Effect of ATP-sensitive potassium channel agonists on sympathetic hyperinnervation in postinfarcted rat hearts

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Kang C, Chen C, Lin C, Chang N, Lee T. Effect of ATP-sensitive potassium channel agonists on sympathetic hyperinnervation in postinfarcted rat hearts. Am J Physiol Heart Circ Physiol 296: H1949–H1959, 2009. First published April 3, 2009; doi:10.1152/ajpheart.00903.2008.—Although the acute administration of ATP-sensitive potassium (KATP) channel agonists provides a neuroprotection, it is unclear whether similar benefits are found by modulating sympathetic innervation in chronic settings after myocardial infarction. We assessed whether KATP channel agonists can attenuate the sprouting of cardiac sympathetic nerves after infarction. Male Wistar rats after ligation coronary artery were randomized to either saline, nicorandil, pinacidil, glibenclamide, or a combination of 1) nicorandil and glibenclamide or 2) pinacidil and glibenclamide for 4 wk. To elucidate the role of mitochondrial KATP channels in modulating nerve growth factor, 5-hydroxydecanoate was assessed in an in vitro model. The measurement of myocardial norepinephrine levels revealed a significant elevation in saline-treated infarcted rats compared with sham-operated rats, consistent with excessive sympathetic innervation. Excessive sympathetic innervation was blunted after giving the rats either nicorandil or pinacidil, compared with saline, as assessed by the immunohistochemical analysis of tyrosine hydroxylase, growth associated protein-43, and neuropeptide and Western blot analysis and real-time quantitative RT-PCR of nerve growth factor. The arrhythmic scores during programmed stimulation in the saline- or glibenclamide-treated infarcted rats were significantly higher than those of rats treated with KATP channel agonists. In contrast, the beneficial effects of nicorandil and pinacidil were abolished by administering either glibenclamide or 5-hydroxydecanoate. The sympathetic hyperinnervation after infarction is attenuated by the activation of mitochondrial KATP channels. The chronic use of mitochondrial KATP channel agonists after infarction may attenuate the arrhythmogenic response to programmed electrical stimulation.

Adenosine 5′-triphosphate-sensitive potassium channel; myocardial infarction; norepinephrine; sympathetic innervation

There is general agreement that the activation of ATP-sensitive potassium (KATP) channels in neurons has a protective effect during acute settings of cell-damaging conditions (53). In the cardiac tissues, the KATP channels are observed on cardiomyocytes (36) and pre- and postsynaptic membranes of sympathetic nerves, which can be inhibited by glibenclamide (18). Burgdorf et al. (5) have shown that the release of norepinephrine from sympathetic nerves supplying the heart can be modulated via KATP channels. In acute settings, the antiarrhythmic activity with KATP channel agonists is probably a secondary effect resulting from its anti-ischemic action and pharmacological preconditioning (46). Thus, although an acute administration of KATP channel agonists provides a neuroprotection, it is unclear whether similar benefits are observed by modulating sympathetic hyperinnervation in chronic settings after myocardial infarction (MI).

Nerve growth factor (NGF) is a trophic factor that is critical for the differentiation, survival, and synaptic activity of the peripheral sympathetic and sensory nervous systems (43). In ischemic hearts, an increase in cardiac NGF leads to a regeneration of sympathetic nerves (6, 21). The expression of cardiac NGF correlates with the density of sympathetic innervation in the heart (42), and the amount of NGF can affect the sympathetic nerve survival and synaptic transmission between neurons and cardiac myocytes (29). These results demonstrate the importance of NGF in the regulation of sympathetic innervation.

Increased sympathetic nerve density after myocardial injury has been shown to be responsible for the occurrence of lethal arrhythmias and sudden cardiac death in humans (7). During the chronic stage of MI, a regional increase of sympathetic nerves was commonly observed at the remote zone (56). Increased sympathetic nerve activity plays an important role in the generation of ventricular arrhythmia and sudden cardiac death (7). Cardiac myocytes contain two distinct KATP channels with one subtype located in the sarcolemma and the other in the inner membrane of the mitochondria (28). Mitochondrial KATP channels share some pharmacological properties with sarcomemmal KATP channels, while possessing a distinct pharmacological response. KATP channels are activated by numerous compounds with distinct chemical structures (39). These agents, collectively termed as KATP channel agonists, cause various biological effects through the modulation of the sarcolemma and mitochondrial KATP channels. Pinacidil has been shown to activate both sarcolemmal and mitochondrial KATP channels, whereas nicorandil activates only mitochondrial KATP channels (39). The activation of KATP channels has been shown to attenuate the expression of endothelin-1 (ET-1) (55). ET-1 can upregulate NGF mRNA by augmenting the expression of the NGF promoter during the development of cardiac sympathetic innervation (16). The purpose of this study was 1) to investigate how two KATP channel agonists, nicorandil and pinacidil, affect sympathetic hyperinnervation; 2) to determine which subtype of KATP channels plays a role in sympathetic hyperinnervation by the use of 5-hydroxydecanoate (5-HD), a specific mitochondrial KATP channel blocker; and 3) to test whether ET-1 acts as a mediator of the effect of KATP channel agonists on NGF expression.
KATP CHANNELS AND NEURAL INNERVATION

METHODS

Animals: in vivo study. Male Wistar rats (300–350 g) were subjected to ligation of the anterior descending coronary as previously described (26), resulting in the infarction of the left ventricular (LV) free wall. Rats were randomly assigned into six groups so as to have approximately the same number of survivors in each group: 1) saline group; 2) nicorandil (0.1 mg·kg⁻¹·day⁻¹, Chugai Pharmaceutical), a specific mitochondrial K<sub>ATP</sub> channel agonist; 3) pinacidil (0.1 mg·kg⁻¹·day⁻¹, Sigma), a nonselective K<sub>ATP</sub> channel agonist; 4) glibenclamide (1.4 mg·kg⁻¹·day⁻¹), a K<sub>ATP</sub> channel blocker; 5) a combination of nicorandil and glibenclamide; and 6) a combination of pinacidil and glibenclamide.

