Pentamidine-Induced Long QT Syndrome and Block of HERG Trafficking

1Yuri A Kuryshhev, 1Eckhard Ficker, 1Lu Wang, 2Peter Hawryluk, 1Adrienne T Dennis, 1,2Barbara A Wible, 1,2 Arthur M Brown, 3Jiesheng Kang, 3Xiao-Liang Chen, 3Kaoru Sawamura, 3William Reynolds and 3David Rampe

1Rammelkamp Center for Education and Research, MetroHealth Campus, Case Western Reserve University, Cleveland Ohio (YAK, EF, LW, ATD, BAW, AMB), 2ChanTest Inc, Cleveland, Ohio (PH, BAW, AMB) and 3Drug Safety Evaluation, Aventis Pharmaceuticals Inc, Bridgewater, NJ (JK, X-LC, KS, WR, DR)
Running title: Pentamidine-induced block of hERG trafficking

Corresponding authors:

Eckhard Ficker, Rammelkamp Center, MetroHealth Medical Center, 2500 MetroHealth Dr., Cleveland, OH 44109. Tel.: 216-778-8977; Fax: 216-778-8282
Email: eficker@metrohealth.org

Arthur M Brown, ChanTest Inc., 14656 Neo Parkway, Cleveland, OH 44128. Tel.: 216-332-1665; Fax: 216-332-1706
Email: abrown@chantest.com

Number of text pages: 25
Number of figures: 8
Number of references: 31
Number of words in the Abstract: 245
Number of words in the Introduction: 481
Number of words in the Discussion: 815

Abbreviations: APD, action potential duration, hERG, human ether a-go-go-related gene, $I_{Kr}$, rapidly activating delayed rectifier K current, pentamidine, 1,5-Bis(p-amidinophenoxy)pentane

Section assignment: Cardiovascular
Abstract

The diamidine pentamidine is used to treat leishmaniasis, trypanosomiasis and *Pneumocystis carinii* pneumonia. Treatment may be accompanied by prolongation of the QT interval of the electrocardiogram and torsades de pointes tachycardias. Up to now it has been thought that therapeutic compounds causing QT prolongation are associated with direct block of the cardiac potassium channel hERG, which encodes the α-subunit of cardiac I\(_{Kr}\) currents.

We show that pentamidine has no acute effects on currents produced by hERG, KvLQT1/mink, Kv4.3 or SCNA5. Cardiac calcium currents and the guinea pig cardiac action potential were also not affected. After overnight exposure, however, pentamidine reduced hERG currents and inhibited trafficking and maturation of hERG with IC\(_{50}\)s of 5-8 µM similar to therapeutic concentrations. Surface expression determined in a chemiluminescence assay was reduced on exposure to 10, 30 and 100 µM pentamidine by about 30, 40 and 70%, respectively. These effects were specific for hERG since expression of hKv1.5, KvLQT1/minK and Kv4.3 was not altered. In isolated guinea pig ventricular myocytes, 10 µM pentamidine prolonged action potential duration APD\(_{90}\) from 374.3 ± 57.1 to 893.9 ± 86.2 ms on overnight incubation. I\(_{Kr}\) tail current density was reduced from 0.61 ± 0.09 to 0.39 ± 0.04 pA/pF. We conclude that pentamidine prolongs the cardiac action potential by block of hERG trafficking and reduction of the number of functional hERG channels at the cell surface. We propose that pentamidine like arsenic trioxide produces QT prolongation and torsades de pointes in patients by inhibition of hERG trafficking.
Introduction

The antiprotozoal agent pentamidine isethionate is used in developing countries for the treatment of parasitic diseases such as trypanosomiasis and antimony-resistant visceral leishmaniasis (Burchmore et al., 2002; Nacher et al., 2001). In the US it is used in the treatment of Pneumocystis carinii pneumonia, a common opportunistic infection in patients who have contracted the human immunodeficiency virus or in patients immunosuppressed during chemotherapy (Sands, et al., 1985; Goa and Campoli-Richards, 1987). Therapy with pentamidine is often accompanied by prolongation of the QT interval on the electrocardiogram (ECG) and, in some instances, by torsades de pointes tachycardias (TdP) that can degenerate into ventricular fibrillation and cause sudden cardiac death (Wharton et al., 1987; Bibler et al., 1988; Girgis et al., 1997).

