Cardioprotection by Ecto-5’-Nucleotidase (CD73) and A2B Adenosine Receptors

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Background—Ecto-5’-nucleotidase (CD73)–dependent adenosine generation has been implicated in tissue protection during acute injury. Once generated, adenosine can activate cell-surface adenosine receptors (A1AR, A2AAR, A2BAR, A3AR). In the present study, we define the contribution of adenosine to cardioprotection by ischemic preconditioning.

Methods and Results—On the basis of observations of CD73 induction by ischemic preconditioning, we found that inhibition or targeted gene deletion of cd73 abolished infarct size-limiting effects. Moreover, 5’-nucleotidase treatment reconstituted cd73−/− mice and attenuated infarct sizes in wild-type mice. Transcriptional profiling of adenosine receptors suggested a contribution of A2BAR because it was selectively induced by ischemic preconditioning. Specifically, in situ ischemic preconditioning conferred cardioprotection in A2AR−/−, A3AR−/−, or A3AR−/− mice but not in A2BAR−/− mice or in wild-type mice after inhibition of the A2BAR. Moreover, A2BAR agonist treatment significantly reduced infarct sizes after ischemia.

Conclusions—Taken together, pharmacological and genetic evidence demonstrate the importance of CD73-dependent adenosine generation and signaling through A2BAR for cardioprotection by ischemic preconditioning and suggests 5’-nucleotidase or A2BAR agonists as therapy for myocardial ischemia. (Circulation. 2007;115:1581-1590.)

Key Words: adenosine ■ infarction ■ ischemia ■ reperfusion ■ nucleotidase

Myocardial ischemia represents a major health problem in Western countries. Current therapeutic interventions focus mainly on early and persistent coronary reperfusion, and additional pharmacological strategies to increase resistance to myocardial ischemia are currently areas of intense investigation. A powerful strategy for cardioprotection would be to recapitulate the consequences of ischemic preconditioning (IP), in which short and repeated episodes of ischemia and reperfusion before myocardial infarction occur during conditions of limited oxygen availability, as may occur during myocardial ischemia. Nevertheless, pharmacological studies on the role of CD73-dependent adenosine generation in cardioprotection during ischemia and reperfusion have yielded conflicting results.

Extracellular adenosine produced by CD73 can signal through any of 4 extracellular adenosine receptors (A1AR, A2AAR, A2BAR, or A3AR). All 4 ARs have been associated with tissue protection in a variety of physiological settings. Although all 4 ARs are expressed in cardiac tissues, the contribution of individual receptors to cardioprotection from ischemia and reperfusion remains controversial and may in part be related to a lack of studies in which all 4 AR gene-targeted mice are subjected to the same IP protocol in parallel.

Recent studies have implicated extracellular adenosine in the modulation of acute inflammation and tissue protection, particularly during conditions of hypoxia. Extracellular adenosine is derived mainly via phosphohydrolysis of AMP. Ecto-5’-nucleotidase (CD73), a ubiquitously expressed glycosyl phosphatidylinositol-anchored ectoenzyme, is the pace-maker of this reaction. Because of its transcriptional induction by hypoxia, CD73-dependent adenosine generation is particularly prominent during conditions of limited oxygen availability, as may occur during myocardial ischemia. Nevertheless, pharmacological studies on the role of CD73-dependent adenosine generation in cardioprotection during ischemia and reperfusion have yielded conflicting results.

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To elucidate the contribution of CD73-dependent adenosine generation and to clarify the role of individual ARs in cardioprotection during IP, we used a recently described model of murine in situ preconditioning incorporating a hanging weight system for intermittent coronary artery occlusion, thus minimizing the variability associated with knot-based coronary occlusion systems. In the present study, we applied this model in mice gene targeted for cd73 or each individual AR. In addition, we used specific pharmacological adenosine therapeutics to confirm the findings from gene-targeted mice. We found a critical role for CD73-dependent adenosine production and, surprisingly, signaling through the A_{2B}AR for cardioprotection by IP. Consistent with these findings, we observed a significant reduction in infarct size after acute ischemia by treatment with soluble 5'-nucleotidase or a specific A_{2B}AR agonist.

**Methods**

**Mice**

All animal protocols were in accordance with the German guidelines for use of living animals and were approved by the Institutional Animal Care and Use Committee of the Tübingen University Hospital and the Regierungspräsidium Tübingen. C57BL/6J mice were obtained from Charles River Laboratories (Sulzfeld, Germany). Mice deficient in cd73, A_{1}AR, or A_{2A}AR on the C57BL/6 strain or in A_{2B}AR on the CD1 strain have been described previously. We next pursued the functional contribution of CD73 to cardioprotection by IP.

