hERG Potassium Channel Blockade by the HCN Channel Inhibitor Ivabradine

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Background—Ivabradine is a specific bradycardic agent used in coronary artery disease and heart failure, lowering heart rate through inhibition of sinoatrial nodal hCN channels. This study investigated the propensity of ivabradine to interact with KCNHI-encoded human Ether-à-go-go–Related Gene (hERG) potassium channels, which strongly influence ventricular repolarization and susceptibility to torsades de pointes arrhythmia.

Methods and Results—Patch clamp recordings of hERG current (IhERG) were made from hERG expressing cells at 37°C. IhERG was inhibited with an IC50 of 2.07 μmol/L for the hERG 1a isoform and 3.31 μmol/L for coexpressed hERG 1a/1b. The voltage and time-dependent characteristics of IhERG block were consistent with preferential gated-state-dependent channel block. Inhibition was partially attenuated by the N588K inactivation-mutant and the S624A pore-helix mutant and was strongly reduced by the Y652A and F656A S6 helix mutants. In docking simulations to a MthK-based homology model of hERG, the 2 aromatic rings of the drug could form multiple π-π interactions with the aromatic side chains of both Y652 and F656. In monophasic action potential (MAP) recordings from guinea-pig Langendorff-perfused hearts, ivabradine delayed ventricular repolarization and produced a steepening of the MAPD90 restitution curve.

Conclusions—Ivabradine prolongs ventricular repolarization and alters electrical restitution properties at concentrations relevant to the upper therapeutic range. In absolute terms ivabradine does not discriminate between hERG and HCN channels: it inhibits IhERG with similar potency to that reported for native If and HCN channels, with S6 binding determinants resembling those observed for HCN4. These findings may have important implications both clinically and for future bradycardic drug design. (J Am Heart Assoc. 2015;4:e001813 doi: 10.1161/JAHA.115.001813)

Key Words: bradycardic agent • HCN • HCN4 • hERG • ivabradine • QT interval • repolarization

Ivabradine is a specific bradycardic agent used to reduce heart rate in the treatment of coronary artery disease and heart failure.1,2 Heart rate is a determinant of cardiac metabolic demand, and elevated rate against a background of coronary artery disease can induce ischemia in affected individuals.2 Lowering heart rate in this setting increases diastolic time, reducing oxygen demand and wall stress.2 β-Adrenoceptor inhibitors and calcium channel blockers can reduce rate effectively, but can also be associated with hypotensive and negative inotropic side-effects.2,3 In contrast, ivabradine reduces the diastolic depolarization rate of sinoatrial node pacemaker cells through the inhibition of Hyperpolarization-activated cyclic-nucleotide gated (HCN)-channel mediated “funny” current, If, which results in bradycardia without a concomitant negative inotropic effect.1–5

Ivabradine has generally been considered to exhibit a good overall safety profile without significant effect on heart rate corrected QT interval (QTc).3,6 Accordingly, ivabradine has been considered to have no “direct” propensity to produce torsades de pointes (TdP) arrhythmia,3 though as QT interval varies with rate it is recommended that co-administration of this bradycardic agent with known QT-prolonging drugs should be avoided.3 However, some concerns regarding cardiac safety of ivabradine have recently been raised. In the
SIGNIFY trial, which focused on patients with stable coronary heart disease without clinical heart failure, ivabradine was associated with an increase in the combined end point of the trial, which included death from all cardiovascular causes and myocardial infarctions that were nonfatal, in patients with limiting symptoms of angina as a result of physical activity. Also, a recently published meta-analysis of 11 clinical trials has concluded that ivabradine treatment is associated with a 15% increase in relative risk of atrial fibrillation, although the underlying mechanism for this is not clear. Additionally, in April 2014, ivabradine was added to the list of “drugs with a conditional risk” of TdP in the “CredibleMeds” database of QT interval–prolonging drugs, with the update stating “There is substantial evidence that ivabradine is associated with TdP when taken with other medicines that prolong the QT interval, diuretics or drugs that block the metabolic breakdown of ivabradine, or electrolyte abnormalities (low potassium or low magnesium), which may be induced by co-administration of diuretics.”