Prolongation of the QT interval and torsades de pointes are usually seen in patients with inherited (congenital) long QT syndrome (Keating and Sanguinetti, 2001) or in association with a wide variety of structurally diverse medications including antiarrhythmic, antihistamine, antibiotic and psychotropic compounds (Fermini and Fossa, 2003). Most drugs known to cause acquired long QT syndrome do so by direct blockade of the cardiac potassium channel hERG (Redfern et al., 2003, Pearlstein et al., 2003), which underlies the rapid component of the delayed rectifier potassium current I_{Kr} in human heart (Sanguinetti et al., 1995; Keating and Sanguinetti, 2001). While some of these drugs such as class III antiarrhythmics were designed to prolong cardiac repolarization with hERG as the intended target (Vaughn Williams et al., 1982), for the vast majority, block of hERG constitutes an unwanted adverse side effect. To determine drug-related cardiac toxicity HERG block is usually detected directly by patch clamp electrophysiology on the cloned hERG channel. Although hERG/I_{Kr} is most extensively studied,
other cardiac potassium currents e.g. the slow component of the delayed rectifier current $I_{Ks}$ (encoded by KvLQT1/minK), the ultra-rapidly activating delayed rectifier current $I_{Kur}$ (encoded by Kv1.5) or the transient outward current $I_{to}$ (encoded by Kv4.3) may provide additional plausible substrates for acquired long QT syndrome.

Recently, we have reported a completely different mechanism associated with acquired long QT syndrome and TdP. We have shown that arsenic trioxide ($\text{As}_2\text{O}_3$) used in the treatment of acute promyelocytic leukemia reduced hERG/I$_{Kr}$ currents not by direct block, but by inhibiting the processing of hERG protein in the endoplasmic reticulum (ER) thereby decreasing surface expression of hERG (Ficker et al., 2004). Another compound that reduces hERG currents by trafficking inhibition is geldanamycin, a benzoquinoid antibiotic that specifically inhibits function of the cytosolic chaperone Hsp90 (Ficker et al., 2003). Derivatives of geldanamycin are in clinical trials for the treatment of various forms of cancer with no reports of adverse cardiac events currently available. In the present report, we examine a novel compound class represented by the antiprotozoal agent pentamidine which has been associated clinically with QT prolongation and TdP and show that the aromatic diamidine pentamidine acts via inhibition of hERG channel trafficking.

Methods

**Cellular electrophysiology**-HEK293, L-cells or Chinese hamster ovary (CHO) cells stably expressing hERG, hKv1.5, KvLQT1/minK, or Kv4.3 potassium channels were studied using the whole cell configuration of the patch clamp technique. Patch pipettes were filled with (in mM): K-aspartate, 100, KCl, 20, MgCl$_2$, 2, CaCl$_2$, 1, EGTA, 10, HEPES 10 (pH7.2). The extracellular solution was (in mM): NaCl, 140, KCl, 5, MgCl$_2$, 1, CaCl$_2$, 1.8, HEPES 10,
glucose, 10 (pH 7.4). Stably transfected cells lines used in this study were regularly checked for responses to positive control compounds: cisapride was used for hERG; 4-aminopyridine (4-AP) for hKv1.5; chromanol 293B for KvLQT1/mink; flecainide for Kv4.3 and lidocaine for SCN5A expressing cells. In guinea pig ventricular myocytes nisoldipine was used to validate L-type calcium currents. To study delayed effects of pentamidine on heterologously expressed hERG, hKv1.5, KvLQT1/minK and Kv4.3 potassium currents, drug was added to stable cell lines for 16-20 hrs (overnight) prior to recording. Sodium currents were recorded in HEK293 cells stably expressing the human cardiac Na+ channel gene SCN5A using the following extracellular solution (in mM): NaCl, 40, NMDG, 55, CsCl, 20, KCl, 5.4, MgCl2, 2, CaCl2, 0.02, TEA Cl, 30, 4-AP, 5, HEPES, 10 (pH 7.4). The intracellular solution was (in mM): CsCl, 120, MgCl2, 2, CaCl2, 1, EGTA 11, HEPES 10, glucose 10, Mg-ATP, 1 (pH 7.2). Cardiac L-type calcium currents were recorded in freshly isolated guinea pig ventricular myocytes using the following extracellular solution (in mM): NaCl, 137, CsCl, 5.4, MgCl2, 1.8, CaCl2, 1.8, glucose, 10, HEPES, 10 (pH 7.4). The intracellular solution was (in mM): Cs MeSO4, 130, TEA Cl, 20, MgCl2, 1, EGTA 10, HEPES 10, Mg-ATP, 4, Tris-phosphocreatine, 14, Tris-GTP, 0.3, creatine phosphokinase 50U/ml (pH 7.2). Action potentials and cardiac I_{Kr}/hERG currents were recorded in ventricular guinea pig myocytes either freshly isolated or cultured overnight in M199 medium using the following intracellular solution (in mM): K-gluconate, 119, KCl, 15, MgCl2, 3.75, EGTA, 5, HEPES, 5, K-ATP, 4, phosphocreatine, 14, Tris-GTP, 0.3 and 50U/ml creatine phosphokinase (pH 7.2). The extracellular solution was (in mM): NaCl, 132, KCl, 4, MgCl2, 1.2, CaCl2, 1.8, HEPES 5 (pH 7.4). Measurements of cardiac I_{Kr} currents were performed in the presence of 1µM nisoldipine to block L-type Ca^{2+} currents. The specific blocker E4031 was used to pharmacologically isolate I_{Kr}. To analyze current densities, membrane capacitances were
measured using the analogue compensation circuit of an Axon 200B patch clamp amplifier (Axon Instruments, Foster City, CA). pCLAMP software (Axon Instruments) was used to generate voltage-clamp protocols and for data acquisition. All recordings were performed at room temperature (20-22°C). Data are expressed as means ± SEM.

