Heart Failure

Adenosine A3 Receptor Deficiency Exerts Unanticipated Protective Effects on the Pressure-Overloaded Left Ventricle

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Background—Endogenous adenosine can protect the overloaded heart against the development of hypertrophy and heart failure, but the contribution of A1 receptors (A1R) and A3 receptors (A3R) is not known.

Methods and Results—To test the hypothesis that A1R and A3R can protect the heart against systolic overload, we exposed A1R and A3R gene–deficient (A1R knockout [KO]) mice and A3R KO mice to transverse aortic constriction (TAC). Contrary to our hypothesis, A3R KO attenuated 5-week TAC-induced left ventricular hypertrophy (ratio of ventricular mass/body weight increased to 7.6±0.3 mg/g in wild-type mice compared with 6.3±0.4 mg/g in KO mice), fibrosis, and dysfunction (left ventricular ejection fraction decreased to 43±2.5% and 55±4.2% in wild-type and KO mice, respectively). A3R KO also attenuated the TAC-induced increases of myocardial atrial natriuretic peptide and the oxidative stress markers 3′-nitrotyrosine and 4-hydroxynonenal. In contrast, A1R KO increased TAC-induced mortality but did not alter ventricular hypertrophy or dysfunction compared with wild-type mice. In mice in which extracellular adenosine production was impaired by CD73 KO, TAC caused greater hypertrophy and dysfunction and increased myocardial 3′-nitrotyrosine. In neonatal rat cardiomyocytes induced to hypertrophy with phenylephrine, the adenosine analogue 2-chloroadenosine (CADO) also attenuated the TAC-induced increases of myocardial 3′-nitrotyrosine. In mice in which extracellular adenosine production was impaired by CD73 KO, TAC caused greater hypertrophy and dysfunction and increased myocardial 3′-nitrotyrosine. In neonatal rat cardiomyocytes induced to hypertrophy with phenylephrine, the adenosine analogue 2-chloroadenosine reduced cell area, protein synthesis, atrial natriuretic peptide, and 3′-nitrotyrosine. Antagonism of A1R significantly potentiated the antihypertrophic effects of 2-chloroadenosine.

Conclusions—Adenosine exerts protective effects on the overloaded heart, but the A1R acts counter to the protective effect of adenosine. The data suggest that selective attenuation of A3R activity might be a novel approach to treat pressure overload–induced left ventricular hypertrophy and dysfunction. (Circulation. 2008;118:1713-1721.)

Key Words: adenosine ■ free radicals ■ heart failure ■ hypertrophy ■ oxidative stress

Recently, we demonstrated that genetic deletion of CD73 (an ectonucleotidase that produces extracellular adenosine) exacerbated myocardial hypertrophy and heart failure resulting from left ventricular (LV) pressure overload produced by transverse aortic constriction (TAC),1 suggesting that endogenous extracellular adenosine can protect against maladaptive hypertrophy. Adenosine exerts multiple functions through activation of individual adenosine receptor subtypes.2–5 A1 receptors (A1R) and A3 receptors (A3R) are expressed in cardiomyocytes, and a substantial body of evidence indicates that adenosine can protect the heart during and after an ischemic insult.6–7 Liao et al8 demonstrated that the adenosine analogue 2-chloroadenosine (CADO) also attenuated pressure overload–induced LV hypertrophy through activation of the A1R. Similar to A1R, the A3R are Gi protein–coupled receptors that have been shown to activate similar downstream signaling pathways.9,10 A3R activation has also been reported to protect the heart against ischemic11,12 and doxorubicin-induced damage.13 On the other hand, transgenic overexpression of the A1R14 or A3R15,16 promotes cardiac dilation and dysfunction, suggesting that these receptors may also exert adverse effects on cardiac function. Although we and others have demonstrated that adenosine protects against LV hypertrophy and maladaptive remodeling during pressure overload, the distinct contributions of the A1R and A3R to this protective effect are not known. Here we examined the effect of A1R knockout (KO) mice and A3R KO mice on TAC-induced ventricular hypertrophy in vivo and extended our examination to the roles of A1R and A3R in modulating hypertrophy in cultured neonatal rat cardiomyocytes, free from hemodynamic and neurohormonal factors that can influence the in vivo heart.