**Murine Model for Cardiac IP**

In pharmacological studies, age-, gender- and weight-matched C57BL/6J mice were used. Cardiac IP was performed using a hanging weight system as described previously.

**Heart Enzyme Measurement**

Blood was collected by central venous puncture for troponin I (cTnI) enzyme activity. Similarly, AMP-induced bradycardia was determined (see the expanded Materials and Methods section in the online Data Supplement).

**Transcriptional Analysis**

To assess the influence of IP on cd73, A_{1}AR, A_{2A}AR, A_{2B}AR, and A_{2A}AR transcript levels, 4 cycles of IP (5 minutes of ischemia, 5 minutes of reperfusion) were performed, the area at risk (AAR) was delineated by Evan’s blue staining, and excised and transcript levels were determined (see the expanded Materials and Methods section in the online Data Supplement).

**Immunoblotting Experiments**

In subsets of experiments, we determined CD73 and adenosine A_{2B}AR protein content from the AAR as described previously.

**Ecto-5'-Nucleotidase Enzyme Assays**

Ecto-5'-nucleotidase enzyme activity was evaluated as described previously.

**Adenosine Measurements**

Tissue adenosine and AMP levels were determined via high-performance liquid chromatography as described previously.

**Neutrophil Depletion**

In selected experiments, neutrophil depletion was achieved with an anti-Gr-1 monoclonal antibody (BD Biosciences/Pharmingen, San Jose, Calif) as described previously.

**Data Analysis**

Data were compared by 2-factor ANOVA or Student t test where appropriate. Values are expressed as mean±SD from 4 to 6 animals per condition. For analysis of changes in transcript, data are expressed as mean±SEM, and the Dunnett test was used (P < 0.05 was considered 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**

**Cardiac CD73 Is Induced by IP**

Because previous studies demonstrated tissue protection by extracellular adenosine generated via hypoxia-inducible CD73, we hypothesized that CD73-dependent adenosine generation also may be critical for cardioprotection during IP. Therefore, we investigated the transcriptional consequences of cardiac IP on CD73 expression and function using a previously described model of cardiac IP (Figure 1A). Briefly, we performed 4 cycles of intermittent left coronary artery occlusion and reperfusion (5 minutes of ischemia, 5 minutes of reperfusion) in an open-chest in situ model of IP using a hanging weight system, which causes virtually no surgical tissue trauma during IP. The so-called AAR (myocardial tissue supplied by the intermittently occluded coronary artery) was identified using retrograde injection of Evan’s blue and was compared with myocardial tissue from unpreconditioned matched littermates. To define the transcriptional effects of IP, preconditioned myocardial tissue was harvested at indicated time points after IP treatment and used for real-time reverse-transcriptase polymerase chain reaction. We found a robust induction of cd73 mRNA (eg, 90 minutes after cardiac IP; 14.5 ± 2.7-fold; P < 0.01) (Figure 1B). Similarly, Western blots of the AAR confirmed CD73 protein induction after IP (Figure 1C). Immunohistological staining of the AAR and imaging via confocal laser scanning microscopy confirmed the strong induction of CD73 protein (Figure 1D). Conventional microscopy confirmed CD73 induction on both cardiomyocytes and endothelia within the AAR 90 minutes after IP (Figure 1E), whereas isotype controls were negative (Data Supplement Figure 1). We also demonstrated functional induction of CD73 by IP by measuring ecto-5'-nucleotidase enzyme activity (Figure 1F).