Virtually all drugs associated with QTc interval prolongation and TdP share the ability to inhibit the cardiac rapid delayed rectifier potassium current, IKr, and its recombinant equivalent “HERG” (the protein product of human Ether-à-go-go-Related Gene; alternative nomenclature KCNH2). Ivabradine (3 μmol/L) was reported to have little effect on delayed rectifier K+ current from rabbit sinoatrial node myocytes. However, other in vitro data have suggested a propensity for ivabradine to delay ventricular repolarization. To our knowledge, there is no published study of whether or not the drug interacts with hERG potassium channels, and the present investigation was conducted to address this issue. The resulting data demonstrate that ivabradine both inhibits hERG with a potency similar to that reported previously for native I, and cloned HCN channels and, furthermore, at therapeutically relevant levels can produce a delay in ventricular repolarization and changes electrical restitution properties in intact perfused hearts.

Materials and Methods

Whole Heart Studies

Adult male Dunkin Hartley guinea pigs (n=11, 420 to 520 g) were used following ethical approval and in accordance with the UK Animal Scientific Procedure Act (ASPA) 1986, the US National Institute of Health (NIH Publication No. 85-23, revised 1985) guide for the care and use of laboratory animals, and the European Union directive on the protection of animals for scientific research (2010/63/EU).

Wild-Type and Mutant hERG Channel Constructs

The Human Embryonic Kidney (HEK 293) cell line stably expressing wild-type (WT) hERG channels was kindly donated by Prof Craig January. The hERG 1b construct in pcDNA3.1 was donated by Prof Gail Robertson. HEK cells stably expressing the hERG S6 mutant Y652A and transfection with and use of the inactivation mutant N588K and the S6 mutants S624A and F656A were as described previously.

Mammalian Cell-Line Maintenance and Transfection

HEK 293 cells stably or transiently expressing hERG constructs were maintained as previously described. Cells were plated on small sterilized glass shards in 40-mm Petri dishes after at least 6 hours of incubation at 37°C (5% CO2). At least 48 hours after plating, cells were transfected with Lipofectamine™ LTX (Invitrogen) following the manufacturer’s instructions. The amount of transfected hERG construct DNA varied between 0.2 and 1.0 μg, depending on the level of protein expression and current conductance of each particular hERG channel construct. In the case of hERG 1a/1b, 0.25 μg of hERG 1a was co-transfected with the same amount of hERG 1b as previously described. Between 0.5 and 1.0 μg of CD8 was co-transfected as a transfection marker; in order to identify successfully transfected cells, Dynabeads® (Invitrogen) were used. Electrophysiological recording was conducted after at least 24 hours of incubation at 37°C (5% CO2) to allow the cells to fully recover and to allow sufficient time for hERG construct expression.

Patch Clamp Electrophysiology

For electrophysiological recording of hERG current (IhERG), glass shards containing plated cells were placed in a small recording chamber mounted on an inverted microscope (Nikon Diaphot, USA) and continuously superfused with a preheated (37°C) standard Tyrode’s solution containing (in mmol/L): 140 NaCl, 4 KCl, 2.5 CaCl2, 1 MgCl2, 10 glucose, and 5 HEPES (titrated to pH 7.4 with NaOH). Patch-pipettes (Schott #8250 glass; A-M Systems Inc, USA) were pulled (Narishige, PP 830) and polished (Narishige, MF 83) to obtain a final resistance between 2 and 4 MΩ. The intracellular solution used to fill the patch-pipettes contained (in mmol/L): 130 KCl, 1 MgCl2, 5 EGTA, 5 MgATP, and 10 HEPES (titrated to pH 7.2 with KOH). All hERG currents were recorded with an Axopatch 200B amplifier (Axon Instruments, now Molecular Devices) and a CV-4/100 or CV203BU head-stage. Pipette resistance compensation was between 70% and 80%. Data acquisition was performed through a Digidata 1320.
(Axon Instruments, now Molecular Devices). Data digitization rates were 10 to 25 kHz during all protocols and an appropriate bandwidth of 2 to 10 kHz was set on the amplifier.