In each treated group, the drugs were given orally by gastric gavage once a day. To prevent hypoglycemic attacks during the administration of glibenclamide, 2.5% (wt/vol) sucrose in filtered water was infused for 30 min. The doses of nicorandil, pinacidil (8), and 5-HD (34) used were approximately the same number of survivors in each group:

- 1) Saline
- 2) Nicorandil
- 3) Pinacidil
- 4) Glibenclamide
- 5) Combination of nicorandil and glibenclamide
- 6) Combination of pinacidil and glibenclamide

In vitro study. Although the results of the above study showed that K<sub>ATP</sub> channel antagonist-induced sympathetic innervation was altered at 4 wk after infarction (see RESULTS), glibenclamide was used as an antagonist of K<sub>ATP</sub> channels, which can block both mitochondrial and sarcoplasmic K<sub>ATP</sub> channels and has multiple actions independent of K<sub>ATP</sub> channels. Four weeks after the induction of MI by coronary ligation, the injured rat hearts were isolated and subjected to no treatment (vehicle), nicorandil (50 μM), pinacidil (50 μM), 5-HD (100 μM), nicorandil + 5-HD, or pinacidil + 5-HD. Each heart was perfused with a noncirculating modified Tyrode solution containing (in mM) 117.0 NaCl, 23.0 NaHCO<sub>3</sub>, 4.6 KCl, 0.8 NaH<sub>2</sub>P<sub>4</sub>, 1.0 MgCl<sub>2</sub>, 2.0 CaCl<sub>2</sub>, and 5.5 glucose, equilibrated at 37°C and oxygenated with a 95% O<sub>2</sub>-5% CO<sub>2</sub> gas mixture. The perfusion medium was maintained at a constant temperature of 37°C with a constant flow at 4 ml/min as previously described (24). The drugs were infused for 30 min. The doses of nicorandil (20), pinacidil (8), and 5-HD (34) used in this study have been shown to modulate K<sub>ATP</sub> channels in an isolated heart. At the end of the study, all the hearts (n = 10 in each group) were used for performing Western blot analysis from samples at the remote zone (>2 mm outside the infarct). The animal experiments were approved by the Chi-Mei Medical Center and conducted in accordance with its local guidelines for the care and use of laboratory animals. The investigation conformed with the Guide for the Care and Use of Laboratory Animals, published by the National Institutes of Health (NIH Publication No. 85-23, Revised 1996).

Echocardiogram. At 28 days after operation, the rats were lightly anesthetized with an intraperitoneal injection of ketamine-HCl (25 mg/kg). Echocardiographic measurements were done with a HP Sonos 5500 system with a 15-6L (6–15 MHz, SONOS 5500; Agilent Technologies, Palo Alto, CA) probe. The M-mode tracing of the LV was obtained from the parasternal long-axis view to measure the LV end-diastolic diameter dimension (LVEDD) and LV end-systolic dimension (LVESD), and fractional shortening (in %) was calculated. After this, the hearts quickly underwent hemodynamic measurement after systemic heparinization.

Hemodynamics and infarct size measurements. Hemodynamic parameters were measured in anesthetized rats with ketamine (90 mg/kg) intraperitoneally at the end of the study. A polyethylene Millar catheter was inserted via the right carotid artery and connected to a transducer (Model SPR-407, Miller Instruments, Houston, TX) to measure LV systolic and diastolic pressure as the mean of measurements of five consecutive pressure cycles as previously described (26). The maximal rates of LV pressure rise and decline were measured. After the arterial pressure measurement, the heart was paced for the in vivo electrophysiological tests. At the completion of the electrophysiological tests, the atria and the right ventricle were trimmed off, and the LV was rinsed in cold physiological saline, weighed, and immediately frozen in liquid nitrogen after obtaining a coronal section of the LV for infarct size estimation. A section, taken from the equator of the LV, was fixed in 10% formalin and embedded in paraffin for the determination of infarct size. Each section was stained with hemotoxylin-eosin and trichrome. The infarct size was determined as previously described (40). With respect to clinical importance (40), only the rats with a large infarction (>30%) were selected for analysis.

