Genetic Deletion of the A1 Adenosine Receptor Limits Myocardial Ischemic Tolerance

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Abstract—Adenosine receptors may be important determinants of intrinsic ischemic tolerance. Genetically modified mice were used to examine effects of global A1 adenosine receptor (A1AR) knockout (KO) on function and ischemic tolerance in perfused mouse hearts. Baseline contractile function and heart rate were unaltered by A1AR KO, which was shown to abolish the negative chronotropic effects of 2-chloroadenosine (A1AR-mediated) without altering A2 adenosine receptor–mediated coronary dilation. Tolerance to 25 minutes global normothermic ischemia (followed by 45 minutes reperfusion) was significantly limited by A1AR KO, with impaired contractile recovery (reduced by ≈25%) and enhanced lactate dehydrogenase (LDH) efflux (increased by ≈100%). Functional effects of A1AR KO involved worsened systolic pressure development with little to no change in diastolic dysfunction. In contrast, cardiac specific A1AR overexpression enhanced ischemic tolerance with a primary action on diastolic dysfunction. Nonselective receptor agonism (10 μmol/L 2-chloroadenosine) protected wild-type and also A1AR KO hearts (albeit to a lesser extent), implicating protection via subtypes additional to A1ARs. However, A1AR KO abrogated effects of 2-chloroadenosine on ischemic contracture and diastolic dysfunction. These data are the first demonstrating global deletion of the A1AR limits intrinsic myocardial resistance to ischemia. Data indicate the function of intrinsically activated A1ARs appears primarily to be enhancement of posts ischemic contractility and limitation of cell death. (Circ Res. 2005;96:363-367.)

Key Words: adenosine ■ A1 adenosine receptor ■ gene knockout ■ ischemia ■ reperfusion

The heart possesses protective or retaliatory mechanisms providing tolerance to ischemia/reperfusion. These may represent targets for therapeutic manipulation of ischemic tolerance, and conversely, alterations in these mechanisms could underlie changes in outcome with aging and/or disease. We and others have been studying the role of the purine nucleoside adenosine and its receptors in modulating injury during ischemia/reperfusion.1,2 There are currently four known and potentially protective adenosine receptor (AR) subtypes encoded by distinct genes: the A1, A2A, A2B, and A3ARs.1,2 All are G-coupled, with A1, A2A, and A3ARs possessing higher affinities for adenosine, whereas the A2BAR has a relatively low affinity. Although contentious,2 the AR system may be an integral component of the hearts intrinsic protective arsenal, limiting damage during ischemia and after ischemic challenge.6 Although this is consistent with benefit via AR agonists,1–3,7 effects of AR antagonism (to unmask responses to endogenous adenosine) are equivocal, with studies supporting4–6,8–11 and refuting12–15 a role for endogenous adenosine in dictating ischemic tolerance. Some of this controversy may stem from inherent limitations in pharmacological approaches to abrogating receptor-mediated responses: these can be hampered by potentially poor antagonist selectivity or potency, and/or potentiation of local agonist levels as a result of opening feedback loops linking “signal” (adenosine generation in this case) to tissue “response” (protection of cellular homeostasis).16–18 An alternative approach involves selective gene deletion, which, coupled with complementary analysis of effects of transgenic overexpression, may facilitate assessment of the specific role of a protein in wild-type tissue.19,20 In this study, we document for the first time the ability of genetic removal of A1ARs to modify intrinsic tolerance to ischemia.

Materials and Methods

Investigations conformed to the Guide for the Care and Use of Laboratory Animals published by the US National Institutes of Health (NIH Publication no. 85-23, revised 1996).

Experimental Protocol

A1AR knockout (A1AR KO) mice (Jackson Laboratories, Bar Harbor, Me) were generated and genotyped as described previously,21 with genotypes determined via PCR analysis of genomic DNA. All mice were on a mixed 129sv/C57BL/6J background and phenotypic comparisons were performed among littersmates. Details of generation
of C57/BL/6J mice selectively overexpressing cardiac A1ARs have been reported previously.22 Hearts for this study were isolated from young (2 month) mice from the following groups: A1AR KO (n=20); wild-type littermates (n=24); A1AR overexpression (n=15); and wild-type C57/BL/6J (n=16).