Western blot analysis-The HEK/hERG cell line, the L/hKv1.5 cell line and antibodies used in the present study have been described previously (Ficker et al., 2003)). Briefly, stably transfected cells expressing either hERG or hKv1.5 were solubilized for 1h at 4°C in a lysis buffer containing 1% Triton X-100 and protease inhibitors (Complete, Roche Biochemicals, Indianapolis, IN). Protein concentrations were determined by the BCA method (Pierce, Rockford, IL). Proteins were separated on SDS polyacrylamide gels, transferred to polyvinylidene difluoride membranes and developed using appropriate antibodies and ECL Plus (Amersham Biosciences, Piscataway, NJ). For quantitative analysis, chemiluminescence signals were captured directly on a Storm Phosphoimager (Amersham Biosciences). Normalized image densities are expressed as means ± SEM.

Chemiluminescence detection of cell surface hERG protein-A hemagglutinin (HA) tag was inserted into the extracellular loop of hERG between transmembrane domains S1 and S2 (Ficker et al., 2003). Stably transfected HEK/hERG WT HA\textsubscript{ex} cells were plated at 40,000 cells/well in a 96-well plate. After overnight incubation with pentamidine, cells were fixed with ice-cold 4% paraformaldehyde, blocked by incubation with 1% goat serum and incubated for one hour with rat anti-HA antibody (Roche Diagnostics). After washing, HRP-conjugated goat anti-rat IgG (Jackson Labs, West Grove, PA) and the dsDNA stain SYBR Green (Molecular Probes, Eugene, OR) were added for one hour (Myers, 1998; Margeta-Mitrovic et al., 2000). SYBR Green fluorescence was measured to determine cell numbers. Chemiluminescent signals were
developed using SuperSignal (Pierce) and captured in a luminometer. If necessary luminescence signals in pentamidine treated wells were corrected for cell loss as measured by SYBR Green fluorescence with the data presented as normalized surface expression relative to control (means ± SEM). For correction of cell loss a standard curve of SYBR Green fluorescence was generated using four different amounts of cells per well (10, 20, 30 or 40*10^3, n=3).