In vivo electrophysiological studies. After the arterial pressure measurement, the rats were intubated and artificially ventilated with humidified room air supplied with oxygen. Because the residual neural integrity at the infarcted site is one of the determinants of the response to electrical induction of ventricular arrhythmias (14), only rats were included with the infarcted area of the LV totally replaced by scar tissue. Body temperature was maintained at 37°C by a thermostatically controlled heated lamp. Programmed electrical stimulation was performed through electrodes sewn on the epicardial surface of the right ventricular outflow tract. Induced arrhythmias were effected using an electrical Bloom stimulator. To induce ventricular arrhythmias, eight paced beats at a cycle length of 120 ms (S<sub>1</sub>) were applied, followed by one to three extrastimuli (S<sub>2</sub>, S<sub>3</sub>, and S<sub>4</sub>) at shorter coupling intervals. The end point of ventricular pacing was the induction of ventricular tachyarrhythmias. Ventricular tachyarrhythmias including ventricular tachycardia and ventricular fibrillation were considered nonsustained when it lasted <15 beats and sustained when it lasted >15 beats. An arrhythmia scoring system was modified as previously described (35): 0, noninducible preparations; 1, nonsustained tachyarrhythmias induced with three extrastimuli; 2, sustained tachyarrhythmias induced with three extrastimuli; 3, nonsustained tachyarrhythmias induced with two extrastimuli; 4, sustained tachyarrhythmias induced with two extrastimuli; 5, nonsustained tachyarrhythmias induced with one extrastimulus; 6, sustained tachyarrhythmias induced with one extrastimulus; and 7, tachyarrhythmias induced during the eight paced beats. If the heart stopped before the pacing, the arrhythmia score assigned to that heart was 8. When multiple forms of arrhythmias occurred in one heart, the highest score was used. The experimental protocols were typically completed within 10 min.

Real-time RT-PCR of NGF. Real-time quantitative reverse transcription-polymerase chain reaction (RT-PCR) was performed from samples obtained from the remote zone with the TaqMan system (Prism 7700 Sequence Detection System, PE Biosystems) as previously described (26). For NGF, the primers were 5'-TCCACCCAC-CCGTCCTTCCA-3' (sense) and 5'-GGCTTCCTGCTGACACACA-3' (antisense). For glyceraldehyde-3-phosphate dehydrogenase (GAPDH), the primers were 5'-CTTCACCACTTGGAGAGG-3' (sense) and 5'-GGATGACTGTGTGGTACG-3' (antisense). Standard curves were plotted with the threshold cycles versus the log template quantities. For quantification, NGF expression was normalized to the expressed housekeeping gene GAPDH. Reaction conditions were programmed on a computer linked to the detector for 40 cycles of the amplification step.

Western blot analysis of NGF. Samples obtained from the remote zone were homogenized with a polytron blender. Homogenates were centrifuged at 10,000 g for 30 min to pellet the particulate fractions. The supernatant protein concentration was determined with the BCA protein assay reagent kit (Pierce). Protein (20 μg) was separated by 10% SDS-PAGE and electrotransferred onto a nitrocellulose mem-

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brane. After incubation with rabbit polyclonal anti-NGF antibodies (Chemicon) at 1:500 dilution, the nitrocellulose membrane was then rinsed with a blocking solution and incubated for 2 h at room temperature. Antigen-antibody complexes were detected with 5-bromo-4-chloro-3-indolyl-phosphate and nitroblue tetrazolium chloride (Sigma). Films were volume integrated within the linear range of the exposure using a scanning densitometer. Experiments were replicated three times, and the results were expressed as the mean value.

**Immunohistochemical studies of tyrosine hydroxylase, growth associated protein-43, and neurofilament.** To investigate the spatial distribution and quantification of sympathetic nerve fibers, an analysis of immunohistochemical staining for tyrosine hydroxylase, growth associated protein-43 (GAP-43, a marker peptide for neuronal regeneration and outgrowth), and neurofilament (a marker for sympathetic nerve; Ref. 31) was performed on LV muscle from the remote regions. Papillary muscles were excluded from the study because a variable sympathetic innervation has been reported (9). Paraffin-embedded sections were performed at a thickness of 5 μm. Tissues were incubated with anti-tyrosine hydroxylase antibodies (1:200; Chemicon), anti-GAP-43 (1:400; Chemicon), and anti-neurofilament (1:1,000; Chemicon) in 0.5% BSA in PBS overnight at 37°C. Immunostaining was performed using a standard immunoperoxidase technique (N-Histofine Simple Stain MAX PO kit, Nichirei, Tokyo, Japan). Isotype-identical directly conjugated antibodies served as a negative control. The experiments were replicated three times, and the results were expressed as the mean value.

The slides were coded so that the investigator was blinded to the rat identification. The nerve density was measured on the tracings by computerized planimetry (Image ProPlus, Media Cybernetics, Silver Spring, MD) as described previously (27). The density of nerve fibers was qualitatively estimated from 10 randomly selected fields at a magnification of ×400 and expressed as the ratio of labeled nerve fiber area to the total area.

**Laboratory measurements.** To determine the confounding roles of glucose and insulin in nerve remodeling, blood samples from the aorta were assayed at the end of the study. Plasma insulin concentration was measured by collecting 4 ml of blood in test tubes containing 2% ethylenediaminetetraacetic acid (80 μl/ml of blood). Blood samples were immediately centrifuged at 3,000 g for 10 min, and the plasmas were stored at −70°C until further analysis. Insulin was measured by ultrasensitive rat enzyme immunoassay (Mercodia, Uppsala, Sweden).

