Endogenous Adenosine Does Not Activate ATP-Sensitive Potassium Channels in the Hypoxic Guinea Pig Ventricle In Vivo

Jiang Xu, MD; Li Wang, MD; Carl M. Hurt, BA; Amir Pelleg, PhD

**Background**  The activation of ATP-sensitive K⁺ (K⁺<sub>ATP</sub>) channels by K⁺<sub>ATP</sub> openers, eg, pinacidil, hypoxia, and ischemia, is known to shorten the ventricular action potential. Since adenosine is released in increased amounts during cardiac hypoxia and ischemia, the hypothesis that endogenous adenosine activates K⁺<sub>ATP</sub> channels was tested in vivo in a guinea pig model.

**Methods and Results**  Anesthetized animals (n=37) were subjected to transient acute global hypoxia by ventilation with 100% N₂. Monophasic action potentials (MAP) were recorded in ventricular and atrial myocardium by use of custom-made Ag/AgCl electrode catheters. In addition, right atrial and left ventricular electrogams as well as systemic arterial blood pressure were monitored throughout the experiments. Under normoxic conditions, pinacidil (1.8 µg/kg IV, n=8), a K⁺<sub>ATP</sub> channel opener, shortened ventricular MAP duration (APD); this effect was reversed by glibenclamide, a potent K⁺<sub>ATP</sub> channel blocker, but not by 8-cyclopentyl-1,3-dimethylxanthine (CPT), a potent A₁-selective adenosine antagonist. Global hypoxia shortened atrial and ventricular APD. Glibenclamide but not CPT reversed this effect of hypoxia on ventricular but not atrial MAP. CPT but not glibenclamide reversed the effect of hypoxia on atrial MAP. In addition, CPT delayed the appearance of the atrioventricular (AV) nodal conduction block associated with global hypoxia. Finally, the ability of CPT to selectively attenuate A₁-adenosine receptor-mediated effects of adenosine agonists in ventricular and supraventricular tissues was confirmed in 17 animals. CPT reversed the negative dromotropic effect of adenosine on AV nodal conduction and the antiadrenergic effect of N<sup>6</sup>-cyclopentyladenosine (CPA) mediated by A₁-adenosine receptor but not the adenosine-induced decrease in systemic blood pressure caused by the vasodilatory action of the nucleoside mediated by A<sub>2a</sub>-adenosine receptor.

**Conclusions**  (1) Endogenous adenosine released during global cardiac hypoxia mediates, in part, AV nodal conduction delay and shortening of atrial but not ventricular APD. (2) The action of adenosine on atrial APD is mediated by A₁ adenosine receptors, probably via I<sub>K,ATP</sub>. (3) Endogenous adenosine apparently does not play an important role in the early stages of acute global hypoxia–induced activation of K⁺<sub>ATP</sub> channels. The present results are consistent with the hypothesis that the shortening of ventricular APD in the hypoxic heart is due, in part, to activation of K⁺<sub>ATP</sub> channels. (Circulation. 1994;89:1209-1216.)

**Key Words**  • adenosine  • potassium  • hypoxia  • action potentials  • receptors

Coronary arteries. Since the activation of K⁺<sub>ATP</sub> channels has been proposed to exert a protective effect in the ischemic/hypoxic myocardium, it is tempting to speculate that activation of these channels by adenosine is another manifestation of its cardioprotective effects.

Thus, the present experiments were aimed at testing the hypothesis that endogenous adenosine activates K⁺<sub>ATP</sub> channels during acute global myocardial hypoxia in vivo. For this purpose, a guinea pig model was used in which the release of endogenous adenosine and activation of A₁-AdoR during global myocardial hypoxia have been well documented. 12, 13

**Methods**

**Animal Preparation and Instrumentation**

Guinea pigs (n=62) anesthetized with 98% ketamine plus 2% acepromazine 1.65 mL/kg IV and intubated with an endotracheal tube were ventilated with room air supplemented as necessary with oxygen using a Harvard respirator (model 665). The heart was exposed via longitudinal sternotomy. Bipolar electrode catheters were introduced via the right jugular vein and positioned in the right atrium (RA) and right ventricle (RV) for RA and RV pacing. The left brachial artery was cannulated for recording of blood pressure (BP). A small-bore catheter was inserted into the left jugular vein and positioned in the right atrium for the administration of drugs. A custom-made monophasic action potential (MAP) electrode...
catheter was introduced through the left carotid artery and positioned in the left ventricle for recording of left ventricular endocardial MAP. RA epicardial MAPs were recorded with a custom-made suction catheter.