Results

**Pentamidine does not directly block hERG currents.** Direct block of the cardiac potassium channel hERG is the most common mechanism underlying acquired long QT syndrome. Therefore we first studied the effects of acute application of extracellular pentamidine on hERG currents activated with depolarizing pulses to +20mV from a holding potential of –80mV. Pentamidine block was evaluated by analyzing peak tail current amplitudes on return to –40mV (Fig. 1A). Pentamidine demonstrated no significant inhibition of hERG currents with ascending concentrations ranging from 0.3 to 10 µM (Fig 1B). With 10 µM pentamidine in the extracellular perfusate we observed a maximum inhibition of 13 ± 3%, which was similar to current run-down observed over the same time period (12 ± 5%, n=6). To exclude the possibility that access of the dicationic pentamidine to an intracellular blocking site was hindered, we performed experiments with 10µM pentamidine added to the intracellular pipette solution. With intracellular application of pentamidine, hERG currents showed a small time-dependent run-down averaging 14 ± 5% when measured 10min after initiation of whole cell recordings (n=4). This value was similar to that observed for vehicle-treated (0.1% DMSO) control cells (15 ± 5% reduction after 10min, n=3).
Since block of other repolarizing cardiac potassium currents such as Kv4.3 or KvLQT1/minK may also prolong the cardiac action potential (Nerbonne, 2000), we tested whether those currents were affected by pentamidine. Both KvLQT1/minK and Kv4.3 channels were activated by depolarizing step pulses to +20mV from a holding potential of –80mV. Currents were continuously recorded while 10µM pentamidine was applied for 10min with the extracellular bath solution. Neither KvLQT1/minK nor Kv4.3 currents were blocked at this concentration (p>0.05, paired t-test; n=5-6; Fig 2A and B). In addition, we studied a possible contribution of cardiac inward currents to the proarrhythmic effects exerted by pentamidine. We elicited sodium currents in HEK293 cells stably expressing the cardiac sodium channel gene SCN5A using depolarizing pulses to –20mV from a holding potential of –110mV while perfusing 10µM pentamidine for 10min. At this concentration neither peak currents nor current kinetics were affected (p>0.05, paired t-test, n=6, Fig 2C). Since cardiac calcium currents are composed of multiple subunits and are not easily reconstituted in heterologous expression systems, we used freshly isolated guinea pig ventricular myocytes to evaluate pentamidine effects. Cardiac calcium currents were activated from a holding potential of –40mV with depolarizing step pulses to 0mV. In these experiments we detected a small reduction in peak current amplitudes of 4.4 ± 3.7% (n=3) while steady state currents remained stable in the presence of 10µM pentamidine (Fig 2D).

**Prolonged exposure to pentamidine inhibits maturation of hERG.** Since pentamidine did not directly block cardiac membrane currents, we explored whether prolonged exposure to pentamidine might interfere with hERG processing as reported for the anti-neoplastic drugs geldanamycin (Ficker et al., 2003) and As2O3 (Ficker et al., 2004). To this end, we exposed stably transfected HEK/hERG cells overnight (16-20hrs) to increasing concentrations of
pentamidine. We found that hERG currents were reduced in a dose-dependent manner with an IC$_{50}$ of 5.1 µM as determined by analyzing changes in tail current amplitudes (n=8-10, Fig 3A and B). To validate our electrophysiological analysis we performed Western blots of hERG protein isolated under control conditions and after overnight exposure to increasing concentrations of pentamidine. HERG channels are synthesized as a core-glycosylated, immature ER form of about 135kDa and as a mature, fully-glycosylated cell surface form of about 160kDa. Incubation with pentamidine produced a dose-dependent decrease in the amount of mature fully-glycosylated hERG protein (Fig 4A). Expression of the mature, cell surface form of hERG was suppressed with an IC$_{50}$ of 7.8µM (n=3; Fig 4B), which is similar to the IC$_{50}$ of 5.1µM determined in electrophysiological experiments on chronic exposure to pentamidine. To quantify pentamidine-induced changes in surface expression of hERG protein more directly, we used a chemiluminescence assay. This assay was performed with HEK293 cells stably expressing a modified hERG protein with an extracellular hemagglutinin (HA) epitope tag inserted in the extracellular S1-S2 linker (Ficker et al., 2003). HEK/hERG-HA$_{ex}$ cells were treated overnight with 10, 30µM or 100µM pentamidine and surface expression of hERG-HA$_{ex}$ was reduced by 30, 40 and 70%, respectively (Fig 4C).