All mice were anesthetized with 50 mg/kg sodium pentobarbitone administered intraperitoneally, a thoracotomy performed, and hearts excised into ice-cold perfusion fluid for cannulation and perfusion on a Langendorff perfusion system.5,23 Hearts were stabilized at intrinsic rate a further 10 minutes before acquiring concentration-response curves for 2-chloroadenosine–mediated A1AR and A2AAR-dependent bradycardia/coronary dilation. Concentration-response curves were acquired in unpaced normoxic hearts from A1AR KO (n=6), wild-type littermates (n=7), A1AR overexpressing mice (n=7), and wild-type C57/BL/6J mice (n=7), as described previously.24 Chronotropic and vasodilatory responses were scaled as percentage of baseline, and data were analyzed via nonlinear regression to acquire individual pEC50 values, as outlined previously.24,25

In ischemic studies, hearts were stabilized for 20 minutes at intrinsic heart rate before pacing at 420 bpm followed by a further 10 minutes stabilization period.5,23 Baseline measurements were then made, and hearts were subjected to 25 minutes global normothermic ischemia followed by 45 minutes aerobic reperfusion. Coronary venous effluent was collected on ice for enzymatic analysis of lactate dehydrogenase (LDH) activity.23 Total LDH efflux during reperfusion was expressed as international units (IU) per gm wet weight, and has been previously shown to correlate with measures of oncotic injury/infarction in this model.26 Ischemic responses were assessed in A1AR KO (n=7) and wild-type littermate (n=9) mice, and A1AR overexpressing (n=8) and wild-type littermate (n=9) mice.

Effects of adenosinergic cardioprotection with 10 μmol/L of the nonselective agonist 2-chloroadenosine were also assessed in wild-type (n=8) and A1AR KO hearts (n=7) subjected to 25 minutes ischemia and 45 minutes reperfusion. Based on concentration-response data in Figure 1, >3 μmol/L 2-chloroadenosine is required to maximally activate a functional A1AR response (less for an A2AR response). Thus, in an attempt to achieve near-maximal activation of all adenosine receptor subtypes in all murine lines studied, we used a 10 μmol/L agonist concentration. Although it is feasible prolonged treatment with high concentrations of 2-chloroadenosine might induce adenosine receptor-independent actions (because it is a substrate for nucleoside transporters), this is unlikely to be an issue in the current acute studies. The 10 μmol/L concentration is equivalent to or less than functional EC50 values for 2-chloroadenosine activation of adenosine receptor responses in cardiovascular and other cell types.27–31 recent studies confirm this concentration induces receptor-mediated actions in cardiomyocytes and cardiac fibroblasts (mimicked by selective receptor agonists and/or blocked by adenosine receptor antagonists).32–34 and our preliminary experiments (data not shown) confirmed acute chronotropic and vasodilatory responses to 10 μmol/L 2-chloroadenosine were sensitive to 100 μmol/L of the competitive receptor antagonist 8-sulfophenyltheophylline.

Statistical Analyses
All data are presented as mean±SEM. Baseline data, pEC50 values, final recoveries, and LDH efflux were analyzed via one-way ANOVA. Time course data were compared via two-way ANOVA for repeated measures. When significant differences were detected in ANOVA tests, a Newman-Keuls post hoc test was used for specific comparisons. A value of P<0.05 was considered significant in all tests.

Results
There were no differences in baseline contractile function or coronary flow between groups (Table). However, intrinsic heart rate was reduced in A1AR-overexpressing hearts. Concentration-response analysis confirmed A1AR KO abrogates A1AR-mediated bradycardia without altering sensitivity of A2AAR-mediated vasodilation (Figure 1). Conversely, A1AR overexpression increased the sensitivity of A1AR-mediated bradycardia without altering coronary responses. The pEC50 values for the different responses are provided in Table.