**CD73 Inhibition Attenuates Cardioprotection by IP**

We next pursued the functional contribution of CD73 to cardioprotection by IP by treating mice with an intra-arterial infusion of the specific CD73-inhibitor adenosine 5'-(α,β-methylene) diphosphosphate (APCP; 40 mg · kg⁻¹ · h⁻¹) or vehicle control before cardiac IP and/or ischemia. As shown in Figure 2A, this resulted in a 3-fold reduction in cardiac CD73 enzyme activity. Similarly, AMP-induced bradycardia was significantly attenuated in APCP-treated animals (heart rate reduction from 480 to 360 bpm versus from 480 to 120 bpm in control mice; P < 0.0001; Figure 2B). After having shown effective inhibition of cardiac CD73 enzyme activity with APCP, we investigated the role of CD73 in cardioprotection...
by IP by subjecting mice to 60 minutes of left coronary artery occlusion, followed by 2 hours of reperfusion with or without prior IP (4 cycles; 5 minutes of ischemia, 5 of minutes reperfusion) and with or without APCP. All mice survived this experiment. Heart rate and blood pressure did not differ between APCP-treated and untreated mice. To assess myocardial tissue damage, we measured plasma levels of a previously described marker for murine myocardial ischemia, cTnI.21 Consistent with previous studies,15 plasma cTnI concentrations were attenuated by IP (Figure 2C). However,
APCP treatment abolished the cardioprotective effects of IP. Similarly, measurement of infarct size via 2,3,5-triphenyltetrazolium chloride (TTC) staining confirmed inhibition of cardioprotection by IP after APCP treatment (Figure 2D and 2E). Taken together, these data provide pharmacological evidence for a critical role of CD73 in cardioprotection by IP.

Cardioprotection by IP Is Abolished in cd73−/− Mice

To further demonstrate the importance of CD73 in the cardioprotective effects of IP, we next studied mice with targeted deletion of the cd73 gene. We first confirmed the absence of CD73 enzyme activity in the cardiac tissue of these mice (Figure 3A). Similarly, AMP-induced bradycardia was significantly attenuated in cd73−/− mice compared with littermates (Figure 3B). We next performed IP in cd73−/− mice and littermate controls. In striking contrast to results with wild-type mice, infarct sizes and increased plasma cTnI levels caused by 60 minutes of ischemia were not attenuated by IP in cd73−/− mice (Figure 3C and 3D). The protection afforded by IP persisted for at least 90 minutes after the completion of IP in wild-type mice but was abolished in cd73−/− mice (Data Supplement Figure II). Moreover, cd73−/− mice had significantly bigger infarcts after 60 minutes of ischemia without IP compared with controls.

To suggest that the absence of cardioprotection by IP in cd73−/− mice reflects a lack of extracellular adenosine, we reconstituted extracellular adenosine levels via intra-arterial infusion, and enzyme activity was evaluated by measuring the conversion of [14C]IMP to [14C]inosine. Results are expressed as nanomoles per hour per 1 mg protein of APCP-inhibitable IMP-hydrolyzing activity. B, AMP-induced bradycardia is blocked by APCP. Mice were anesthetized and infused with APCP as in a. After 30 minutes, a bolus of AMP (50 µL, 8 mg/mL) was given, and heart rate was measured by surface ECG. Bradycardia is expressed as the percentage change in heart rate. C, APCP treatment prevents IP-induced reduction in troponin I levels. In situ preconditioning with 4 cycles of IP (5 minutes of ischemia, 5 minutes of reperfusion) was performed with and without APCP infusion before 60 minutes of myocardial ischemia. After 2 hours of reperfusion, troponin I plasma levels were measured by ELISA. D, APCP treatment prevents IP-induced decreases in infarct size. In situ preconditioning was performed as in c, and infarct sizes were measured by double staining with Evan’s blue and TTC. Infarct sizes are expressed as the percent of the AAR that underwent infarction (mean±SD; n=6). E, Representative images of infarcts from the experiment in d are displayed (blue indicates retrograde Evan’s blue staining; red and white, AAR; and white; infarcted tissue).
 Increases in Cardiac Adenosine With IP Are Attenuated in cd73⁻/⁻ Mice

On the basis of the above findings of CD73 induction and abolished cardioprotection by IP in cd73⁻/⁻ mice, we hypothesized that increases in cardiac adenosine levels with IP are attenuated in cd73⁻/⁻ mice. Consistent with

5'-nucleotidase treatment was associated with a significant reduction in infarct size in wild-type animals (Figure 3F). Taken together, these data reveal for the first time genetic evidence for CD73-dependent cardioprotection by IP. Furthermore, we show treatment with soluble 5'-nucleotidase as a potential novel therapy during acute myocardial ischemia.
The production of A2BAR protein on cardiomyocytes and endothelium was expressed. Similarly, immunohistochemistry confirmed the induction of cardiac adenosine during preconditioning.

Studies demonstrate that CD73 functions to increase myocardial adenosine levels in conjunction with increased AMP production via CD73 is crucial for preconditioning. We next investigated the contribution of individual ARs to cardioprotection by IP using previously described A1AR−/−, A2AR−/−, A3AR−/−, and A2BAR−/− mice, as well as commercially available A2AR−/− mice. Studies of myocardial A2BAR expression and function in these mice confirmed structural and functional deletion of the receptor (see Data Supplement Figure IV). Moreover, transcript levels of other ARs (A1AR, A2AR, A3AR) were unaltered in A2BAR−/− mice compared with controls (data not shown).