Protocols

Animals were randomly divided into eight groups. In all groups, protocols were performed after a stabilization period of 20 minutes. In group 1 (n=8), the effects of pinacidil (1.8 μmol/kg IV) on sinus cycle length, BP, and ventricular MAP amplitude (APA) and duration (APD) were determined before and after glibenclamide (15 μmol/kg IV). In groups 2 (n=17; 10 without and 7 with cardiac pacing) and 3 (n=6), transient global hypoxia was induced by ventilating the animals with 100% nitrogen for 130 seconds followed by a recovery period of 10 minutes. This protocol was repeated in the presence of either 8-cyclopentyl-1,3-dimethylxanthine (CPT; 0.3 mg/kg IV), a selective A1-AdoR antagonist,14 or glibenclamide (15 μmol/kg IV), a blocker of KATP channels.

To eliminate potential complications from the antiadrenergic action of adenosine and to determine the temporal pattern of APD, group 4 animals (n=7) were subjected to global hypoxia as described above after administration of propranolol (1 mg/kg IV). In group 5 (n=7), CPT (0.3 mg/kg IV) was also administered before hypoxia. In both groups (ie, 4 and 5), RV pacing was operative (paced cycle length, 240 milliseconds) throughout experimentation.

Characterization of CPT Actions

To verify that CPT is a selective A1-AdoR antagonist in ventricular and supraventricular tissues of the guinea pig heart in vivo, the following experiments were performed. First, the effects of CPT on the negative dromotropic and vasodilatory actions of adenosine mediated by A1-AdoR and A2-AdoR, respectively, were determined. In group 6 (n=6), exogenous adenosine (0.5, 1.0, and 1.5 μmol/kg) was given during right atrial pacing in the absence and presence of CPT (0.3 mg/kg IV), and AV nodal conduction was quantified. In five other animals (group 7), the vasodilatory action of adenosine (1.5 μmol/kg) on peripheral resistive blood vessels quantified as systemic arterial blood pressure was determined during sequential AV pacing (to exclude interference by AV conduction delays caused by adenosine) in the absence (control) and presence of CPT (0.3 mg/kg IV).

Finally, to determine the effect of CPT on ventricular A1-AdoR, the antiadrenergic action of A1-AdoR agonist 8-cyclopentyl-N4-cyclopentyladenosine (CPA, 2 μmol/kg IV) was determined in group 8 (n=6) as follows: The positive inotropic action of isoproterenol (0.1 μg/kg IV) quantified as left ventricular dP/dt was determined during AV sequential pacing in the absence (control) and presence of CPA followed by CPT (0.3 mg/kg IV).

MAP Recordings

Custom-made electrodes were used for MAP recordings. For epicardial recording, a mini suction electrode was constructed from polyethylene tubing 2 mm in diameter and two isolated silver wires (Ag, 5T, Medwire Co, New York, NY), the tip of which was chlorinated to create a Ag/AgCl junction. Then silver wires were inserted into the polyethylene tubing and glued in place such that their tips were 0.5 mm proximal to the tip of the tubing and 1 mm away from each other. Negative pressure was applied to the polyethylene tubing using a 3-mL syringe fitted with a stopcock.

For intramyocardial MAP recording, one silver wire, the same as described above, was plunged by use of a needle (23 gauge), and the other wire was positioned epicardially next to the plunge site by use of saline-soaked cotton.

MAP electrodes were connected to a high-impedance amplifier with negative capacitance.