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Methods

Mice

Male C57BL/6 (Taconic, Germantown, NY) body weight–matched A3R KO mice (crossed back to Taconic C57BL/6 mice at least 16 times), 8 to 12 weeks old, were used for TAC or control. A3R KO mice (129 background) and their control wild-type (WT) mice were generated as described previously. The CD73 KO strain and control WT mice were generated as described previously. This study was approved by the Institutional Animal Care and Use Committee of University of Minnesota.

Minimally Invasive TAC Procedure

TAC of moderate (with the use of a 26-gauge needle to calibrate the degree of constriction) or severe (with the use of a 27-gauge needle) degree was created as described previously. To ensure that similar pressure overload was produced in the KO and WT mice, the TAC procedure was performed on KO and corresponding WT mice on the same day by the same surgeon who was blinded regarding the genotype of the mice.

Echocardiography

Mice were anesthetized with 1.5% isoflurane. Echocardiographic images were obtained with a Visualsonics Veve 770 system as described previously.

Sample Collection and Western Blots

Myocardial samples for protein analysis were flash-frozen in liquid nitrogen, weighed on an electronic balance, and stored in liquid nitrogen until transfer into a freezer where they were maintained until analysis. Samples for histological analysis were fixed in formaldehyde. Protein expression was analyzed by Western blots as described previously with the use of antibodies against atrial natriuretic peptide (ANP) (Peninsula Biolabs), 3-nitrotyrosine, 4-hydroxynonenal (Millipore), cyclooxygenase-2 (COX-2), c-Jun N-terminal kinase (JNK), phosphorylated JNK (p-JNKThr183/Tyr185) (Santa Cruz Biotechnology, Santa Cruz, Calif), endothelial nitric oxide synthase (eNOS) (Transduction Laboratories), extracellular signal-regulated kinase (ERK), and p-ERKThr202/Tyr204, p-AktSer473, and p-GSK-3βSer21/9 (Cell Signaling Technology, Danvers, Mass).

Histological Staining and Measurement of Fibrosis

Tissue sections (6 μm) from the central portion of the LV were stained with Sirius red (Sigma, St Louis, Mo) for fibrosis and FITC-conjugated wheat germ agglutinin (AF488, Invitrogen, Carlsbad, Calif) to evaluate myocyte size. For mean myocyte size, the cross-sectional areas of at least 120 cells per sample and at least 4 samples per group were averaged.

Neonatal Rat Cardiomyocyte Isolation and Culture

Neonatal rat cardiomyocytes were isolated from 2-day-old Sprague-Dawley rats as described previously. To induce hypertrophy, cells were treated with 50 μmol/L phenylephrine for 48 hours. The stable adenosine analogue CADO (5 μmol/L) was used to activate adenosine receptors (the affinities of CADO at rat A1R and A3R are 9.3 and 1890 nmol/L, respectively). The selective inhibitors DPCPX and MRS1191 were used at 5 μmol/L to block A1R and A3R, respectively. It has been reported that 5 μmol/L MRS1911 selectively inhibits A3R activation without affecting A1R-dependent responses. After treatment, cells were fixed with 4% paraformaldehyde and stained with rhodamine-conjugated phalloidin (5 U/mL in PBS, Invitrogen), DAPI, ANP (Peninsula Biolabs), and 3-nitrotyrosine (Millipore), followed by Alexa Fluor 488– or Alexa Fluor 633–labeled secondary antibodies (Invitrogen). Protein synthesis was measured over 48 hours of treatment in 96 well plates by H3-phenylalanine incorporation.

Data Analysis

All values are expressed as mean±SE. Kaplan-Meier survival analysis was performed with SigmaStat with the use of the Gehan-Breslow test. Two-way ANOVA was used to test for differences among treatment groups, followed by pairwise multiple comparisons of the Tukey test. Statistical significance was defined as P<0.05.