**Langendorff Preparation**

Animals were cycled by cervical dislocation and the heart was immersion in cold Tyrode solution with 1000 IU of heparin. The ascending aorta was cannulated with hearts retrogradely perfused in Langendorff mode (20 mL/min) via a Gilson minipulse 3 peristaltic pump (Anachem, Luton, UK). Tyrode solution contained (in mmol/L): Na+ 138.0; K+ 4.0; Ca2+ 1.8; Mg2+ 1.0; HCO3− 24; H2PO4− 0.4; Cl− 124; and glucose 11 (mmol/L), maintained at 37°C and at a pH of 7.4 by constant bubbling with 95% O2/5% CO2. A 2-mm-diameter polypropylene catheter (Portex, Kent, UK) was inserted at the apex of the left ventricle for thebesian venous effluent drainage. Hearts were instrumented to record left ventricular pressure, coronary perfusion pressure, and monophasic action potentials (MAP) at the left ventricle apex and base with MAP contact electrodes (73-0150, Harvard Apparatus, Kent, UK) using a custom made DC-coupled high-input impedance differential amplifier (Joint Biomedical Workshop, University of Leicester, UK). The effect of ivabradine was investigated at 0.1, 0.2, 0.3, 0.4, and 0.5 μmol/L in incremental concentrations, and by measuring MAP duration during constant ventricular pacing and electrical restitution (described in detail in Data S1).

**Docking of Ivabradine to a hERG Homology Model**

The docking of ivabradine to WT hERG was tested by using a homology model of the hERG channel pore region (pore helix, selectivity filter, and S6 helices) in the open configuration based on the crystal structure of MthK channel,22 as previously conducted in our laboratory.16,19,23 Further details of docking simulation methods are given in Data S1.

**Data Analysis and Statistics**

Details of data analysis including equations used for data fits are given in the Data S1. Statistical analysis and data distribution were tested using Graphpad Prism versions 5.03, 6.0c, and the Kolmogorov–Smirnov normality test. Statistical comparisons were made using paired or unpaired 2-tailed t tests, Wilcoxon matched-pairs signed-rank test, and 1-way (repeated measures, where indicated) or 2-way ANOVA, as appropriate. Details of the statistical test used to evaluate significance for results of particular experiments are given alongside the “P” values in the “Results” text or in the relevant Table or Figure legend.

**Results**

**Ivabradine Inhibits IhERG**

In order to determine the sensitivity of IhERG to ivabradine, IhERG “tail” amplitude was monitored during repetitive application of the protocol shown in the lower panel of Figure 1A.16,24 Figure 1A shows currents in control and in the presence of 3 μmol/L ivabradine, demonstrating a >50% reduction in IhERG tail amplitude and also a marked reduction in pulse current. Inhibition of IhERG by this concentration of ivabradine developed with a time-constant of 20.7±2.6 seconds (n=5); at a higher concentration of 30 μmol/L IhERG inhibition developed more rapidly with a time-constant of 6.5±0.2 seconds (see Figure S1). Reversibility of block was investigated for 30 μmol/L ivabradine (the highest drug concentration tested); on washout of the drug IhERG recovered to 80.7±3.3% of the control value (see Figure S1). In Figure 1B, mean IhERG tail data for inhibition by 5 ivabradine concentrations are plotted and fitted with a Hill function (equation 2, Data S1), yielding an IC50 value of 2.07 μmol/L (CI: 1.80 to 2.37) and Hill slope (nH) of 0.80 (CI: 0.72 to 0.89). Both fast and slow time-constants of IhERG deactivation (measured on repolarization to −40 mV) were slower in the presence of 3 μmol/L ivabradine than in control (τfast: 263.3±16.8 ms and 584.9±38.2 ms; P<0.01 paired t test; τslow: 1731.0±117.5 ms and 3253.0±388.1 ms; P<0.001 paired t test; for control and ivabradine, respectively). In additional experiments to simulate hypokalemia (not shown), effects of ivabradine on IhERG inhibition were compared at 2 and 4 mmol/L [K+]e (for both 3 and 10 μmol/L ivabradine) and were found not to differ at the 2 [K+]e levels. There is evidence that native IKr channels may comprise heteromeric hERG1 a/1b channels;15,25,26 consequently, additional concentration-response experiments were performed on co-expressed hERG1 a/1b. The concentration-response relation for ivabradine inhibition of hERG 1a/1b IhERG is also included in Figure 1B, with a derived IC50 of 3.31 μmol/L (CI: 2.97 to 3.70); and nH of 1.06 (CI: 0.93 to 1.19). As the IC50 values for hERG 1a and hERG 1a/1b were similar to one another, all subsequent experiments were performed using hERG 1a.