**Specificity of pentamidine effects on hERG trafficking.** Since processing of hERG may be handled by proteins shared between different ion channels, the question arises whether the observed pentamidine effect is specific for hERG or whether other cardiac potassium channel are affected in a similar manner. To test for specificity, we exposed L-cells stably expressing the ultrarapid delayed rectifier hKv1.5 overnight (16-20hrs) to increasing concentrations of pentamidine and performed Western blots. For all concentrations tested we detected hKv1.5 protein as a core-glycosylated, immature ER form of about 68kDa and as a mature, fully-
glycosylated cell surface form of about 75kDa (Fig 5A). Incubation with pentamidine did not alter the expression pattern of hKv1.5 (Fig 5B). In line with our biochemical data, we found that hKv1.5 current densities were not significantly altered upon overnight incubation with 10μM pentamidine (Fig 4C). We measured $636.6 \pm 60\text{pA/pF}$ under control conditions and $625.6 \pm 135.5\text{pA/pF}$ after overnight exposure to pentamidine ($p>0.05$, Student’s t-test, $n=6$). We also recorded currents from HEK 293 cells stably expressing KvLQT1/minK and Kv4.3 channels under control conditions and after overnight exposure to pentamidine (Fig 6Aa, 6Ba) and found for both channels that current densities were not altered ($p>0.05$, Student’s t-test). For KvLQT1/minK we measured current densities of $40.5 \pm 8.7\text{pA/pF}$ ($n=6$) under control conditions and of $48.1 \pm 13.2\text{pA/pF}$ ($n=8$) after overnight exposure to 10 μM pentamidine (Fig 6Ab). In Kv4.3 expressing cells we measured $240 \pm 38.5\text{pA/pF}$ ($n=16$) under control conditions and $195.7 \pm 88.3\text{pA/pF}$ ($n=10$) in the presence of 10 μM pentamidine (Fig 6Bb).

Prolonged exposure to pentamidine prolongs the cardiac action potential and reduces $I_{Kr}$ in guinea pig ventricular myocytes. To test whether our results obtained in heterologous expression systems can also be applied to cardiomyocytes, we studied the effects of pentamidine on the cardiac action potential. Acute application of 10 μM pentamidine failed to alter action potentials measured in freshly isolated guinea pig ventricular myocytes (Fig 7). In these experiments APD$_{90}$ was $535 \pm 32\text{ms}$ under control conditions (0min) and $522 \pm 31\text{ms}$ after extracellular perfusion of 10 μM pentamidine. Action potentials were further studied by culturing myocytes overnight in the absence or presence of 10 μM pentamidine. We found that 10 μM pentamidine prolonged APD$_{90}$ significantly from $374.3 \pm 57.1$ to $893.9 \pm 86.2\text{ms}$ ($p<0.05$; Student’s t-test, $n=10-11$, Fig 8A and B). This indicated that chronic drug exposure
induces changes compatible with clinically observed QT prolongation and TdP. Since our experiments in heterologous expression systems pointed towards a reduction of the native $I_{Kr}/hERG$ current as a possible cause for the observed action potential prolongation, we determined $I_{Kr}$ current densities in voltage clamp experiments performed in guinea pig ventricular myocytes. $I_{Kr}$ currents were elicited in myocytes cultured overnight using a ramp protocol and isolated as E4031 sensitive tail current component upon return to -40mV (Fig 8C). In these experiments chronic exposure to 10 µM pentamidine significantly reduced $I_{Kr}$ tail current density by about 35% from $0.61 \pm 0.09$ to $0.39 \pm 0.04$ pA/pF (p<0.05, Student’s t-test, n=6-7, Fig 8D).

Discussion

This report is the first to describe the effects of the antiprotozoal drug pentamidine on cardiac ion channels. Pentamidine is known to produce QT prolongation and TdP in clinical use. Most drugs that produce adverse cardiac events do so via a direct block of the cardiac potassium channel hERG that is easily detected with patch clamp techniques (Redfern et al., 2003, Pearlstein et al., 2003). We were, therefore, surprised to find that acute administration of pentamidine had no immediate effect on hERG currents. Similarly, acute administration of pentamidine failed to affect four different, major cardiac ion channels including KvLQT1/minK, Kv4.3, SCN5A Na+ channels and L-type calcium channels. By contrast, prolonged treatment of hERG-expressing cells resulted in a dose-dependent reduction of hERG currents with an IC$_{50}$ of about 5 µM. The effect was specific since current densities of heterologously expressed hKv1.5, KvLQT1/minK and Kv4.3 channels were not altered. Western blots revealed that the reduction in hERG current density was associated with a decrease in the fully glycosylated cell surface
form of the hERG protein. Accordingly, $I_{Kr}$ density was reduced and the cardiac action potential was prolonged in cardiomyocytes. Based on these data, we propose that QT prolongation and ventricular tachycardias observed in patients treated with pentamidine are not caused by direct block of hERG or other cardiac ion channels, but rather are the result of a reduction in $I_{Kr}$ current density due to an acquired trafficking block of hERG/$I_{Kr}$ channels.