### Table 1. Effects of Pinacidil, CPT, and GLI During Normoxia

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>PIN</th>
<th>PIN+CPT</th>
<th>PIN+GLI</th>
</tr>
</thead>
<tbody>
<tr>
<td>APDv, ms</td>
<td>121±6</td>
<td>103±6*</td>
<td>93±9*</td>
<td>114±9†</td>
</tr>
<tr>
<td>APAv, mV</td>
<td>23±2</td>
<td>22±2</td>
<td>19±3</td>
<td>19±2</td>
</tr>
<tr>
<td>SCL, ms</td>
<td>260±13</td>
<td>254±13</td>
<td>245±12*</td>
<td>256±11</td>
</tr>
<tr>
<td>BP, mm Hg</td>
<td>55±2</td>
<td>48±4*</td>
<td>49±4*</td>
<td>55±3†</td>
</tr>
</tbody>
</table>

CPT indicates 8-cyclopentyl-1,3-dimethylxanthine (0.3 mg/kg IV); GLI, glibenclamide (15 μmol/kg IV); PIN, pinacidil (1.8 μmol/kg IV); APDv, ventricular action potential duration; APAv, ventricular monophasic action potential amplitude; SCL, sinus cycle length; and BP, blood pressure. n=8. P<.05 vs control, †vs CPT, ‡vs PIN and CPT.

Data Acquisition and Analysis

Data were collected in the absence (groups 1 through 3) and presence (group 2) of RA pacing (paced cycle length, 195±7 milliseconds) and in the presence of RV pacing (paced cycle length, 240 milliseconds) (groups 4 and 5). The negative dromotropic action of exogenous adenosine on AV nodal conduction was quantified as changes in PR and atrio-His intervals as well as the number of induced blocked atrial beats (group 6). The vasodilatory action of exogenous adenosine was quantified as changes in systemic arterial blood pressure (group 7). The inotropic effect of isoproterenol was quantified as dP/dt (group 8). The following parameters were recorded as applicable: RA and left ventricular electrograms, systemic arterial BP, and atrial and ventricular MAPs. Sinus cycle length was obtained from the RA electrogram. MAP duration at 50% repolarization (APD90) and amplitude were obtained for MAP tracings.

Data are mean±SEM. ANOVA, Fisher’s least significant difference, and corrected t tests were used to determine significance at the level of P<.05.

### Results

#### Effects of Pinacidil

Under normoxic conditions, pinacidil shortened ventricular APD without significantly affecting either MAP amplitude, sinus cycle length, or systemic arterial blood pressure (Figs 1 and 2, Table 1). CPT did not alter this effect, but glibenclamide completely abolished it (Table 1).

#### Effects of Hypoxia on Ventricular APD

Global myocardial hypoxia significantly shortened ventricular APD in the absence and presence of cardiac pacing (Tables 2 and 3). This was associated with a mild decrease in systemic arterial blood pressure and the appearance of AV nodal conduction block (Tables 2 and 3). Glibenclamide reversed the effect of hypoxia on APD but not on AV nodal conduction. In contrast, CPT delayed the appearance of a complete AV nodal conduction block but did not affect the shortening of ventricular APD (Tables 2 and 3).

#### Effects of Hypoxia on Atrial APD

Global myocardial hypoxia significantly shortened atrial APD compared with normoxic conditions (Table 4). This effect of hypoxia was abolished by CPT but was not affected by glibenclamide.
CPT Versus Glibenclamide

The actions of CPT versus glibenclamide are summarized in Figs 3 and 4. As can be seen in these figures, the actions of CPT and glibenclamide in the atria were the opposite of those in the ventricles. Although CPT reversed the shortening of atrial APD induced by global hypoxia, it was ineffective in the ventricles. In contrast, glibenclamide effectively reversed the ventricular APD shortening caused by global hypoxia but was ineffective in the atria. In addition, CPT but not glibenclamide significantly delayed the appearance of a complete AV nodal conduction block during global myocardial hypoxia (Figs 3 and 4).

Temporal Pattern of APD During β-Adrenergic Receptor Blockade

Fig 5 shows data obtained in groups 4 and 5 during RV pacing and in the presence of propranolol. As can be seen, APD<sub>90</sub> was shortened in a time-dependent manner. There was no difference between the temporal pattern of APD shortening in the control group (group 4) versus that obtained in animals treated with the A<sub>1</sub>-AdoR blocker CPT (group 5).