As shown in Figures 5G and 6B and 6C, all AR gene–targeted mice showed cardioprotection by IP, except A2AR−/− mice. Abolished infarct size reduction also was present in A2BAR−/− mice at 90 minutes of reperfusion time after IP treatment (data not shown). The cardioprotective effects of IP as assessed by plasma cTnI levels also were abolished in A2AR−/− mice (Figure 6A). Because measurements of heart rate and blood pressure did not reveal any differences between gene-targeted mice (Data Supplement Tables I and II), it seems unlikely that abolished cardioprotection could be explained by hemodynamic alterations. Taken together, these data provide the first genetic evidence for a pivotal role of A2BAR in cardioprotection by IP. To confirm these findings using a pharmacological approach, we used the highly specific, water-soluble A2BAR antagonist PSB1115. As shown in Figure 6D, intra-arterial treatment with PSB1115 (5 mg kg−1·h−1) abolished infarct size attenuation by IP, thus confirming our findings in A2BAR−/− mice. To demonstrate that PSB1115 does not exhibit its anti-cardioprotective effects through blockade of A1AR, we also treated A1AR−/− mice with PSB1115. As shown in Figure 6E, cardioprotection by IP in A1AR−/− mice was attenuated by specific blockade of A2BAR. Taken together, these studies provide genetic and pharmacological evidence for a role of A2BAR in cardioprotection by IP.

A2BAR Agonist Treatment Results in Smaller Infarcts During Acute Myocardial Ischemia

Next, we pursued a potential therapeutic role of a novel specific A2BAR agonist (BAY 60–6583). The chemical structure and selectivity are displayed in Figure 7A and 7B, and functional in vivo evidence is shown in Data Supplement Figure IV. Wild-type, but not A2BAR−/− mice treated with a single bolus of intra-arterial BAY 60–6583 (10 μg/kg body weight) over 40 minutes before 60 minutes of myocardial ischemia exhibited a significant attenuation of infarct size (Figure 7C and 7D). These studies confirm the specificity of the cardioprotective effects of BAY 60–6583 through A2BAR signaling and provide strong rationale for therapeutically targeting A2BAR during myocardial ischemia.

Discussion

In the present study, we pursued the contribution of extracellular adenosine production and signaling to cardioprotection...
by IP. Transcriptional profiling of preconditioned cardiac tissue revealed a prominent induction of cd73 and A2B AR mRNA. Pharmacological inhibition or targeted gene deletion of cd73 abolished the cardioprotective effects of in situ IP. Similarly, IP was abrogated in mice gene targeted for A2B AR, whereas mice deficient in each of the other ARs (A1AR, A2A AR, A2A AR) showed reduced infarct sizes after IP. Moreover, soluble 5'-nucleotidase or A2B AR agonist treatment mimicked cardioprotection by IP because it was associated with significant attenuation of myocardial infarct sizes after ischemia. Taken together, these studies suggest manipulation of CD73 enzyme activity to increase extracellular adenosine concentrations and signaling through A2B AR as therapeutic strategies for the treatment of coronary artery disease.

Previous studies on adaptation to hypoxia have revealed coordinated transcriptional induction of cd73 and A2B AR by hypoxia inducible factor (HIF)-1. In fact, hypoxia exposure of intestinal epithelia (Caco2 cells) or human endothelia (HMEC-1) was associated with robust induction of cd73 transcript, protein, and function. Furthermore, hypoxia exposure of cd73−/− mice resulted in dramatic increases in vascular leakage, suggesting a functional role of CD73-dependent adenosine production in maintaining vascular barrier function during limited oxygen availability. Moreover, examination of the cd73 gene promoter identified a site for HIF-1α binding, and further studies with promoter constructs and site-directed mutagenesis of the HIF-1α binding site confirmed an HIF-1α-dependent regulatory pathway for cd73 induction. Similarly, hypoxia exposure of endothelia (HMEC-1) resulted in a selective induction of A2B AR mRNA. Further studies examining HIF-1α DNA binding and HIF-1α loss and gain of function confirmed strong dependence of A2B AR induction by HIF-1α in vitro and in vivo. Therefore, it is not surprising that repeated episodes of ischemia/hypoxia as used during cardiac IP resulted in coordinated transcriptional induction of cd73 and A2B AR mRNA. In addition, mice with normoxic stabilization of HIF-1α by in vivo siRNA knockdown of HIF-1α-prolyl-4-hydroxylase-2 showed cardioprotection from ischemia and reperfusion. Therefore, it is likely that the observed cardioprotective effects of CD73-dependent adenosine production and signaling through the A2B AR during cardiac IP are related to a transcriptional response coordinated by HIF-1α.