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

A3R KO Attenuated LV Hypertrophy and Dysfunction Produced by Moderate Pressure Overload

LV structure and function were not different between A3R KO and WT mice under control conditions (Figure 1A to 1G), and histological staining of LV tissue showed no difference in cardiac myocyte size or relative fibrosis between A3R KO and WT-TAC.
WT mice (Figure 1C, 1D). After 5 weeks of moderate TAC (with the use of a 26-gauge needle to calibrate the degree of TAC), ventricular weight and the ratio of ventricular weight to body weight were significantly lower in the A3R KO mice than in WT mice (Figure 1A, 1B), indicating that loss of A3R attenuated the TAC-induced myocardial hypertrophy. Histological staining showed that the A3R KO hearts had significantly less TAC-induced increases of LV fibrosis and myocyte hypertrophy (Figure 1C, 1D; Figure I in the online-only Data Supplement). Thus, the lesser hypertrophy in the A3R KO hearts after TAC resulted from both reduced myocyte size and decreased fibrosis. The TAC-induced mortality was not different between A3R KO and WT mice (Figure II in the online-only Data Supplement).

Echocardiographic imaging of the heart 5 weeks after TAC demonstrated significant increases of LV end-systolic diameter and LV end-diastolic diameter in both A3R KO and WT mice in comparison with mice of similar body weight without TAC (Figure 1E, 1F). However, TAC caused significantly less LV dysfunction in the A3R KO mice, as demonstrated by a higher ejection fraction and a smaller LV end-systolic diameter (Figure 1E, 1G). Myocardial ANP (biochemical marker for LV dysfunction) was increased in both WT mice and A3R KO mice 5 weeks after TAC, but this increase was significantly less in the A3R KO mice than in WT mice. The TAC-induced increases of TNF-α tended to be less in the A3R KO mice (P=0.10). In addition, hearts from WT mice had higher levels of 3'-nitrotyrosine and 4-hydroxynonenal after TAC than did A3R KO hearts, implying that the A3R KO mice had lower levels of oxidative stress. eNOS uncoupling can be a source for increased oxidative stress, and we have found that the increase of myocardial eNOS protein after TAC was related to the degree of LV dysfunction. Consistent with our previous report, myocardial eNOS protein was significantly increased in the WT mice after TAC, and this response was attenuated in the A3R KO mice (Figure 2).

Activation of mitogen-activated protein kinases (MAPKs) and the phosphoinositide 3-kinase (PI3K) signaling pathway is often associated with increased oxidative stress and the development of LV hypertrophy or heart failure. Activation of mitogen-activated protein kinases (MAPKs) and the phosphoinositide 3-kinase (PI3K) signaling pathway is often associated with increased oxidative stress and the development of LV hypertrophy or heart failure. Activation of mitogen-activated protein kinases (MAPKs) and the phosphoinositide 3-kinase (PI3K) signaling pathway is often associated with increased oxidative stress and the development of LV hypertrophy or heart failure. To examine signaling pathways related to the protective effect observed in the A3R KO mice after TAC, total JNK and phosphorylated JNK, ERK, Akt, and GSK-3β were determined (Figure 3). Under control conditions A3R KO had no effect on the myocardial content of total or phosphorylated ERK, JNK, Akt, and GSK-3β. TAC caused significant increases of p-ERKThr202/Tyr204 and p-JNKThr183/Tyr185 and the ratio to their total proteins in both KO and WT mice. However, A3R KO significantly attenuated the TAC-induced increases of p-ERKThr202/Tyr204 and p-JNKThr183/Tyr185 (Figure 3), indicating that A3R KO attenuated the TAC-induced activation of the myocardial tumor necrosis factor (TNF)-α and COX-2.

Figure 2. A3R KO significantly attenuates moderate TAC-induced increases of ventricular ANP, nitrotyrosine (NT), 4-hydroxynonenal (4-HNE), and COX-2. TAC caused significant increases of ventricular TNF-α in both A3R KO and WT mice. A3R KO tended to decrease TNF-α after TAC, but this difference was not significant (P=0.10). Data are normalized to WT-TAC. *P<0.05 compared with the corresponding control (Ctr); #P<0.05 compared with WT-TAC. 5W indicates 5 weeks.
MAPK signaling pathways. In addition, the TAC-induced increases of p-AktSer473 and p-GSK-3βSer21/9 were significantly attenuated in the A3R KO mice, suggesting decreased signaling through the PI3K-Akt pathway.