Pentamidine has been widely used in the treatment of *Pneumocystis carinii* pneumonia in patients infected with human immunodeficiency virus (Goa and Campoli-Richards, 1987). The drug is also used in developing countries to treat a variety of parasitic diseases including trypanosomiasis and leishmaniasis (Burchmore et al., 2002; Nacher et al., 2001). Typically the drug is administered via daily intramuscular injection or slow intravenous infusion at a dose of 4 mg/kg of body weight. These doses result in peak serum levels that range from about 1-5 µM (Sands et al., 1985, Conte et al., 1986; Lidman et al., 1994), similar to the concentrations required for inhibition of hERG trafficking in vitro. Prolongation of the QT interval on the electrocardiogram and the development of TdP tachycardias are well-documented adverse events associated with pentamidine treatment (Wharton et al., 1987; Bibler et al., 1988; Girgis et al., 1997; Kroll and Gettes, 2002). However, QT prolongation is not immediately evident in these patients and generally takes several days to develop (Stein et al., 1991; Eisenhauer et al., 1994; Otsuka et al., 1997). We believe that this slow time course is consistent with a pentamidine-induced decrease in the expression of functional hERG channels in the heart, rather than a direct blocking effect of the drug, since QT prolongation by direct hERG channel blockers such as dofetilide are evident immediately upon administration (Lande et al., 1998).

At present it is not clear how pentamidine interferes with hERG processing and maturation. In microbial cells pentamidine has been reported to inhibit topoisomerase activity.
and decrease intracellular ATP content while in mammalian cells it has been shown to inhibit several tyrosine phosphatases (Reddy et al., 1999; Pathak et al., 2002). Other antimicrobial agents such as quinolone antibiotics, which also function as topoisomerase inhibitors in microbial systems, have been shown to directly block hERG currents (Cirioni et al., 1997; Larsen et al., 2003; Anderson et al., 2001). Similarly, the antineoplastic topoisomerase inhibitor amsacrine, which has been associated with adverse cardiac events, reduces hERG currents by direct block (Thomas et al., 2004). Both quinolone antibiotics (sparfloxacin, ofloxacin and ciprafloxacin) and amsacrine do not affect hERG trafficking (unpublished data). Given these observations we speculate that the pentamidine-induced trafficking block of hERG is not due to inhibition of topoisomerasers but rather to inhibition of a protein or proteins required for successful maturation of hERG potassium channels. Further studies will be necessary to elucidate the biochemical mechanism(s) responsible for pentamidine’s effects on hERG protein trafficking.

In summary, the present study demonstrates that the proarrhythmic effects of pentamidine are not due to a direct blockade of hERG currents, but are consistent with inhibition of hERG trafficking and a reduction in the number of functional hERG channels in the heart. Thus, pentamidine joins arsenic trioxide, another non anti-arrhythmic compound that is proarrhythmic as a result of an acquired hERG trafficking defect. Geldanamycin, an anti-neoplastic Hsp90 inhibitor currently in clinical trials, may be proarrhythmic for similar reasons (Ficker et al., 2004; Ficker et al., 2003). In this regard chemotherapeutic agents that disrupt protein synthesis as their intended mechanism of action may be of special concern. Likewise, drugs that produce QT prolongation in the clinic only after prolonged treatment may suggest similar effects on the processing of ion channel proteins. At present, the detection of cardiac risk as a result of
acquired trafficking defects has not been considered and the hERG assay presently recommended by the International Conference of Harmonization\textsuperscript{1} will fail to identify trafficking inhibitors.
References


Footnotes

1 ICH S7B-The nonclinical evaluation of the potential for delayed ventricular repolarization (QT interval prolongation) by human pharmaceuticals. European Medicines Agency EMEA. CHMP/ICH/423/02 (June 2004).