Through the use of depolarizing voltage commands to differing test potentials (see Figure S2 for details), IhERG block by ivabradine was observed to exhibit some voltage dependence: Figure 1C shows a plot of fractional block of IhERG tails against command voltage, with superimposed activation curves in control and 3 μmol/L ivabradine (control V0.5 was −18.15±4.05 mV and k was 5.82±0.27; ivabradine V0.5 was −23.25±3.35 mV and k was 4.78±0.55 [n=5]; see also Figure S2). The voltage range
over which $I_{hERG}$ tail inhibition exhibited marked voltage dependence coincided closely with the rising phase of the $I_{hERG}$ activation relation, consistent with gating (activation)-dependent block. Figure 1D shows the effect of 3 $\mu$mol/L ivabradine under AP voltage clamp: a similar level of peak $I_{hERG}$ block was observed as for the $I_{hERG}$ tail during the conventional protocol shown in Figure 1A. In 5 experiments, peak repolarizing current during the AP command was reduced 52.9±3.1%, which was not significantly different from the $I_{hERG}$ tail reduction under conventional voltage clamp (56.0±3.3%; n=5, unpaired t test $P>$0.05). These findings demonstrate that ivabradine induces a concentration-dependent inhibition of hERG channels with an $IC_{50}$ similar to that reported for native $I_f$ and HCN channels (see Table S1).

Ivabradine Delays Ventricle Repolarization in Intact Perfused Hearts

The effects of ivabradine on cardiac repolarization were investigated in the Langendorff perfused guinea pig heart. Ivabradine decreased heart rate in a dose-dependent manner (Table S2). At concentrations >0.5 $\mu$mol/L, ivabradine produced sinus arrest with a junctional escape rhythm and therefore the effects of higher concentrations were not investigated.

MAP recorded during constant ventricular pacing at 200-ms cycle length, during control, and 0.2 $\mu$mol/L ivabradine (a therapeutically relevant concentration of drug) are illustrated in Figure 2A and 2B. Ivabradine significantly ($P<$0.05; paired t test) prolonged MAP duration at both 50% and 90% repolarization.
ization at both the apex and base (Figure 2C and 2D, respectively, and Table S2).