**A1R KO Did Not Influence Ventricular Hypertrophy Produced by TAC but Exacerbated Mortality After Severe TAC**

Although previous studies have demonstrated that either the adenosine analogue CADO8,32 or endogenous adenosine1 can protect the heart from pressure overload–induced LV remodeling, the specific contribution of A1R activation has been controversial.8,32 To determine whether A1R KO might exacerbate the degree of hypertrophy and myocardial dysfunction later during systolic overload, we studied mice 4 weeks after moderate TAC (using a 26-gauge needle). This moderate systolic overload caused similar increases in the ratio of ventricular mass to body weight, LV end-diastolic diameter, LV end-systolic diameter, and LV wall thickness in A1R KO and WT mice (Figure 4A to 4F). Moderate TAC of 4-week duration also caused similar decreases of LV ejection fraction in the 2 groups (Figure 4C). Although mortality tended to be higher in the A1R KO group during the 4 weeks after moderate TAC (5 of 17 mice died) compared with WT mice (2 of 17 WT mice died), this difference was not significant (Figure 4H).

Because mice with severe LV dysfunction are more likely to die after TAC, the relatively higher TAC-induced mortality in the A1R KO mice than in the WT mice might potentially have influenced ventricular weights of the surviving mice, that is, if the sicker A1R KO mice died early after TAC, the residual surviving animals might underestimate the overall response to systolic overload. Because the TAC-induced death occurred predominantly during the first 2 days after TAC, we determined the degree of hypertrophy 2 days after severe TAC when comparable numbers of A1R KO and WT mice survived. Compared with sham surgery, at 2 days after severe TAC the ratio of ventricular weight to body weight was similarly increased in WT (21.2%2.5%) and A1R KO mice (22.3%), indicating that A1R KO did not alter the acute hypertrophic response to severe pressure overload (Figure III in the online-only Data Supplement). Taken together, the data indicate that A1R KO had no significant influence on TAC-induced ventricular hypertrophy or dysfunction.

Because the A1R KO mice tended to have a higher mortality than their WT controls in this initial study, we subsequently examined whether this trend toward a higher mortality would be statistically significant when a more severe degree of systolic overload (using a 27-gauge needle) was applied. When TAC of severe degree was applied, the excess mortality in the A1R KO animals did in fact become
significant (Figure IV in the online-only Data Supplement). To understand the nature of the TAC-induced increase in mortality in the A1R KO mice, ECG telemetry was performed in additional A1R KO and WT mice. The results demonstrated that animals destined to die generally developed progressive sinus bradycardia with giant P waves that progressed to high-grade atrioventricular block with further bradycardia and death (Figure V in the online-only Data Supplement). Again, the degree of hypertrophy was not different between the surviving A1R KO and WT mice after severe TAC.

Taken together, the data indicate that A1R KO had no significant influence on TAC-induced ventricular hypertrophy or dysfunction but resulted in significantly greater mortality in mice subjected to severe TAC.

**CD73 KO Exacerbated Oxidative Stress and Hypertrophy Produced by Moderate Pressure Overload**

The reduction of extracellular adenosine production produced by CD73 KO significantly exacerbated the hypertrophy (Figure 5A, 5B), fibrosis (Figure 5D, 5E), myocyte

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**Figure 4.** A1R KO had no significant effect on the increase of ventricular mass (A), the ratio of ventricular mass to body weight (B), decrease of LV ejection fraction (C), increase of LV diastolic diameter (D, E), or LV wall thickness (F, G) produced by moderate TAC of 4-week (4W) duration. A1R KO mice tended to have a higher mortality during 4 weeks after moderate TAC, but this difference was not significant (H). *P<0.05 compared with the corresponding control.

