table 1 and Figure 5). There was only a slight trend toward higher postischemic coronary flow in A1-KO mice (Figure 5). PostC also had no effect on the postischemic coronary flow as compared with the corresponding non-PostC groups (P>0.05; Figure 5).

Discussion

The present study has demonstrated the existence of PostC against myocardial ischemia-reperfusion injury in C57BL/6J wild-type mice. The 6 cycles of 10 seconds of reperfusion and 10 seconds of ischemia PostC maneuvers applied at the very onset of reperfusion significantly reduced infarct size in the...
globally ischemic-reperfused mouse hearts (Figures 2 and 3). The degree of infarct size reduction of PostC was approximately 35% from the non-PostC controls, which appears to be less potent than the ~42% reduction observed in our previous ischemic preconditioning study in ICR outbred mice performed in Langendorff perfused hearts with similar duration of ischemia-reperfusion. These results are comparable to the previous studies demonstrating efficacy of PostC in mice with 31% reduction in infarct size6 and 37% reduction in cardiac troponin I release—a specific marker for cardiac cell necrosis.7 These results also support the concept that protective efficacy of PostC is somewhat less robust as compared to ischemic preconditioning based on the findings in conscious rats4 and anesthetized rabbits.8 Furthermore, the infarct-limiting effect of PostC was not associated with any improvement in ventricular contractile function at 5 minutes or 30

Table 2. Postischemic Cardiac Function

<table>
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<tbody>
<tr>
<td></td>
<td>(n=8)</td>
<td>(n=8)</td>
<td>(n=7)</td>
<td>(n=7)</td>
<td>(n=9)</td>
<td>(n=9)</td>
<td>(n=7)</td>
<td>(n=7)</td>
</tr>
<tr>
<td>Heart rate, bpm</td>
<td>368±25</td>
<td>339±18</td>
<td>336±18</td>
<td>362±29</td>
<td>360±23</td>
<td>308±22</td>
<td>341±22</td>
<td>347±27</td>
</tr>
<tr>
<td>Developed force, g</td>
<td>0.48±0.13</td>
<td>0.47±0.14</td>
<td>0.53±0.19</td>
<td>0.43±0.16</td>
<td>0.61±0.15</td>
<td>0.58±0.18</td>
<td>0.27±0.10</td>
<td>0.41±0.14</td>
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<tr>
<td>Rate-force product, g×bpm</td>
<td>182±46</td>
<td>168±53</td>
<td>178±62</td>
<td>168±66</td>
<td>216±53</td>
<td>195±69</td>
<td>85±25</td>
<td>158±61</td>
</tr>
</tbody>
</table>

Values are Mean±SEM. bpm indicates beats per minute. No significant difference was found between the groups for any of the functional parameters (2-way ANOVA with Bonferroni post-hoc test).

At 5 minutes of reperfusion

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</tr>
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<tbody>
<tr>
<td>Heart rate, bpm</td>
<td>345±26</td>
<td>309±17</td>
<td>324±19</td>
<td>321±26</td>
<td>288±24</td>
<td>301±32</td>
<td>354±24</td>
<td>334±24</td>
</tr>
<tr>
<td>Developed force, g</td>
<td>0.53±0.15</td>
<td>0.48±0.13</td>
<td>0.55±0.20</td>
<td>0.42±0.16</td>
<td>0.55±0.14</td>
<td>0.59±0.19</td>
<td>0.27±0.14</td>
<td>0.28±0.09</td>
</tr>
<tr>
<td>Rate-force product, g×bpm</td>
<td>190±53</td>
<td>151±45</td>
<td>172±59</td>
<td>143±55</td>
<td>148±36</td>
<td>164±62</td>
<td>85±36</td>
<td>103±37</td>
</tr>
</tbody>
</table>

At 30 minutes of reperfusion

Cardiac Function at 5 min of Reperfusion

Cardiac Function at 30 min of Reperfusion

Figure 4. Postischemic cardiac function, indicated by Developed Force (A and C) and double product of heart rate and developed force (Rate-Force Product; B and D; mean±SEM) at 5 minutes (top) or 30 minutes (bottom) of reperfusion. No statistically significant difference was found among the 8 experiment groups.
minutes of reperfusion (Table 2 and Figure 4). This dissociation of infarct size and ventricular function was previously observed by our laboratory and others in various settings of preconditioning17-19 and PostC.9,10 Some previous studies did report significant improvement in cardiac function after adenosine A2A receptors7 were used.