The fact that both groups pretreated with propranolol did not show altered effects of hypoxia on APD indicates that potential modulation of the effect of endogenous catecholamines on APD by endogenous adenosine did not play a major role in hypoxia-induced APD shortening in this model.

Characterization of CPT Action

As can be seen in Table 5, CPT acted as a selective A<sub>1</sub>-AdoR antagonist in this guinea pig model. Specifically, CPT markedly attenuated the negative chronotropic action of exogenous adenosine (mediated by A<sub>2</sub>-AdoR) on AV nodal conduction expressed as prolongation of adenosine of PR and atrio-His intervals and the number of adenosine-induced nonconducted atrial beats (Table 5, A). In contrast, CPT did not significantly affect the reduction of systemic arterial blood pressure caused by the vasodilatory action of adenosine (mediated by A<sub>1</sub>-AdoR) on peripheral resistive vessels (Table 5, B). Data in Table 5, C indicate that CPT effectively antagonizes the antiadrenergic action of the adenosine derivative CPA mediated by ventricular A<sub>1</sub>-AdoR. Indeed, CPA markedly attenuated the positive inotropic action of isoproterenol expressed as left ventricular dP/dt, and CPT reversed this action of CPA (Table 5, C).

Discussion

Present Findings

The major findings of the present study were that (1) CPT, a selective A<sub>1</sub>-AdoR antagonist, did not alter the effects of global cardiac hypoxia on ventricular myocardial MAP, nor did it alter their temporal pattern; (2) in contrast, CPT prevented the shortening of the atrial myocardial MAP duration caused by hypoxia; (3) CPT also antagonized hypoxia-induced AV nodal conduction delay; (4) glibenclamide markedly attenuated the pina-
TABLE 4. Effects of CPT and GLI During Normoxia and Hypoxia

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>GLI</th>
<th>CPT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \text{O}_2 )</td>
<td>( \text{N}_2 )</td>
<td>( \text{P} )</td>
</tr>
<tr>
<td>( \text{APDA} ), ms</td>
<td>37±1</td>
<td>24±2</td>
<td>.05</td>
</tr>
<tr>
<td>( \text{APA} ), mV</td>
<td>13±1</td>
<td>11±1</td>
<td>NS</td>
</tr>
<tr>
<td>( \text{AVB} ), s</td>
<td>...</td>
<td>64±11</td>
<td>...</td>
</tr>
<tr>
<td>( \text{SCL} ), ms</td>
<td>222±13</td>
<td>213±9</td>
<td>NS</td>
</tr>
<tr>
<td>( \text{BP} ), mm Hg</td>
<td>62±2</td>
<td>57±2</td>
<td>.05</td>
</tr>
</tbody>
</table>

CPT indicates 8-cyclopentyl-1,3-dimethylxanthine (0.3 mg/kg IV); GLI, glibenclamide (15 μmol/kg IV); \( \text{APDA} \), atrial monophasic action potential duration; \( \text{APA} \), atrial monophasic action potential amplitude; \( \text{AVB} \), time to atrioventricular nodal conduction block; \( \text{SCL} \), sinus cycle length; and \( \text{BP} \), blood pressure. n=6.

*Vs control and GLI.

cil- as well as hypoxia-induced shortening of ventricular but not the hypoxia-induced shortening of atrial myocardial MAP; and (5) glibenclamide did not alter the effects of hypoxia on AV nodal conduction. In addition, the present results are consistent with previous observations that hypoxia is associated with increased release of endogenous adenosine, reduced amplitude and shortened duration of atrial and ventricular action potentials, and depressed AV nodal conduction.

CPT as a Pharmacological Tool

In the present study, CPT was used as a selective \( \text{A}_{1} \)-AdoR antagonist in the ventricular and supraventricular tissues of the guinea pig heart in vivo. Data of Table 5 confirm previous studies\(^{14} \) that indicated that CPT is a selective \( \text{A}_{1} \)-AdoR antagonist. Indeed, CPT antagonized the negative dromotropic action of adenosine on AV nodal conduction and the antiadrenergic action of CPA, both of which are known to be mediated by \( \text{A}_{1} \)-AdoR without significantly altering the vasodilatory action of adenosine, which is known to be mediated by \( \text{A}_{2} \)-AdoR.