Effects of ivabradine on electrical restitution were also examined. Figure 3A shows MAPD-restitution curves measured at the left ventricle base of a typical heart in control conditions and with progressively increasing concentrations of ivabradine (0.1 to 0.5 µmol/L). During ivabradine perfusion, the restitution curve was profoundly altered, with shifts upwards and to the left. Mean maximal MAPD₉₀ increased significantly (Table S2) and the mean maximal restitution slope was significantly (P<0.05; repeated-measures ANOVA with Bonferroni post hoc test) steeper, but in the basal region only (Figure 3B and 3C). Mean effective refractory period was also significantly (P<0.05; repeated measures ANOVA with Bonferroni post hoc test) prolonged during ivabradine perfusion (Table S2). When the interval between the pacing stimulus and S₂-activation was plotted (Figure 3D and 3E), it was evident that ivabradine prolonged S₂ delay, indicating a delay in extrastimulus conduction through the left ventricle. At 140 ms S₁ to S₂ interval, S₂ delay was significantly (P<0.05; paired t test) increased at both apex (20.07±0.47 to 22.05±0.85 ms) and the base (24.57±1.25 to 27.75±1.41 ms) at 0.1 µmol/L ivabradine. These results demonstrate that ivabradine can induce substantial effects on ventricular repolarization and conduction in the intact heart.

Mechanism of I₇ERG Inhibition: Gating Dependence and Molecular Determinants

The time-dependent gating dependence of I₇ERG inhibition was pursued through the use of an “envelope of tails” protocol (Figure 4A, bottom of lower panel), with representative traces in control and 3 µmol/L ivabradine shown in upper and lower panels, respectively, of Figure 4A. With short activating pulses during the protocol, comparatively little I₇ERG block was observed, with block progressively increasing with depolarizing step duration over the first ≈200 ms of the protocol. Figure 4B shows mean normalized data for the time-course of I₇ERG development during the envelope protocol, while Figure 4C shows the time-course of fractional block of the I₇ERG tail during the envelope of tails protocol, which was well fitted by a single exponential (equation 5, Data S1) with a time-constant of
111.6±21.3 ms (n=5). This indicates strong time-dependence of the drug’s inhibitory action during progressively longer periods of gating during the depolarizing command, consistent with rapid open channel block. Figure 5A shows the protocol used to study voltage-dependent availability (inactivation) of hERG in the absence and presence of ivabradine,18,27 with representative traces during the second depolarization following the repolarizing ladder of steps, shown in Figure 5B and 5C (selected sweeps). There was a modest shift in hERG availability (inactivation) with ivabradine. This is illustrated more clearly in Figure 5D, which shows mean normalized availability plots in the absence and the presence of the drug, fitted with equation 6 (Data S1). In control, the inactivation V0.5 was −77.6±1.5 mV and k was 21.7±1.9, whereas in ivabradine, the V0.5 was −86.8±1.7 mV and k was 23.2±0.4 (n=6). Figure 5E shows plots of the inactivation time-constant at +40 mV, following the brief repolarizing step to −120 mV; inactivation time-course was not significantly altered by ivabradine (n=6; P>0.05 Wilcoxon matched-pairs signed-rank test).

A number of hERG inhibitors (typically, but not exclusively high-affinity inhibitors) are markedly dependent on intact channel inactivation for channel inhibition to occur,16,28–31 and the −10-mV shift in voltage dependence of inactivation with ivabradine shown in Figure 5 is consistent with some stabilization of the inactivated state in the presence of the drug. Inactivation-dependence of ivabradine inhibition of hERG was probed further using the N588K attenuated-inactivation mutant.16,30,31 Figure 6A shows representative traces of N588K hERG before and during exposure to ivabradine, elicited using the same experimental protocol employed to study WT hERG, whereas Figure 6B shows the concentration dependence of ivabradine inhibition of N588K hERG, superimposed on that for the WT channel. The IC50 for N588K inhibition was 10.29 µmol/L (CI: 8.73 to 12.15); nH 0.68 (CI: 0.57 to 0.79), which was 5-fold that for WT hERG. This compares with potency shifts of 12- to 20-fold reported previously for methanesulphonanilide inhibitors (E-4031 and d-sotalol;31,32). Collectively, our data indicate gated-state dependence of ivabradine block by ivabradine, with inactivation likely contributing to stabilizing drug binding to the channel.