More importantly, the present study is the first investigation using adenosine A1 and bradykinin B1 or B2 receptors knockout mice to determine the possible participation of these membrane receptors in triggering PostC. This is because the genetic deletion of a particular receptor gene could circumvent many confounding factors involved with the pharmacological antagonists of membrane receptors, such as suboptimal dose, target tissue availability, receptor affinity and selectivity, and other nonspecific effects of the drugs. To our knowledge, there were only 2 previous PostC studies in which the mice with targeted deletion of connexin-436 or our knowledge, there were only 2 previous PostC studies in which the mice with targeted deletion of connexin-436 or genetic deficiency of bradykinin B2 receptors did not significantly modify myocardial tolerance to ischemia-reperfusion17,21 when PostC was used immediately after reperfusion in the two in vivo studies.3,11

Adenosine A1 Receptors and PostC

Despite a general agreement for the involvement of adenosine receptors in cardioprotection at reperfusion such as PostC,12 the exact receptor subtype(s) that are responsible for triggering PostC remain controversial. One study addressed this issue by using the blockers of adenosine A1 (DPCPX); A2A (ZM241385) or A3 (MRS1523) receptors at the onset of reperfusion in an in vivo rat model and the authors concluded that A2A and A3, but not A1 receptors are important for PostC-induced cardioprotection.3 The role of adenosine A3A receptors was recently confirmed by abrogation of PostC in mice lacking A3A.7 However, another in vivo rabbit study reported blockade of PostC by an A3B receptor antagonist, MR51754, but not by DPCPX and A2A receptor antagonist, 8-(13-chlorostyryl)caffeine.11 In contrast, the present study clearly indicated complete loss of PostC-induced cardioprotection in A1-KO mice (Figure 3), which strongly suggests that adenosine A1 receptors are also essential for eliciting PostC. Interestingly, the findings are supported by a recent publication,19 which reported that administration of A1 blocker DPCPX (200 nmol/L) abolished PostC-induced infarct size reduction in isolated rabbit hearts subjected to global ischemia-reperfusion. In addition, activation of A1 receptors by endogenous adenosine at reperfusion has been shown to protect the mouse heart.20 To explain this apparent discrepancy, we would suspect that the intravenous administration of DPCPX shortly before or at the onset of reperfusion may not effectively block A1 receptors in cardiomyocytes when PostC was used immediately after reperfusion in the two in vivo studies.3,11

Bradykinin B1 Receptors and PostC

The pathophysiological function of bradykinin B1 receptors in ischemia-reperfusion injury remains ambiguous. From the few previous studies on B1-KO mice, both of beneficial21 and detrimental22,23 effects of B1 receptors on myocardial infarction and/or remodeling have been proposed. Our current study also yielded a blurry picture on the role of B1 receptors in PostC. We found that PostC produced a marginally smaller infarct size in B1-KO mice (25.6±2.9%) than the non-PostC B1-KO mice (30.9±3.6%; P>0.05; Figure 3). These results suggest that PostC was only partially attenuated in the absence of B1 receptors. Therefore, we believe that bradykinin B1 receptors do not play an important role in triggering PostC.

Role of Other G Protein–Coupled Receptors in PostC

It is notable that other types of G protein–coupled receptors could also involve with the signaling cascades of PostC. As we previously discussed, in addition to the involvement of adenosine A1 demonstrated by our present study and others,19 other subtypes of adenosine receptors were also shown to be indispensable for PostC by several research groups. These G protein–coupled receptors include adenosine A2A,3,7 A3B,11...
and A$_3$. Furthermore, a few recent studies suggested that opioid receptors are the likely participants in PostC signaling,27–29 which essentially confirmed the concept originally proposed by Gross and colleagues that pharmacological activation of opioid receptors at the early phase of reperfusion is as protective as preconditioning with the opioid receptor agonists in the rat heart.30 However, it remains unclear how these G protein–coupled receptors cross-talk with each other, which leads to loss of PostC-induced cardioprotection in the absence of one of these receptors.

**Conclusion**
The present study using 3 distinctive strains of gene knockout mice has provided conclusive evidence for the essential role of both adenosine A$_1$ and bradykinin B$_2$ receptors on infarct-limiting protection of PostC in globally ischemic-reperfused mouse hearts. Future studies are necessary to elucidate the exact signaling cascades after the PostC-induced activation of each of these membrane receptor subtypes that ultimately lead to the cytoprotective phenotype against cardiac reperfusion injury.

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**Disclosures**
None.

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