This work was supported by National Institutes of Health Grants HL 71789 and CA106028 (to E.F) and HL36930, and HL55404 (to AMB).
Legends for figures

Figure 1. Effects of pentamidine on hERG currents. A, whole-cell hERG currents were elicited by 2-s depolarizing pulses to +20 mV from a holding potential of –80 mV at 40-s intervals. The membrane potential was then returned to –40 mV to generate large outward tail currents. The effects of 3 and 10 µM pentamidine are shown. B, dose-response relationship of pentamidine block. Pentamidine produced 13 ± 3% inhibition of hERG currents at the highest concentration tested (10 µM, n=6), a value similar to the current run-down observed over the same time period (approximately 10 minutes).

Figure 2. Pentamidine has no effect on other major cardiac membrane currents.
A, Heterologously expressed KvLQT1/minK currents recorded under control conditions and after extracellular application of 10 µM pentamidine. Pentamidine had no effect on KvLQT1/minK (n=5). B, Effects of pentamidine on heterologously expressed Kv4.3 currents and C, cardiac Na⁺ currents (expressed from SCN5A gene) recorded under control conditions and in the presence of 10 µM pentamidine. As in the case of KvLQT1/minK, 10 µM pentamidine has no effect on either Kv4.3 or Na⁺ currents (n=6). D, effect of 10 µM pentamidine on native L-type calcium currents recorded in guinea pig ventricular myocytes. Exposure to 10 µM pentamidine failed to significantly reduce cardiac Ca²⁺ currents (n=3). Voltage protocols for each experiment are shown above current traces.

Figure 3. Prolonged exposure to pentamidine suppresses hERG currents heterologously expressed in HEK293 cells. A, representative hERG current recordings obtained under control
conditions (left panel) and from an HEK/hERG cell incubated overnight with 10 µM pentamidine (right panel). Currents were elicited from a holding potential of -80 mV with pulses from -60 to +60 mV in 20 mV increments. Tail currents were recorded on return to -50 mV. B, concentration-dependence of pentamidine effect (24 h treatment). IC₅₀ is 5.1 µM (n=8-10).

**Figure 4. Pentamidine inhibits maturation of hERG.** A, Western blot showing effects of overnight treatment with pentamidine on hERG channel protein stably expressed in HEK293 cells. On Western blots pentamidine reduces fully glycosylated, mature 160 kDa hERG in a concentration-dependent manner. Treatment with 10 µM of As₂O₃ was used as positive control. B, concentration-dependent reduction of fully glycosylated 160kDa hERG after overnight exposure to pentamidine. Image densities on Western blots were quantified using Storm PhosphorImager and normalized to control. IC₅₀ is 7.8 µM (n=3). C, overnight treatment with pentamidine reduces in a concentration-dependent manner surface expression of HAex-tagged hERG protein stably expressed in HEK293 cells as determined by chemiluminesence measurements. Surface expression levels were normalized relative to control.

**Figure 5. Pentamidine does not alter the expression pattern of hKv1.5.** A, Western blot showing steady-state levels of hKv1.5 protein stably expressed in L-cells after prolonged exposure to increasing concentrations of pentamidine. HKv1.5 is expressed as a fully-glycosylated protein of 75 kDa and as a core-glycosylated protein of 68 kDa. B, image densities of fully glycosylated and core-glycosylated hKv1.5 protein were quantified as a function of pentamidine concentrations using a PhosphorImager. All image densities were normalized to the
fully-glycosylated 75 kDa protein form measured under control conditions (n=3). \( C \), hKv1.5 current densities measured after overnight culture under control conditions and in the presence of 10\( \mu \)M pentamidine (n=6). Current densities are presented in statistical box charts and were not significantly different (Student’s T test). In box charts asterisks represent outliers, whiskers determine the 5\(^{th}\) and 95\(^{th}\) percentiles, boxes determine the 25\(^{th}\) and 75\(^{th}\) percentiles and means are represented by square symbols.