**Figure 5.** Disrupting extracellular adenosine production by CD73 KO exacerbated ventricular hypertrophy (A, B), cardiomyocyte hypertrophy (C, E), and ventricular fibrosis (D, E) produced by 4 weeks (4W) of moderate TAC. *P<0.05 compared with the corresponding control; #P<0.05 compared with WT-TAC.
hypertrophy (Figure 5C, 5E), LV dilation, and decrease of LV ejection fraction produced by moderate TAC of 4-week duration (Figure VI in the online-only Data Supplement). CD73 KO also exacerbated the TAC-induced increases of ventricular ANP and TNF-α (Figure VII in the online-only Data Supplement). In addition, CD73 KO exacerbated the TAC-induced increase of myocardial 3-nitrotyrosine (Figure VII in the online-only Data Supplement), indicating increased oxidative stress. To validate these findings, we examined the ability of the adenosine analogue CADO to rescue the increased ventricular hypertrophy produced by TAC in the CD73 KO mice. We found that CADO attenuated the myocardial hypertrophy produced by moderate TAC of 2-week duration in the CD73 KO mice (Figure VIII in the online-only Data Supplement).

The A₁R Antagonist MRS1911 Potentiates the Antihypertrophic Effect of CADO in Neonatal Cardiomyocytes

Understanding the role of A₁R and A₃R in the response of the cardiomyocytes to systolic overload in vivo may be complicated by effects of adenosine on blood flow, neurohormonal responses, and inflammatory or paracrine responses. Therefore, we sought to determine the role of A₁R and A₃R in isolated cardiomyocytes in the setting of saturating levels of the nonselective adenosine analogue CADO. We previously demonstrated that CADO or adenosine reduced phenylephrine-induced hypertrophy and ANP expression in neonatal cardiomyocytes. To examine the role of A₁R and A₃R in mediating antihypertrophic effects of CADO, we treated cells with 50 µmol/L phenylephrine and 5 µmol/L CADO in the presence or absence of selective A₁R and A₃R antagonists and then measured cell area, protein synthesis, and the oxidative stress marker 3'-nitrotyrosine. Phenylephrine increased cardiomyocyte protein synthesis (Figure 6A, 6E), cell area (Figure 6B), ANP expression (Figure 6C), and 3'-nitrotyrosine production (Figure 6D, 6E) over 48 hours of treatment, whereas CADO significantly attenuated the phenylephrine-induced increases in these variables. Blocking A₁R with DPCPX slightly reversed the CADO-induced reductions of cell area (Figure 6B) and ANP levels (Figure 6C) in the phenylephrine-treated cells. Inhibition of A₁R caused a substantial increase in 3'-nitrotyrosine (Figure 6D), suggesting a role for A₁R in modulating oxidative stress in the hypertrophying myocytes. Inhibition of the A₁R with MRS1191 reduced protein synthesis, ANP expression, and 3'-nitrotyrosine production beyond the reduction caused by CADO alone (Figure 6). The reduction in 3'-nitrotyrosine by MRS1191 was confirmed by Western blot analysis (data not shown). The reduction in hypertrophy by the A₁R antagonist was associated with reduced sustained activation of the MAPKs ERK and JNK (Figure IX in the online-only Data Supplement). These results suggest that A₁R contributes to increased oxidative stress, higher sustained activation of ERK and JNK, and an increased hypertrophic response to phenylephrine.

Discussion

To the best of our knowledge, this is the first report assessing the effect of A₁R KO and A₃R KO on chronic pressure overload–induced ventricular hypertrophy and contractile function. The major new finding is that A₁R KO attenuated TAC-induced LV hypertrophy, fibrosis, oxidative stress, and dysfunction. Because adenosine has been reported to be cardioprotective in the setting of chronic pressure overload, the finding that disruption of A₁R attenuated the TAC-induced hypertrophy and dysfunction is unexpected and intriguing. Our finding that the A₁R antagonist MRS1191 augmented the antihypertrophic effect of CADO in phenylephrine-treated isolated cardiomyocytes is in agreement with the concept that selective A₁R blockade can enhance the beneficial effect of adenosine. These results support the novel concept that the adenosine A₁R exerts adverse effects in the pressure-overloaded heart and suggest that A₁R blockade may have potential to protect the heart against pressure overload–induced oxidative stress, LV remodeling, and contractile dysfunction.