Previous studies on the contribution of AR signaling to cardioprotection during IP have revealed conflicting results.
on the role of individual ARs. For example, a very thorough study using 3 different A1AR antagonists [CPX (1,3-dipropyl-8-cyclopentylxanthine), BG 9719, or BG 9928] did not block cardioprotection by IP, suggesting that receptor subtypes other than A1AR may be involved in this phenomenon. In contrast, other studies found an absence of the infarct size–limiting effects of IP in A1AR gene-targeted mice, whereas A1AR-overexpressing mice were protected. Why the results of these latter studies disagree with our own is not clearly understood. Because previous studies suggest that adenosine signaling through the A1AR is responsible for activation of protein kinase C (PKC) and PKC is critically important for activation of CD73, it is conceivable that A1AR signaling may result in PKC activation, which in turn activates CD73. In fact, we found that transcriptional induction of CD73 by IP was abolished after PKC inhibition or in A1AR−/− mice. Similarly, infarct size–limiting effects by IP were attenuated by PKC inhibition (Data Supplement Figure VI). In conjunction with our findings that cardioprotection afforded by IP was less in A1AR−/− than in wild-type mice, it becomes possible that signaling through A1AR or α-adrenergic receptors activates PKC, which in turn is responsible for CD73 activation, production of extracellular adenosine, and subsequent signaling through A2BAR. In vitro studies have indicated a critical role of signaling through the A2BAR in resealing of endothelia during transendothelial migration of neutrophils, particularly during conditions of limited oxygen availability. Moreover, pharmacological inhibition of A2BAR during hypoxia exposure is associated with increased pulmonary edema and vascular leakage. Thus, the findings of the present study are consistent with previous work on adenosine signaling, transcriptional responses of A2BAR after myocardial ischemia, and reperfusion, as well as studies suggesting a cardio-protective role of A2BAR during ischemic preconditioning, but highlight for the first time a pivotal role of A2BAR signaling in cardioprotection by IP.

At present, the source of extracellular adenosine generated during conditions of hypoxia or ischemia remains unknown. Previous reports have indicated that polymorphonuclear neutrophils release ATP during conditions of inflammation or hypoxia. Such extracellular ATP either may signal directly to vascular ATP receptors or may function as a metabolic
substrate for conversion to adenosine via ecto-apyrase (CD39, conversion of ATP/ADP to AMP) and ecto-5'-nucleotidase. Under such conditions, adenosine is available to activate ARs. Besides polymorphonuclear neutrophils, platelets may be an important source for extracellular ATP. In addition, the exact cellular location of A2AR involved in cardioprotection by IP is currently unknown. As we show here, A2AR transcript levels and protein are induced in cardiac tissues by IP, suggesting a role of cardiac A2AR. However, a very carefully executed study on the role of A2AR signaling during myocardial ischemia suggested infarct size reduction by activation of A2AR on T lymphocytes. Further studies are necessary to reveal which A2AR-expressing cells are responsible for the cardioprotective effects of IP.

In summary, the present study reveals cardioprotection during myocardial ischemia via CD73-dependent generation of extracellular adenosine and signaling through the A2AR. In fact, genetically targeted mice with deficiencies in the major extracellular pathway of adenosine generation (CD73) or in A2AR show increased susceptibility to acute myocardial ischemia and are not protected by IP. In addition, soluble 5'-nucleotidase or selective A2AR agonist treatment significantly attenuates infarct sizes after ischemia, suggesting possible new strategies to ameliorate the consequences of myocardial infarction. Future challenges include the development of approaches to deal with AR desensitization and delivery of AR agonists to specific anatomic sites.

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Disclosures

D. Köhler and Drs Eckle, Grenz, Mittelbronn, Osswald, Unerl, and Eltzschig are employees of the Tübingen University Hospital. Use of soluble 5'-nucleotidase is currently under consideration for a patent in the treatment of myocardial ischemia by the Tübingen University Hospital. Dr Krahn is employee of Bayer HealthCare. Bayer HealthCare has filed patents on the use of BAY 60–6583. The other authors report no conflicts.

References


of ischemic preconditioning is blunted by inhibition of 5'-nucleotidase activity and attenuation of adenosine release. Circulation. 1994;89:1237–1246.


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