**Figure 6.** KvLQT1/minK and Kv4.3 channels are not sensitive to overnight treatment with 10 \( \mu \)M pentamidine. \( A \), KvLQT1/minK channels stably expressed in HEK293 cells. \( Aa \), representative current recordings obtained from control (left) and pentamidine treated (right) cell. Currents were elicited from a holding potential of -80 mV with 2 s pulses from -60 to +20 mV in 20 mV increments. Tail currents were recorded on return to -50 mV. \( Ab \), current density measured in cells cultured overnight under control conditions and in the presence of 10 \( \mu \)M pentamidine. Current densities were determined from current amplitudes at +20 mV and normalized to cell capacitance. Data are presented in statistical box charts as described in the legend to Figure 5. \( B \), Kv4.3 channels stably expressed in HEK293 cells. \( Ba \), representative current recordings obtained from control (left) and pentamidine treated (right) cells. Currents were elicited from a holding potential of -80 mV with depolarizing 400ms voltage steps from -60 to +20 mV in increments of 20 mV. \( Bb \), Current densities were measured in the absence and presence of 10\( \mu \)M pentamidine as peak currents at 0 mV and normalized to cell capacitance. Data are presented in statistical box charts.
Figure 7. Acute application of pentamidine does not prolong cardiac action potentials.

Cardiac action potentials elicited in a freshly isolated ventricular myocyte immediately after establishing whole-cell configuration (0min) and 5min after start of extracellular perfusion with 10μM pentamidine. Membrane potential was –80mV.

Figure 8. Prolonged exposure to pentamidine prolongs cardiac action potentials and reduces I_{Kr} in cultured guinea pig ventricular myocytes. A, representative cardiac action potentials recorded from ventricular myocytes cultured overnight (24hr) under control conditions (left panel) and after incubation with 10μM pentamidine (right panel). B, Action potential duration (APD_{90}) measured in control and pentamidine treated (10 μM; 24 hr) cardiomyocytes. C, isolation of E4031-sensitive I_{Kr} current in a ventricular myocyte cultured overnight. Current traces were elicited with a 1sec voltage ramp from –80 to +80mV. Holding potential was –80mV. I_{Kr} currents were isolated as E4031-sensitive tail current component on return to –40mV. E4031-sensitive subtraction currents are shown in right part of panel for a control myocyte and for a myocyte cultured overnight in the presence of 10μM pentamidine. Dashed lines indicate zero current levels. D, I_{Kr} current densities quantified in control and pentamidine (10μM, 24hr) treated myocytes (n=6-7). * indicates significant difference at p<0.05 (Student’s t-test).
Figure 1

A

Current (pA)

Time (ms)

Control

3 µM Pentamidine

10 µM Pentamidine

B

HERG current
(Fraction of control)

[ Pentamidine ], logM

0

1.0

0

2000

3000

4000

-1000

0

20 mV

-40 mV

-80 mV

-80 mV

-40 mV

-80 mV

-80 mV
Figure 2

A. KvLQT1/minK

B. Kv4.3

C. Na\(^+\) Channel

D. Ca\(^{2+}\) Current

This article has not been copyedited and formatted. The final version may differ from this version.
Figure 3

A

control (24hr) 10µM pentamidine (24hr)

B

Normalized currents

Normalized currents

0.0 0.2 0.4 0.6 0.8 1.0

0.1 1 10 100 µM
Figure 4

A

B

C

Normalized Image Densities

Normalized Surface Expression

0.0 0.2 0.4 0.6 0.8 1.0

0.1 1 10 100 µM

0.1µM 1.0µM 10µM 30µM 100µM

con

Normalized Surface Expression

con 1 10 30 100 µM

0.0 0.2 0.4 0.6 0.8 1.0

The diagram shows the effect of pentamidine on image density and surface expression over different concentrations of As₂O₃.
Figure 5

A

B

C

pentamidine (µM)

Kv1.5

1

10

30

100

75

68

normalized image density

Kv1.5, fg/cg

con

1 µM

10 µM

30 µM

100 µM

1.2

1.0

0.8

0.6

0.4

0.2

0.0

1200

800

400

0

control

10 µM pentamidine

Kv1.5 current density (+20 mV, pA/pF)

(6)
A. KvLQT1/minK

B. Kv4.3

Figure 6
Figure 8

A. Control/24 h vs. Pentamidine.

B. APD$_{90}$ (ms) with 10 µM Pentamidine compared to control.

C. Voltage-gated potassium current density (pA/pF) with E4031.

D. I$_{Kr}$ density (pA/pF) with 10 µM Pentamidine compared to control.