The effect of the A₁R on LV remodeling is controversial. CADO has been reported to attenuate TAC-induced LV hypertrophy in mice through A₁R activation. Furthermore, an A₁R antagonist was reported to attenuate the antihypertrophic effect of CADO in vitro. However, a subsequent study from the same group reported that A₁R blockade had no effect on infarct-induced cardiomyocyte hypertrophy or LV remodeling in rats. We have observed that moderate A₁R overexpression in mice failed to exert a beneficial effect on myocardial infarct–induced ventricular remodeling (Y. Chen, PhD, unpublished data, 2007). It is unclear why A₁R blockade would attenuate the antihypertrophic effect of CADO, whereas A₁R KO had no effect on TAC-induced hypertrophy. Nevertheless, the present finding that A₁R KO exacerbated the death rate in mice exposed to severe TAC demonstrates that activation of the A₁R can exert some degree of cardioprotection in the pressure-overloaded heart.

Although no previous reports have directly examined the effect of A₁R KO on systolic overload–induced ventricular remodeling, there is evidence that A₁R signaling can affect cardiac structure and function. Thus, transgenic mice with cardiac-specific overexpression of A₁R developed a dilated cardiomyopathy characterized by increased ventricular mass, LV dilation, expression of biomarkers of hypertrophy, bradycardia, and systolic dysfunction, suggesting that chronically augmented A₁R signaling in the heart is detrimental. The MAPK and PI3K signaling pathways are often activated in response to extracellular stresses such as inflammation or oxidative stress and have been shown to contribute to cardiac hypertrophy and heart failure. The increased myocardial oxidative stress after TAC in the present study, associated with activating phosphorylations of p-AktSer473, p-ERKThr202/Tyr204, and p-JNKThr183/Tyr185 and inactivating phosphorylation of GSK3βSer21, is consistent with previous reports. The decreases in TAC-induced oxidative stress, p-ERKThr202/Tyr204, p-JNKThr183/Tyr185, and p-AktSer473 as a result of A₁R KO likely contributed to the lesser degrees of fibrosis and cardiac myocyte hypertrophy in the A₁R KO mice. TAC-induced ventricular hypertrophy is associated with increased eNOS expression and eNOS uncoupling, so that attenuation of the increase of eNOS in the A₁R KO...
mice after TAC may have contributed to the decreased oxidative stress in this strain.

The effect of A<sub>R</sub> on activation of myocardial PI3K/Akt signaling pathways in vivo has not been reported previously. However, the A<sub>R</sub> agonist 2-chloro-N<sup>6</sup>-(3-iodobenzyl)adenosine-5'-N-methylcarboxamide (Cl-IB-MECA) or adenosine dose- and time-dependently increased p-Akt<sup>Ser473</sup> in cultured neonatal rat cardiomyocytes and A375 human melanoma cells, which is consistent with our finding that A<sub>R</sub> KO attenuated the increase of myocardial p-Akt<sup>Ser473</sup> and its downstream target p-GSK<sup>Ser21/9</sup> after TAC. Similarly, previous studies have reported that the A<sub>R</sub> agonist Cl-IB-MECA or adenosine can activate p-ERK<sup>Thr202/Tyr204</sup> in cultured cardiomyocytes and tumor cell lines, whereas the increase of p-ERK<sup>Thr202/Tyr204</sup> in response to A<sub>R</sub> agonist is PI3K/Akt dependent. The finding that A<sub>R</sub> activation increased p-ERK<sup>Thr202/Tyr204</sup> in cultured cell lines is conceptually consistent with our finding that A<sub>R</sub> KO attenuated the TAC-induced increase of p-ERK<sup>Thr202/Tyr204</sup>. The effect of A<sub>R</sub> on p-JNK<sup>Thr183/Tyr185</sup> has not been reported previously.