Because of a local release of norepinephrine after sympathetic innervation, the tissues from the border zone (0 to 2 mm outside the infarct) and remote zone were obtained for measurements of local norepinephrine levels at the end of the study. The myocardium was minced and suspended in a 0.4 N perchloric acid with 5 mmol/l reduced glutathione (pH 7.4), homogenized with a polytron homogenizer for 60 s in 10 vol. Samples were immediately centrifuged at 3,000 g for 10 min, and the supernatant was stored at −70°C until further analysis. The supernatant protein concentration was determined with the BCA protein assay reagent kit (Pierce). Total norepinephrine was measured using a commercial ELISA kit (Noradrenalin ELISA, IBL Immuno-Biological Laboratories, Hamburg, Germany).

To confirm the downstream pathways of the $K_{ATP}$ channel, we collected tissues from the remote zone for ET-1 measurements at the end of the study. The myocardium was homogenized using a polytron homogenizer for 60 s in 10 vol of 1 mol/l acetic acid containing 10 μg/ml of pepstatin and then immediately boiled for 10 min at 4°C. ET-1 was measured using an immunoassay (R&D Systems, Minneapolis, MN).

**Statistical analysis.** Results were presented as means ± SD. Statistical analysis was performed using the SPSS statistical package (SPSS, version 11.0, Chicago, IL). Differences among the groups of rats were tested by a one-way ANOVA. Subsequently, an analysis for significant differences between the two groups was performed with a multiple comparison test (Scheffé’s method). Electrophysiological data (scoring of programmed electrical stimulation-induced arrhythmias) were compared by a Kruskal-Wallis test followed by a Mann-Whitney test. The interaction term of nicorandil, pinacidil, and glibenclamide effects was incorporated into the model. The significant level was assumed at value of $P < 0.05$.

**RESULTS**

Differences in mortality among the infarcted groups were not found throughout the study. Either nicorandil, pinacidil, or glibenclamide had little effect on the cardiac gross morphology in the sham-operated rats (data not shown). Four weeks after infarction, the infarcted area of the LV was very thin and was totally replaced by fully differentiated scar tissue. The weight of the LV inclusive of the septum remained essentially constant 4 wk among the infarcted groups (Table 1). When compared with saline-treated infarcted rats, nicorandil- or pinacidil-treated infarcted rats had a significantly lower right ventricular weight-to-body weight ratio and lung weight-to-body weight ratio, consistent with favorable LV remodeling. LV end-systolic pressure and infarct size did not differ among the infarcted groups. Insulin concentrations were significantly increased in rats administered with glibenclamide (Table 2).

**Norepinephrine and ET-1 levels.** Circulating norepinephrine levels remained similar among the infarcted groups (Table 2). To investigate the possible role of cardiac norepinephrine synthesis, we determined the LV norepinephrine levels. Either nicorandil, pinacidil, or glibenclamide administration did not affect tissue norepinephrine concentrations in sham-operated rats. LV norepinephrine levels were significantly upregulated 1.7-fold at the border zone in the saline-treated infarcted rats than in the sham-operated rats (2.33 ± 0.20 vs. 1.37 ± 0.35 μg/g protein, $P < 0.0001$). The expression was region dependent with a significant increase at the remote zone (2.95 ± 0.25 μg/g protein) compared with that at the border zone (2.33 ± 0.20 μg/g protein, $P = 0.03$) after infarction in the saline group. When compared with saline-treated infarcted rats, nicorandil- or pinacidil-treated infarcted rats had significantly lower LV norepinephrine levels at the remote regions. The beneficial effect of nicorandil and pinacidil on LV norepinephrine levels was reversed by administering glibenclamide. The changes of myocardial ET-1 at the remote regions were similar to those of LV norepinephrine (Table 2).

**Echocardiographic data.** When compared with sham-operated hearts, MI hearts showed structural changes such as increased LV diastolic and systolic diameters (Table 3), consistent with LV remodeling. Both LVEDD and LVESD in rats with MI were significantly reduced by nicorandil or pinacidil treatment ($P < 0.0001$). LV fractional shortening was significantly higher in the nicorandil- or pinacidil-treated infarcted group compared with the saline-treated infarcted group. Conversely, the rats to which glibenclamide was administered developed impaired LV systolic function and progressive LV dilation than those in the nicorandil- and pinacidil-treated groups alone.

**Immunohistochemical analyses.** The tyrosine hydroxylase-immunostained nerve fibers appeared to be oriented in the longitudinal axis of adjacent myofibers (Fig. 1, top). Tyrosine hydroxylase-positive nerve density was significantly increased in the saline-treated infarcted rats compared with sham-operated rats (Fig. 1, bottom). Rats in the nicorandil- and pinacidil-treated groups showed less nerve density at the remote regions than that in saline-treated rats (0.06 ± 0.03%, 0.07 ± 0.05% vs.
### Table 1. Cardiac morphology and hemodynamics at the end of study

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sham</th>
<th>Infarction with Treatment</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Saline</td>
<td>Nic</td>
</tr>
<tr>
<td>Number of rats</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Body weight, g</td>
<td>421±24</td>
<td>410±20</td>
</tr>
<tr>
<td>Heart rate, beats/min</td>
<td>396±25</td>
<td>409±22</td>
</tr>
<tr>
<td>LVEDP, mmHg</td>
<td>11±7</td>
<td>102±6</td>
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<tr>
<td>Insulin, μU/ml</td>
<td>2.1±0.2</td>
<td>2.2±0.23</td>
</tr>
<tr>
<td>LVET-1, pg/mg tissue</td>
<td>1.3±0.03</td>
<td>1.6±0.04</td>
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</tbody>
</table>

Values are means ± SD. LVESP, left ventricular (LV) end-systolic pressure; LVEDP, LV end-diastolic pressure; +dP/dt, LV pressure rise; −dP/dt, LV pressure decline; BW, body weight; LVW, LV weight; RVW, right ventricular weight; LungW, lung weight. *P < 0.05 compared with infarcted groups treated with saline and nicorandil (Nic) + glibenclamide (Glib); †P < 0.05 compared with infarcted groups treated with saline and pinacidil (Pin) + Glib.