Relation to Previous Studies

Numerous in vitro and in vivo studies using cellular electrophysiological techniques have documented the pronounced alterations in cell membrane action potential caused by acute hypoxia/ischemia. These include cell membrane depolarization leading to reduced am-

Fig. 1. Example of recordings obtained during baseline conditions. Tracings are, from top to bottom, standard leads I and II ECGs (ECG I, II), left ventricular electrogram (LV), atrial (MAP\(_{a}\)) and ventricular (MAP\(_{v}\)) monophasic action potentials, and systemic arterial blood pressure (BP).

Fig. 2. Example of ventricular (V) and atrial (A) monophasic action potential recordings during control (C) and after pinacidil (PIN, 1.8 μmol/kg IV) as well as during global hypoxia (Hypo) before and after 8-cyclopentyl-1,3-dimethylxanthine (CPT, 0.3 mg/kg IV) and glibenclamide (GLI, 15 μmol/kg IV). Horizontal bar=200 milliseconds; vertical bar=10 mV and 5 mV for ventricular and atrial recordings, respectively.
plamplitude of the action potential and shortening of the APD. Similar observations were obtained with MAP recordings in vitro and in vivo. The present data confirm these findings; i.e., the induction of global hypoxia was associated with reduction in the amplitude and the duration of atrial and ventricular MAP. It has been proposed that the shortening of the APD during hypoxia/ischemia is the result of decreased intracellular concentrations of ATP and the subsequent activation of glibenclamide-sensitive K\(^{+}\)\(_{\text{ATP}}\) channels. The fact that glibenclamide markedly attenuated the effect of pinacile and hypoxia on APD in the ventricular myocardium supports this hypothesis. However, glibenclamide did not affect the response of atrial APD to hypoxia, suggesting that a mechanism other than K\(^{+}\)\(_{\text{ATP}}\) channel activation is responsible for the hypoxia-induced shortening of atrial APD. This is in agreement with the view that the density of K\(^{+}\)\(_{\text{ATP}}\) channels in atrial myocytes is relatively low compared with ventricular myocytes.

The shortening of the atrial APD and increased AV conduction delay caused by adenosine are attributed to the activation of I\(_{\text{K}_{\text{ATP}}}\). Moreover, these effects are mediated by A\(_{\text{1}}\)-AdoR. Thus, the data obtained in the presence of CPT are in congruence with A\(_{\text{1}}\)-AdoR-mediated induction of I\(_{\text{K}_{\text{ATP}}}\) as a probable cause of the altered atrial MAP. This is based on the following well-established facts: (1) acute myocardial hypoxia is associated with the release of endogenous adenosine to the extracellular fluids; (2) extracellular adenosine exerts pronounced electrophysiological effects, includ-
ing negative chronotropic and dromotropic actions on sinus node automatisim and AV nodal conduction, respectively, as well as shortening of atrial myocardial refractoriness; and (3) these actions are mediated by A1-AdoR and pertussis toxin–sensitive G protein.

It can be concluded that CPT prevented the shortening of atrial APD by blocking A1-AdoR in this tissue. This conclusion is supported by the finding that in the present experimental model, CPT antagonized the detrimental effect of hypoxia on AV nodal conduction. This latter observation indicates that substantial amounts of endogenous adenosine were released into the extracellular fluid, which altered AV nodal conduction. Similar conclusions were obtained in a previous study using a different selective A1-AdoR antagonist. Moreover, since CPT did not alter the effects of hypoxia on ventricular APD, it can be concluded that activation of KATP channels by adenosine does not play a major role in the mechanism of hypoxia-induced shortening of ventricular APD. This accords with the fact that no significant IK,AdoR is found in guinea pig ventricular myocytes. Furthermore, since CPT did not alter the temporal pattern of APD shortening, this argues against an early effect of adenosine on KATP channels that is masked by subsequent activation of these channels via change in intracellular ATP levels.