The dependence of ivabradine on canonical drug-binding residues within the hERG channel pore was probed through the use of alanine mutants of pore helix (S624) and S6 helix (Y652 and F656) residues.12 Three and 10 µmol/L ivabradine were tested against each mutant (and their corresponding WT control). The results are summarized in Figure 6C through 6F and Table.
Figure 6C shows representative traces of S624A I_{hERG} before and during the application of 3 µmol/L ivabradine, elicited by the same protocol used to study WT and N588K hERG. The plots in Figure 6F show mean data for 3 and 10 µmol/L ivabradine. Notably, 10 µmol/L ivabradine inhibited S624A I_{hERG} by 47.5±3.6% (n=6) (close to 50% inhibition), consistent with a ≈5-fold reduction in blocking potency. Figure 6E shows the effects of 3 µmol/L ivabradine on Y652A I_{hERG}, with mean data for 3 and 10 µmol/L ivabradine shown as bar charts in Figure 6F and, numerically, in Table. I_{hERG} block was markedly attenuated for the Y652A mutation. Figure 6D shows comparable data for the F656A mutation, for which I_{hERG} was measured as inward tail current in high (94 mmol/L) [K+]o (the voltage step protocol is shown in full above Figure 6F and with the repolarization phase expanded in Figure 6D, lower panel) together with its corresponding WT control (Figure 6D, upper panel). WT I_{hERG} block by 3 and 10 µmol/L ivabradine was moderately reduced for the inward current tail in high [K+]o, compared to that for outward current tails with the same drug concentrations (Table). This is consistent with some interference between the permeant ion and ivabradine interaction with the channel, under conditions of inward K+ flux. When F656A I_{hERG} was studied under the same conditions, inhibition was markedly attenuated compared to the WT channel (Figure 6D and Table). Thus, I_{hERG} inhibition by ivabradine showed a strong dependence on interactions with canonical S6 aromatic binding residues. This was pursued further through docking simulations to an open state hERG homology model based on MthK channel crystal structure. The 6 best-ranked conformations were selected, and 1 of these is shown in Figure 7. In the majority of the poses yielded by GOLD, the ivabradine molecule tended to lie lower in the pocket defined by Y652 and F656 side chains, closer to the pore mouth and far from the selectivity filter (Figure 7A). The drug orientation was almost horizontal (ie, perpendicular to the K+ ion permeation path, Figure 7B) with a folded compact conformation. This conformation allowed the 2 aromatic rings to form multiple π-π interactions with the aromatic side chains of both Y652 and F656 (Figure 7C). In addition, a cation-π interaction between the methylene group adjacent to the protonated nitrogen and F656 side chain may also be involved in the drug binding. These results are consistent with the strong reduction of I_{hERG} inhibition observed for both Y652A and F656A hERG mutants (Figure 6).
Discussion

Results in Context: Ivabradine Effects on Repolarization and hERG

In an early study, 3 µmol/L ivabradine was reported to produce a 14% to 15% prolongation of APD50 and APD90 of rabbit Purkinje fibers, and an ≈24% reduction in sinoatrial nodal rate.34 The drug is the S stereoisomer of the parent racemate (±)-S 15544) and, in a direct comparison, its companion R stereoisomer was reported to produce a more marked effect on repolarization of both guinea-pig papillary muscles and rabbit Purkinje fibers35; only the R stereoisomer prolonged the QTc interval of anesthetized pigs (at intravenous doses of up to 1 mg kg⁻¹).35 In a more recent in vitro study, ivabradine was reported to produce a modest dose-dependent (0.1 to 10 µmol/L) prolongation of canine ventricular action potential duration (APD), an action that was substantially augmented in the setting of pharmacologically impaired repolarization reserve.13 In the same study, a high (10 µmol/L) ivabradine concentration produced an ≈11% lengthening of APD90 from human ventricular papillary muscle.13 The effects of the drug on ventricular repolarization in these previous experimental studies largely occurred at concentrations considerably exceeding the plasma concentration range in humans. Thus, when a 30-mg oral dose of ivabradine has been administered to healthy volunteers, a mean maximum plasma level of 0.17 µmol/L has been reported36 and, in a separate study, multiple dosing with 5 to 20 mg of ivabradine resulted in plasma Cmax values of 34 to 137 nmol/L.37 In the present study, ivabradine concentrations (100 to 500 nmol/L) overlapping this range affected MAPD50 and MAPD90 and effective refractory period in a concentration-dependent fashion, in both apex and base of the guinea-pig left ventricle. It is unclear why the effects of ivabradine seen here are more marked than some previous studies; however, the use