### Table 2. Glucose, insulin, plasma, and tissue NE and tissue ET-1 concentration at the end of study

<table>
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<th>Parameters</th>
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<th>Infarction With Treatment</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Saline</td>
<td>Nic</td>
</tr>
<tr>
<td>Glucose, mg/dl</td>
<td>90±7</td>
<td>85±9</td>
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</table>
| Insulin, μU/ml | 21±8 | 19±6 | 22±10 | 89±15 | 79±12 | 85±18 | 45±10* | 42±13* | 45±15 | 136±21† | 108±23† | 129±25† †
| Plasma NE, ng/ml | 2.7±1.2 | 2.9±1.1 | 3.2±1.6 | 1.7±1.5 | 2.5±1.8 | 2.2±2.2 | 4.6±1.5* | 5.4±1.3* | 5.9±2.1* | 4.9±1.3* | 5.7±1.6* | 5.7±1.5* |
| Remote NE, μg/g protein | 1.52±0.42 | 1.36±0.48 | 1.38±0.74 | 1.33±0.77 | 1.38±0.49 | 1.67±0.54 | 2.95±0.25† | 1.43±0.22 | 1.56±0.27 | 3.19±0.21† | 2.85±0.19†† | 2.39±0.23†† |
| Border NE, μg/g protein | 1.37±0.35 | 1.15±0.45 | 1.54±0.30 | 1.57±0.55 | 1.30±0.36 | 1.44±0.56 | 2.3±0.20* | 1.29±0.25 | 1.25±0.38 | 2.37±0.28* | 2.40±0.25† | 1.89±0.26† |
| ET-1, pg/mg tissue | 1.3±0.2 | 1.1±0.3 | 1.2±0.3 | 1.5±0.3 | 1.2±0.2 | 1.2±0.5 | 2.4±0.3* | 1.7±0.2* | 1.8±0.3* | 2.5±0.2* | 2.6±0.3* | 2.3±0.4†† |

Values are means ± SD. NE, norepinephrine; ET-1, endothelin-1. *P < 0.05 compared with respective sham-operated rats; †P < 0.05 compared with respective infarcted groups without administering Glib; ††P < 0.05 compared with the border zone within the same group.
neurofilament-positive nerve densities were significantly attenuated compared with saline-treated infarcted rats. Our findings were consistent with those in the K<sub>ATP</sub> channel agonists-treated groups alone. These morphometric results mirrored those of norepinephrine contents.

**NGF protein and mRNA expression.** Western blot analysis showed that the NGF levels were significantly upregulated 8.3-fold at the remote zone in the saline-treated infarcted rats than in the sham-operated rats (P < 0.0001, Fig. 3). When compared with saline-treated infarcted rats, nectarandil- and pinacidil-treated infarcted rats had significantly lower NGF levels at the remote zone. The attenuated expression of K<sub>ATP</sub> channel agonists-related NGF can be reversed to the levels similar to the saline-treated infarcted rats after adding glibenclamide. To elucidate the role of mitochondrial K<sub>ATP</sub> channels in modulating NGF, 5-HD was assessed in an in vitro model. Figure 4 shows that 5-HD significantly increased the expression of NGF compared with either nectarandil or pinacidil alone, confirming the role of mitochondrial K<sub>ATP</sub> channels in mediating NGF expression.

PCR amplification of the cDNA revealed that the NGF mRNA levels showed a 5.0-fold upregulation at the remote zone in the saline-treated infarcted rats compared with the sham-operated rats (P < 0.0001, Fig. 5). In either nectarandil- or pinacidil-treated infarcted rats, the NGF mRNA levels were significantly decreased compared with those in the saline-treated infarcted rats. The attenuated magnitude of NGF mRNA levels was similar between nectarandil- and pinacidil-treated rats. Conversely, the glibenclamide-treated infarcted rats showed a marked increase of NGF mRNA than that in the K<sub>ATP</sub> channel agonists-treated groups alone.

Electrophysiological stimulation. To further elucidate the physiological effect of attenuated sympathetic hyperinnervation, ventricular pacing was performed. The arrhythmia score in the sham-operated rats was very low (0.1 ± 0.3) (Fig. 6). In contrast, ventricular tachycardia and ventricular fibrillation were inducible by a programmed stimulation in saline-treated infarcted rats. Nectarandil and pinacidil treatment significantly decreased the inducibility of ventricular tachycardia and ventricular fibrillation compared with that in the saline-treated infarcted group. Glibenclamide administration significantly increased the arrhythmia scores in K<sub>ATP</sub> channel agonists-treated rats, compared with the K<sub>ATP</sub> channel agonists-treated rats alone.