Deletion of A1ARs significantly reduced ischemic tolerance. Recovery profiles for hearts subjected to 25 minutes ischemia and 45 minutes reperfusion are depicted in Figure 2. Effects of A1AR KO were evident in terms of reduced systolic pressure with little change in diastolic dysfunction (Figure 2). Thus, left ventricular pressure development was depressed (Figures 2 and 3). Deletion of the A1AR did not modify the rate of contracture development during ischemia (time to reach 20 mm Hg diastolic pressure)23 (Figure 3B), but significantly worsened cellular damage indicated by posts ischemic efflux of LDH (Figure 3C). Conversely, A1AR overexpression enhanced ischemic tolerance (Figures 2 and 3), with the primary contractile effect being reduced diastolic dysfunction (Figures 2A and 3A). Overexpression of A1ARs only improved systolic function during the initial minutes of reperfusion (Figure 2B). Ischemic contracture development was also reduced by A1AR overexpression (Figure 3B), in contrast to lack of effect of A1AR KO on this parameter.

Treatment of wild-type and A1AR KO hearts with the nonselective agonist 2-chloroadenosine improved posts ischemic outcomes in both groups (Figure 3). However, the
protective actions of the agonist were significantly reduced in
A1AR KO versus wild-type hearts (Figure 3). Furthermore,
beneficial effects of 2-chloroadenosine on diastolic dysfunc-
tion and ischemic contracture observed in wild-type hearts
were abrogated by A1AR KO (Figure 3B).

Values are mean ± SEM. Function was measured after 30 minutes stabilization before ischemia, except for heart rate (measured after 20 minutes stabilization, before pacing). pEC50 values represent -log molar concentrations of 2-chloroadenosine producing 50% of the maximal response. WT indicates wild type; TG, transgenic. *P<0.05 vs WT littermates.

Discussion

The role of endogenous adenosine and adenosine receptors in
determining intrinsic tolerance to ischemic insult remains
controversial. Many studies do not observe effects of ade-
osine receptor antagonists on ischemic outcome in various
species.12-15 Moreover, there is even evidence A1AR block-
ade actually improves outcome from ischemia.36,37 In con-
trast, there is some support for a role for endogenously
generated adenosine in protection of ischemic myocardium4–
6,8,11 and modulation of processes impinging on recovery
from ischemia.38,39 Several explanations may account for
varied findings with antagonists, the most likely involving
mixed selectivity and potency of agents used and the fact that
an antagonist applied to any system in which the signal is
coupled to the response (as with adenosine) will likely
generate an elevation in the signal (ie, opening the feedback
loop). This has been verified in prior work.16–18 On the other
hand, it is also important to note that generally observed
cardioprotection with adenosine agonists1,3,8,10,26,40 indicates
the intrinsic adenosine response must normally be submaxi-
mally (if at all) engaged. In assessing potential roles of
adenosine receptors, an alternate and relatively selective
approach involves gene deletion of receptor protein. In this
study, we provide the first evidence that genetic deletion of
the A1AR significantly limits the ability of mouse myocardi-
um to withstand injury during ischemia/reperfusion (Figures
2 and 3). Conversely, cardiac A1AR overexpression confers
enhanced tolerance, as documented previously.22 These data
collectively provide strong support for a role of A1ARs in
determining intrinsic tolerance to ischemia/reperfusion.

Effects of A1AR KO are evident in terms of reduced
systolic dysfunction and oncotic injury, with little effect on
diastolic dysfunction (Figures 2 and 3). This contrasts effects
of A1AR overexpression, which are manifest as reduced
diastolic contracture with little change in systolic pressure
(except during initial reperfusion). Thus, effects of receptor
deletion do not mirror effects of receptor overexpression.
Rather, data suggest responses mediated by a highly overex-
pressed receptor may be abnormal or “supraphysiological”
and/or that functional effects of A1ARs vary with the level of
activation during insult. This is consistent with effects of
2-chloroadenosine, which did reduce postischemic diastolic
activation during insult. This is consistent with effects of

Field 2. Effects of manipulation of A1AR expression on postis-
chemic recoveries for left ventricular diastolic pressure (A), sys-
tolic pressure (B), and developed pressure (C). Data are shown
for recoveries in hearts from A1AR KO (n=7) and wild-type (WT)
littermate (n=9) mice, and for hearts from transgenic (TG) mice
overexpressing cardiac A1ARs (n=8) and their wild-type litter-
ates (n=9). Values are mean ± SEM. *P<0.05 vs corresponding
wild type.
actions of A1ARs on systolic versus diastolic function are consistent with prior observations regarding A1AR antagonism, revealing that posts ischemic A1AR activation improves systolic force without altering diastolic dysfunction, whereas intraischemic A1AR activation limits diastolic dysfunction in addition to improving systolic force.5 Extent (and timing) of A1AR engagement likely dictates relative effects on diastolic versus systolic dysfunction.