Figure 5. Effect of ivabradine on hERG channel availability. A, Voltage protocol used to study hERG channel availability. B and C, Sample traces of hERG transient current in Control (B) and in the presence of 3 µmol/L ivabradine (C) elicited by the portion of the 3-step protocol shown at the bottom of (C) (expanded from the dashed box in (A). For clarity of display, only selected test voltages are reported, while the full protocol spans from −140 to +50 mV with a 10-mV increase at each step). D, Voltage dependence of the normalized resurgent current elicited by the third step of the 3-step protocol in Control (black) and in the presence of 3 µmol/L ivabradine (gray) (n=6). Experimental data were fitted with equation 6 (dotted lines, Data S1) to give the V0.5 and k values in the Results. E, Time constant of hERG inactivation calculated by fitting the peak transient current at +40 mV after a 2-ms step to −120 mV with a mono-exponential decay function (equation 7, Data S1). The application of 3 µmol/L ivabradine had no significant effect on τ_inactivation (n=6, ns P>0.05, Wilcoxon matched-pairs signed-rank test). hERG indicates human Ether-à-go-go-Related Gene; IhERG, current hERG.
Prior studies have produced conflicting data on the effect of ivabradine on repolarizing K⁺ currents. Koncz et al reported no significant effect of ivabradine on rabbit ventricular inwardly rectifying K⁺ current (I\textsubscript{K1}) at 10 μmol/L, while suggesting that the drug inhibits rabbit ventricular I\textsubscript{K1} with an IC\textsubscript{50} of ~3.5 μmol/L. By contrast, Bois et al reported no effect of 3 μmol/L ivabradine on I\textsubscript{K1} from rabbit sinoatrial cells, with only a small effect at 10 μmol/L. The present study demonstrates unequivocally that ivabradine can inhibit hERG, with an IC\textsubscript{50} of ~2 to 3 μmol/L, concordant with an ability to inhibit native I\textsubscript{K1}. In absolute terms, the IC\textsubscript{50} for ivabradine against hERG is lower (ie, potency higher) than for either disopyramide or ranolazine under similar conditions (~7 to 8 μmol/L), both of which inhibit hERG at clinically relevant antiarrhythmic concentrations. At low plasma ivabradine levels, the “safety margin” for ivabradine use would be >30, consistent with a normally low propensity to produce QT\textsubscript{c} prolongation in patients, although at higher levels this would not neces-

![Figure 6](image-url)