**DISCUSSION**

Our present study shows for the first time that a chronic treatment for 4 wk with K<sub>ATP</sub> channel agonists leads to attenuated sympathetic hyperinnervation after MI. These results were concordant for beneficial effects of K<sub>ATP</sub> channel agonists, as documented structurally by a reduction in cardiac nerve sprouting; molecularly, by myocardial NGF protein and mRNA levels; biochemically, by tissue norepinephrine and ET-1 levels; and functionally, by an improvement of fatal ventricular tachyarrhythmias. The beneficial effects of K<sub>ATP</sub> channel agonists as antiarrhythmic agents were related to the remodeling of the sympathetic nervous system that may be mediated by the K<sub>ATP</sub> channel-ET-1-NGF pathway. Our results were compatible with a recent finding of Kasama et al. (19), showing that nectarandil administration attenuates sympathetic innervation in humans.

The beneficial effect of K<sub>ATP</sub> channel agonists on sympathetic innervation was supported by three lines of evidence. First, mitochondrial K<sub>ATP</sub> channel activation plays a role in the pathogenesis of sympathetic hyperinnervation after infarction. The administration of K<sub>ATP</sub> channel agonists attenuates sympathetic hyperinnervation in chronically infarcted hearts. Either pinacidil or nectarandil administration can attenuate sympathetic hyperinnervation with a similar potency at the remote zone, which may suggest that mitochondrial K<sub>ATP</sub> channels play a role in regulating the nerve sprouting. Although dissimilar structures, pinacidil and nectarandil appear to share a common mediator, NGF, in which transcription levels of NGF may play a role in the signal transduction pathway. The involvement of NGF in mitochondrial K<sub>ATP</sub> channel activation-related sympathetic hyperinnervation after infarction was further supported by administering a mitochondrial K<sub>ATP</sub> antagonist (5-HD). The results are consistent with a recent finding of Lou et al. (30), showing that mitochondrial K<sub>ATP</sub> channel activation is associated with neuroprotection. Second, the beneficial effects of K<sub>ATP</sub> agonists on attenuated sympathetic hyperinnervation might be associated with reduced ET-1 levels. Rats in which K<sub>ATP</sub> agonists were administered had significant reductions of tissue ET-1 compared with saline-treated infarcted rats. Our findings were consistent with those of Xue et al. (52), showing that chronic treatment with a K<sub>ATP</sub> channel agonist (iptakalim) reduces ET-1 concentrations.

**Table 3. Echocardiographic findings**

<table>
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<th>Parameters</th>
<th>Sham</th>
<th>Saline</th>
<th>Nic</th>
<th>Pin</th>
<th>Glib</th>
<th>Nic + Glib</th>
<th>Pin + Glib</th>
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<tr>
<td>Mortality, n (%)</td>
<td>0 (0)</td>
<td>5 (31)</td>
<td>4 (25)</td>
<td>5 (33)</td>
<td>5 (33)</td>
<td>4 (27)</td>
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<tr>
<td>Interventricular septum, mm</td>
<td>1.6±0.1</td>
<td>0.8±0.2*</td>
<td>0.8±0.2*</td>
<td>0.8±0.1*</td>
<td>0.7±0.3*</td>
<td>0.8±0.2*</td>
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</tr>
<tr>
<td>LVESD, mm</td>
<td>3.8±0.2</td>
<td>8.5±0.3*</td>
<td>7.3±0.2†</td>
<td>7.4±0.2‡</td>
<td>8.7±0.3*</td>
<td>9.0±0.2*</td>
<td>8.8±0.2*</td>
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<tr>
<td>LV posterior wall, mm</td>
<td>1.6±0.2</td>
<td>7.0±0.2*</td>
<td>5.5±0.3‡</td>
<td>5.3±0.3*</td>
<td>7.2±0.2*</td>
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<tr>
<td>Fractional shortening, %</td>
<td>37±3</td>
<td>18±4*</td>
<td>25±3†</td>
<td>26±3*‡</td>
<td>17±3*</td>
<td>19±4*</td>
<td>17±3*</td>
</tr>
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</table>

Values are means ± SD. LVESD, LV end-systolic dimension; LVESD, LV end-systolic dimension. *P < 0.05 compared with the sham-operated group; †P < 0.05 compared with infarcted groups treated with saline and Nic + Glib; ‡P < 0.05 compared with infarcted groups treated with saline and Pin + Glib.
Fig. 1. Top: immunohistochemical staining for tyrosine hydroxylase from the remote regions (magnification, ×400). Tyrosine hydroxylase-positive nerve fibers (brown) are located between myofibrils and are oriented in a longitudinal direction as that of the myofibrils. Myocytes are not stained and appear pale in this view. Sham-operated group (A), saline group (B), nicorandil (Nic) group (C), pinacidil (Pin) group (D), glibenclamide (Glib) group (E), Nic + Glib (F), Pin + Glib group (G) are shown. Bar = 50 μm. Bottom: nerve density area fraction (in %) at the remote zone. Bars represent means ± SD. *P < 0.05 compared with saline-, Glib-, Nic + Glib-, and Pin + Glib-treated groups.
Third, the severity of pacing-induced fatal arrhythmias was associated with the degree of sympathetic innervation. The finding was consistent with the findings of Cao et al. (6, 7), showing that an increased postinjury sympathetic nerve density may be responsible for the occurrence of ventricular arrhythmia and sudden cardiac death in animals and patients.