The mechanism by which A<sub>R</sub> KO protected the heart against the LV hypertrophy and dysfunction produced by TAC is of considerable interest. A<sub>R</sub> are expressed in both cardiac myocytes and inflammatory cells. Our data demonstrating that antagonism of the A<sub>R</sub> further reduced oxidative stress and expression of ANP in CADO-treated cardiomyocytes indicates that the A<sub>R</sub> can contribute to oxidative stress and the hypertrophic response independent of the paracrine effects or inflammatory response that occur in vivo. The decrease in nitrotyrosine production in the isolated cardio-

Figure 6. Addition of the A<sub>R</sub> antagonist MRS1191 to CADO-treated cells further attenuated the phenylephrine (PE)-induced increases of protein synthesis (A, E), and the expression of ANP (C, E) and 3'-nitrotyrosine (NT) (D, E) in cultured rat cardiomyocytes. MRS1191 did not further decrease the average cell area (B, E). *P<0.05 between the indicated groups.
myocytes was accompanied by decreases of ERK and JNK activation, similar to the reduced activation of these enzymes in A1R KO mice. These results are consistent with numerous reports associating oxidative stress with activation of MAPK signaling. 

In addition to a direct role of A1R on cardiomyocyte hypertrophy and oxidative stress, the A1R has also been demonstrated to modulate the inflammatory response. Specifically, the A1R appears important for mast cell degranulation, 

neutrophil chemotaxis, 

and infiltration of inflammatory cells. 

It is possible that A1R-mediated augmentation of the inflammatory response to the pressure overload produced by TAC could have exacerbated LV hypertrophy and dysfunction. Guo et al. 

demonstrated that inflammatory cell accumulation and infarct area were decreased in A1R KO mice compared with WT mice 24 hours after ischemia/reperfusion injury, suggesting that the A1R can promote an increased inflammatory response in the heart. Our finding that A1R KO attenuated the TAC-induced increase of COX-2 and tended to decrease TNF-α after TAC supports a role for the A1R in the TAC-induced myocardial inflammatory response.

The finding that A1R KO enhanced the antihypertrophic effect of the CADO in neonatal cardiomyocytes suggests the possibility of interactions between A1R and A3R. There is some previous support for such interactions. Thus, Norton et al. 

demonstrated that adenosine A3R antagonists enhanced A1R-induced antiadrenergic responses in the heart, whereas A3R agonists attenuated the antiadrenergic actions of A1R activation. Although these investigators did not find interaction between A1R activity and A3R-mediated antiadrenergic effects in the heart, interaction between A1R function and A3R has been demonstrated in the hippocampus, where A1R activation desensitized A3R-dependent inhibition of excitatory neurotransmission by adenosine. 

Although examination of potential interactions between adenosine receptors was beyond the scope of the present report, this is clearly an area in need of further study.

Unfortunately, there are no highly potent and selective A3R antagonists available for mice. Therefore, a limitation of the present study is that the protective effect of A3R KO on the pressure-overloaded heart could not be further confirmed by selective A3R inhibition with pharmacological compounds in an in vivo model.

In summary, A3R KO had no effect on LV structure or function in the unstressed heart but significantly attenuated TAC-induced LV hypertrophy, fibrosis, and dysfunction. Deletion of A3R also attenuated the TAC-induced increases of ventricular oxidative stress, COX-2, and the phosphorylation of p-ERK Thr202/Tyr204, p-JNK Thr183/Tyr185, p-Akt Ser473, and p-GSK-3β Ser21/9, suggesting that A3R-mediated increases of oxidative stress and/or inflammation exacerbate detrimental ventricular remodeling by activation of the MAPK and PI3K-Akt pathways. A3R agonists are currently under development to treat tumors, inflammation, and cardiac injury. The present findings suggest that careful evaluation of the effect of selective A3R agonists on ventricular hypertrophy and dysfunction in the overloaded or diseased heart will be of importance.

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**Disclosures**

None.

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42. Norton GR, Woodiwiss AJ, McGinn RJ, Lorbar M, Chung ES. Activation of A3 adenosine receptor agonists in murine autoimmune arthritis facilitates the adaptation of the left ventricle to pressure overload produced by transverse aortic constriction. Contrary to our expectation, mice with genetic ablation of the A3R developed less severe myocardial hypertrophy and left ventricular dysfunction in response to transverse aortic constriction than did wild-type mice, implying that A3R activation during pressure overload has a deleterious effect on the heart. In support of these functional data, A3R deletion decreased myocardial oxidative stress and the expression of proinflammatory cytokines. The findings suggest that selective A3R inhibition might have potential for treatment of pressure overload–induced left ventricular hypertrophy and dysfunction.
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