Adenosine and Cardioprotection

Adenosine has been shown to act as an endogenous cardioprotective agent and a mediator of ischemic/hypoxic preconditioning. Since adenosine was suggested to activate KATP channels, the activation of which is believed to play a mechanistic role in preconditioning, it has been assumed that KATP channels mediate, at least in part, the cardioprotective effects of adenosine. In the present study, glibenclamide did not alter the electrophysiological effects of endogenous adenosine. These data could explain the inability of glibenclamide to prevent preconditioning in rabbit and rat hearts.20 The lack of effect of glibenclamide on preconditioning is in accord with the present conclusion that endogenous adenosine

### Table 5: Characterization of CPT Actions

#### A. Effect of CPT on the negative dromotropic action of exogenous adenosine (n=6)

<table>
<thead>
<tr>
<th>Control</th>
<th>CPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADO, μmol/kg</td>
<td>ADO, μmol/kg</td>
</tr>
<tr>
<td>Saline</td>
<td>0.5</td>
</tr>
<tr>
<td>PR, ms</td>
<td>60±0</td>
</tr>
<tr>
<td>AH, ms</td>
<td>49±1</td>
</tr>
<tr>
<td>NAB, n</td>
<td>0</td>
</tr>
<tr>
<td>BP, mm Hg</td>
<td>56±3</td>
</tr>
</tbody>
</table>

#### B. Effect of CPT on adenosine-induced decrease in systemic blood pressure (n=5)

<table>
<thead>
<tr>
<th>Control</th>
<th>ADO, 1.5 μmol/kg</th>
<th>ADO+CPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP, mm Hg</td>
<td>55±3</td>
<td>51±3*</td>
</tr>
<tr>
<td>AV PCL, ms</td>
<td>178±2</td>
<td>178±2</td>
</tr>
</tbody>
</table>

#### C. Effect of CPT on the antagonistic action of CPA (n=6)

<table>
<thead>
<tr>
<th>Control</th>
<th>+ISO</th>
<th>ISO+CPA</th>
<th>ISO+CPA+CPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV dP/dt, mm Hg/s</td>
<td>590±53</td>
<td>1139±174</td>
<td>694±84*</td>
</tr>
<tr>
<td>BP, mm Hg</td>
<td>56±2</td>
<td>60±2</td>
<td>49±3*</td>
</tr>
<tr>
<td>AV PCL</td>
<td>179±1</td>
<td>179±1</td>
<td>179±1</td>
</tr>
</tbody>
</table>

CPT indicates 8-cyclopentyl-1,3-dimethylxanthine (0.3 μg/kg IV); ADO, adenosine; PR, P wave to R deflection interval; AH, atrial to His bundle interval; NAB, nonconducted atrial beats over 120 seconds after adenosine; BP, blood pressure; AV PCL, atrioventricular sequential pacing cycle length; CPA, 8-cyclopentyladenosine (2 μmol/kg IV); ISO, isoproterenol (0.1 μg/kg IV); and LV dP/dt, time derivation of left ventricular pressure.

*P<.05.
does not activate K⁺_ATP channels. Although most earlier studies used localized ischemia and not global hypoxia as the preconditioning perturbation, recent reports have shown that hypoxic and ischemic preconditioning were equipotent in the rat heart21 and in preventing infarction in the dog22 and that hypoxia-induced APD shortening is mediated in part by the activation of K⁺_ATP channels.23 Thus, the cardioprotective role of adenosine in preconditioning is probably mediated by a mechanism other than K⁺_ATP channel activation. The dog could be an exception, however, since glibenclamide antagonized the cardioprotective effect of an A₁-adenosine agonist in this species.24 It should be noted, however, that the interaction between glibenclamide and adenosine in the canine heart is complex and not well understood.25,26

There is no immediate explanation for the discrepancy between the two in vitro studies that used patch clamp techniques and showed adenosine-induced activation of K⁺_ATP channels3,4 and the present in vivo study. It can be speculated that the conditions of global hypoxia did not cause high enough elevation of extra-

As a result of this, the washout of adenosine prevents its accumulation at the receptor site. Further studies are required before the physiological role of the activation of K⁺_ATP channels by adenosine via A₁-AdoR in cardiac myocytes is determined.

Acknowledgments

Dr Luiz Belardinelli suggested testing of the present working hypothesis. We thank Dwendolyn Dillard for her assistance in preparing the manuscript. Dr Pelleg is supported by grant HL-43006 from the National Institutes of Health.

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