**Mechanisms.** In this study, we demonstrated an attenuated sympathetic hyperinnervation in K<sub>ATP</sub> channel agonists-treated hearts. The mechanisms by which K<sub>ATP</sub> channel agonists affect sympathetic hyperinnervation remain undefined. However, several factors can be excluded. First, hemodynamics: Previous studies have shown a significantly reverse correlation between LV end-diastolic pressure and tyrosine hydroxylase-immunosubtracted profiles (15). Neither nicorandil nor pinacidil exerted any hemodynamic effects at the dose used in this study. Pinacidil is an effective antihypertensive agent in treating patients with essential hypertension (44). The observation was not consistent with our stable hemodynamics throughout the study in pinacidil-treated rats. The discrepancy could be due to differences in doses, study population, and periods of treatment. Indeed, our results were consistent with the finding of Xu et al. (51), showing that nicorandil did not lower blood pressure even in a relatively high dose (6 mg·kg<sup>-1</sup>·day<sup>-1</sup>) in rats. Ito et al. (17) have shown that the neuroprotection effect of K<sub>ATP</sub> channel agonists was independent of changes in hemodynamics and appeared to be mediated by activating K<sub>ATP</sub> channels of cardiomyocytes. Second, differences in infarct sizes: The degree of sympathetic innervation was related to the infarct sizes (13). Successful fiber reinnervation appears dependent on re-populating sheaths with Schwann cells, which would be injured according to the sizes of infarction. The possibility was excluded in this study due to similar infarct sizes among the groups.

**Fig. 2.** A–G: immunohistochemical staining for GAP-43 from the remote regions (magnification, ×400). GAP-43-positive staining was markedly increased in groups treated with saline, Glib, Nic + Glib, and Pin + Glib (P < 0.001).
Exactly how the activation of K\textsubscript{ATP} channels leads to an attenuated sympathetic hyperinnervation cannot be determined from this study. Our results show that the activation of K\textsubscript{ATP} channels in the reinnervated regions caused a relatively greater reduction in NGF expression. The finding was consistent with the results of Tyagi and Jose (48), showing that the activation of K\textsubscript{ATP} channels attenuated the levels of NGF. K\textsubscript{ATP} channel agonists attenuated tissue ET-1 levels in this study. Recently, we have shown that the inhibition of the ET system by administering ET receptor blockers attenuated sympathetic hyperinnervation after infarction (23). ET-1 significantly augmented the activity of the NGF promoter mediated by the ETA receptor, and the deletion of the activator protein-1 element of the NGF promoter markedly decreased this augmentation (16). Thus our results may suggest that the downregulation of NGF expression by K\textsubscript{ATP} channel activation, probably through an ET-1 pathway, plays a role in attenuating sympathetic hyperinnervation after MI.

**Other mechanisms.** Although the present study suggests that the mechanisms of a K\textsubscript{ATP} channel agonist-induced attenuation of sympathetic hyperinnervation may be related to attenuated NGF expression, other potential mechanisms need to be studied. Glibenclamide inhibits the activity of endogenous ecto-5'-nucleotidase and decreases the adenosine concentrations in the interstitial space of the ventricular muscles (38). In contrast, K\textsubscript{ATP} channel agonists stimulate 5'-nucleotidase (47), which in turn resulted in increased adenosine concentrations. Increased interstitial adenosine levels have been shown to induce sympathetic apoptosis (49). Thus it is not surprising that the K\textsubscript{ATP} channel agonists attenuate sympathetic hyperinnervation, whereas glibenclamide abolished the protection.

![Fig. 3](image-url) Western blot analysis of nerve growth factor (NGF) (molecular mass, 13 kDa) in homogenates of the left ventricle from the remote zone. When compared with saline-treated rats, Nic- and Pin-treated rats had significantly lower NGF levels at the remote zone by quantitative analysis. The attenuated expression of ATP-sensitive potassium (K\textsubscript{ATP}) channel agonists-related NGF can be reversed to the levels, similar to the saline-treated infarcted rats after adding Glib. Relative abundance was obtained by normalizing the density of NGF protein against that of β-actin. Results are means ± SD of 3 independent experiments. *P < 0.05 compared with saline-, Glib-, Nic + Glib-, and Pin + Glib-treated groups.

![Fig. 4](image-url) Western blot analysis of NGF to further confirm the mitochondrial K\textsubscript{ATP} channel on NGF in homogenates of the left ventricle from the remote zone in a rat-isolated heart model. A significantly increased NGF is noted in the groups treated with a combination of K\textsubscript{ATP} channel agonists and 5-hydroxydecanoate (5-HD) compared with K\textsubscript{ATP} channel agonists alone. Densitometric quantification of NGF was expressed as the ratio of the density of β-actin. Each point is an average of 3 separate experiments. *P < 0.05 compared with vehicle-, 5-HD-, Nic + 5-HD-, and Pin + 5-HD-treated groups.

![Fig. 5](image-url) Left ventricular NGF mRNA levels of the sham-operated and the saline-, Nic-, Pin-, Glib-, Nic + Glib-, and Pin + Glib-treated infarcted rats. Each mRNA was corrected for an mRNA level of GAPDH. Bars represent means ± SD. *P < 0.05 compared with saline-, Glib-, Nic + Glib-, and Pin + Glib-treated groups.