Development of ischemic contracture was also unaffected by A1AR KO, but was limited by A1AR overexpression and 2-chloroadenosine. The latter response was again abrogated by A1AR KO (Figure 3). Thus, adenosinergic limitation of ischemic contracture is A1AR dependent but evident only with exaggerated receptor agonism or expression. This agrees with early work of Lasley et al3 demonstrating A1AR agonist-mediated protection against ischemic contracture in rat, and prior data demonstrating negligible effects of A1AR blockade on contracture development in mice.5

Although 2-chloroadenosine-mediated protection against contracture and diastolic dysfunction is abrogated by A1AR KO (Figure 3), supporting A1AR-dependent effects of the agonist on diastolic function, the analogue still exerted some beneficial actions in A1AR KO hearts. This is reflected in improved systolic function together with reduced LDH efflux (Figure 3). These effects, refractory to A1AR KO, implicate a protective function for receptor subtypes distinct from A1ARs. Prior evidence that exogenous A1AR but not A2AAR agonism is cardioprotective in the model studied here,26,40 and that A1AR protection selectively enhances systolic function and reduces cell death, argues for a potential role for this subtype in the remaining protection with 2-chloroadenosine. However, this remains to be directly assessed, and we cannot exclude a potential role for the less well-studied A2BAR.

Two study limitations bear mention before closing. As with all gene deletion studies, adaptations may occur to compensate for life-long absence of a targeted protein. Although it may be fruitful to focus on such adaptations (see for example, Godecke et al41 and Warth and Barhanin42), they also complicate interpretation of phenotypic outcomes. We have assessed, in part, obvious changes in other adenosine receptors, verifying that A1AR deletion selectively abrogates an A1AR response (bradycardia) without modifying A2AAR sensitivity. However, we recognize the possibility of undetected compensatory changes contributing to the A1AR KO phenotype. The second limitation relates to the fact that we focus on responses in the isolated buffer-perfused heart. This was deliberate, to assess more directly the myocardial phenotype, because A1AR protection is primarily “direct” and mediated via cardiomyocyte receptors.2,7 However, adenosinergic protection in vivo additionally involves modulation of blood cells and related inflammatory responses.1,2,7 We therefore cannot ascertain potential effects of A1AR deletion on these extracardiac responses. However, these responses are predominantly A1AR-dependent2,7 and thus not predicted to be substantially modified by A1AR KO. In addition, intrinsic A1AR-dependent protection during ischemia/reperfusion in vivo may involve actions of adenosine generated within neutrophils, platelets, and other blood-borne cells. Thus, this extracardiac component will be absent in the present model, potentially leading to an underestimation of the normal extent of A1AR activation by endogenously generated adenosine.

In summary, the current analysis of the effects of A1AR KO supports an important function of A1ARs in dictating intrinsic myocardial resistance to ischemia/reperfusion. Effects of A1AR deletion suggest these receptors normally play a role in enhancing posts ischemic contractility and limiting cell death, with little effect on abnormalities in diastolic function.

**Figure 3.** Effects of manipulation of A1AR expression and the nonselective adenosine receptor agonist 2-chloroadenosine, on ischemic and postischemic outcomes. A, Final recoveries for left ventricular (LV) diastolic and developed pressure. B, Rate of ischemic contracture (time for diastolic pressure to reach 20 mm Hg during ischemia). C, Postischemic LDH efflux during 45 minutes reperfusion. Outcomes are shown for hearts from A1AR KO (n=7) and wild-type (WT) littermate (n=9) mice, and for hearts from transgenic (TG) mice overexpressing cardiac A1ARs (n=8) and their wild-type littermates (n=9). Effects of 10 μmol/L 2-chloroadenosine were assessed in hearts from A1AR KO (n=7) and wild-type littermate (n=8) mice. Values are mean±SEM. *P<0.05 vs corresponding wild-type groups; †P<0.05 vs untreated hearts.
function. Finally, reduced yet significant protection via the nonselective agonist 2-chloroadenosine in A1AR KO hearts implicates a significant cardioprotective response mediated via adenosine receptors additional to the A1AR.

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