![Fig. 6](image-url) Inducibility quotient of ventricular arrhythmias by programmed electrical stimulation 4 wk after myocardial infarction in an in vivo model. *P < 0.05 compared with infarcted groups treated with saline, Glib, Nic + Glib, and Pin + Glib.
Besides, we demonstrated that the activation of K\textsubscript{ATP} channels leads to attenuated tissue norepinephrine levels, probably through an ET-1-dependent pathway. The K\textsubscript{ATP} channel is a high-fidelity metabolic sensor that adjusts the membrane potential-dependent cell functions to match the metabolic state (36). Previous studies have demonstrated an energetic insufficiency in the remote noninfarcted myocardium, such as reductions of ATP and the phosphocreatine-to-ATP ratio (54). Adenosine rapidly accumulates in the interstitial space in response to metabolic distress (33). In parallel with adenosine accumulation, the breakdown of intracellular ATP triggers the opening of K\textsubscript{ATP} channels in ischemic myocardium (12). Because K\textsubscript{ATP} conductance is present in noradrenergic neurons (10), the possibility arises that the K\textsubscript{ATP} channel opening in response to ischemia influences norepinephrine release from the heart. Burgdorf et al. (5) have shown that the activation of K\textsubscript{ATP} channels attenuated norepinephrine release directly at the presynaptic nerve ending during coronary low-flow ischemia. Thus we cannot exclude the possibility that K\textsubscript{ATP} agonists may have decreased the apparent norepinephrine content by reversing the metabolic compromise, independent of the ET-1 effect.

Clinical implications. So far, no studies have directly addressed the question of whether or not the long-term treatment with K\textsubscript{ATP} channel agonist may influence the susceptibility to ventricular arrhythmias after MI. Our results show that an association between K\textsubscript{ATP} channel agonist administration and ventricular arrhythmias is anatomically and functionally linked. After an acute MI, patients remain at high risk for recurrent cardiovascular events and mortality (4). The attenuation of sympathetic hyperinnervation prevents fatal ventricular arrhythmias. Thus the K\textsubscript{ATP} channel agonists may have important biological effects that prevent the occurrence of postinfarcted arrhythmias. Our results explained, at least in part, the clinical findings of the Impact of Nicorandil in Angina (IONA) study group (45), showing that a treatment with nicorandil improves the outcome in terms of reducing the events related to acute coronary disease and the associated requirement for an admission to the hospital.

Study limitations. There are some limitations in the present study that have to be acknowledged. First, the procedure of inducing MI resulted in a variation in the size of infarcts, from the hearts with small MIs (infarct only on the apical LV free wall) to the hearts with larger MIs (infarct from apex to base of the LV free wall). Only rats with large infarcts (>30%) were examined in this study. It is possible that smaller MIs would yield a different profile of sympathetic innervation. Our finding cannot necessarily be extrapolated to animals with small to moderate infarction. Second, because the tissue norepinephrine levels were expressed with reference to gram protein, it may be doubtful whether a pathological modification of protein content per tissue volume in the remote regions might have contributed to the increase in norepinephrine tissue levels. We previously demonstrated a significant degree of LV hypertrophy after MI in the remote zone compared with that in sham-operated rats (25). Compensatory LV hypertrophy might decrease the apparent tissue norepinephrine content expressed per gram protein. Thus the increase in tissue norepinephrine content in the remote zone of infarcted rats should reflect the actual increase in regional norepinephrine levels. Finally, the administration of K\textsubscript{ATP} channel agonists not only attenuated sympathetic hyperinnervation but also prevented ventricular remodeling assessed by a decreased lung weight and right ventricular weight normalized to body weight, and reduced LVEDD and LVESD. K\textsubscript{ATP} channel agonists can attenuate ET-1 expression, which signaling pathway has been linked to not only attenuate sympathetic hyperinnervation but also improve ventricular remodeling, making it difficult to separate the two effects of ET-1-related action of K\textsubscript{ATP} channel agonists. The hypertrophic growth of the surviving myocytes may create a shift in the sympathovagal balance toward a sympathetic prevalence that leaves the myocardium in greater jeopardy for the development of life-threatening arrhythmias (22). One may imagine that the beneficial effects of K\textsubscript{ATP} channel agonists on arrhythmias are the result of their direct favorable ventricular remodeling. However, the improvement of an adverse ventricular remodeling after MI cannot necessarily be extrapolated to the antiarrhythmias. Previous studies have shown that the inducibility of ventricular arrhythmias can be reduced as a result of markedly different effects on ventricular remodeling, indicating that the relationship between ventricular remodeling and arrhythmias is more complex than previously thought (3). Further work is required to differentiate whether there is an effect of K\textsubscript{ATP} channel agonists on the nervous system or on the cardiac tissue directly with a secondary change in autonomic activity.

Conclusions. These data show that sympathetic hyperinnervation after infarction was attenuated by the activation of mitochondrial K\textsubscript{ATP} channels. These effects probably are functionally important because they are linked to the attenuated incidence of fatal arrhythmias. Further studies of the specific role of K\textsubscript{ATP} channels in the myocardium may contribute to the development of novel antiarrhythmic therapies.

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