**Figure 6.** Effect of hERG mutants on ivabradine block of I\textsubscript{hERG}. A, Representative traces of N588K \( I_{\text{hERG}} \) elicited by a step protocol identical to that used to study WT \( I_{\text{hERG}} \) in Figure 1A in control and in the presence of 3 μmol/L ivabradine. B, Concentration response relation for ivabradine action on N588K \( I_{\text{hERG}} \) compared with that for WT \( I_{\text{hERG}} \). Fractional inhibition was assessed for \( I_{\text{hERG}} \) tails at each of 4 concentrations (n≥5 at each concentration). C, Representative traces of S624A \( I_{\text{hERG}} \) elicited by same protocol as used to study N588K in control and in the presence of 3 μmol/L ivabradine. D, Voltage protocol with hyperpolarizing step to −120 mV used to elicit WT (upper panel) and F656A (lower panel) inward currents in high (94 mmol/L) external potassium condition shown as an inset above Figure 6F. The dotted box frames the portion of the protocol shown on an expanded timescale at the bottom of the lower panel. Upper and lower panels each show representative traces in Control and 3 μmol/L ivabradine while the insets to both panels show peak inward currents on expanded scale for clarity of display. E, Representative traces for Y652A \( I_{\text{hERG}} \) elicited by same protocol as used to study N588K and S624A \( I_{\text{hERG}} \), in Control and in the presence of 3 μmol/L ivabradine. The inset shows tail currents on an expanded timescale in order to aid visualization of the peak \( I_{\text{hERG}} \) tail in control and drug. F, Bar charts that summarize the effect of 3 (black bars) and 10 μmol/L (white bars) ivabradine on WT \( I_{\text{hERG}} \) in standard (4 mmol/L) external potassium condition elicited at −40 mV by a standard outward \( I_{\text{hERG}} \) protocol (n=5 for 3 μmol/L and n=6 for 10 μmol/L), on inward WT \( I_{\text{hERG}} \) elicited at −120 mV in high (94 mmol/L) external potassium condition (n=5 for both concentrations), on F656A inward current elicited at −120 mV in high potassium condition (n=5 for both concentrations) and on S624A and Y652A outward current elicited at −40 mV in standard external potassium condition (n≥5 at each concentration) (**P<0.01 against respective Control, ***P<0.0001 against respective Controls; for details of tests used see legend to Table). hERG indicates human Ether-a-go-go-Related Gene; \( I_{\text{hERG}} \), current hERG; WT, wild-type.
Comparison of hERG and HCN Channel Block by Ivabradine

A striking feature of the present study is the similarity between ivabradine inhibition of hERG and that of native If and recombinant HCN channels, both in blocking potency (Table S1) and in mechanism of inhibition. In particular, the drug has been reported to inhibit HCN4 channels, the dominant HCN isoform in sиноatrial nodal If, with an IC50 of 2.0 to 2.1 μmol/L,42,43 very close to the hERG IC50 values in Figure 1. Ivabradine inhibits HCN1 either in the closed state or in a transitional state between closed and open, and the direction of current flow has little effect on block.43 By contrast, for both native If and HCN4 channels, block occurs to open channels and is strengthened by depolarization and relieved on hyperpolarization, coupled to inward ion flow.43,44 The voltage dependence and “envelope of tails” data in this study indicate that hERG block by ivabradine requires channel gating to occur, with a comparatively modest impact on inhibition of inactivation attenuation, consistent with preferential open (activated) channel block. Additionally, although alteration of [K+]e from 4 to 2 mmol/L did not influence ivabradine block of outward hERG, when the direction of K+ flux was reversed in high [K+]e, inhibition of inward hERG was somewhat attenuated (Figure 6), which parallels the effect of inward ion flux on HCN4 block.43 The hERG channel lacks an S6 proline (P-X-P) motif that restricts the inner cavity size in other K+ channels, and this may enable it to accommodate a range of drug molecule sizes.12,45 HCN4 also possesses a comparatively wide pore cavity, which enables ivabradine trapping in the closed configuration.42 The modest effect of the hERG S624A mutation (Figure 6) and lack of close proximity of the drug to S624 in docking simulations (Figure 7) are consistent with an indirect role for this residue in ivabradine binding to hERG.23 Second report, an 80-year-old woman receiving multiple medications for unstable angina, including ivabradine, ranolazine, and diltiazem, developed slow junctional rate, prolonged QTc, and transient TdP.10 Electrolyte levels were normal and QTc normalized once ivabradine and diltiazem were discontinued. The authors highlighted that metabolism of ivabradine (and ranolazine) might have been increased as a consequence of CYP 3A inhibition by diltiazem.10 Potentially, effects of ivabradine on repolarization could be exacerbated in a setting of impaired repolarization reserve,13 a possibility that merits direct examination in heart failure models.

Table. Fractional Inhibition of WT and S6 and Pore Helix Mutant (Y652A, F656A, and S624A) IhERG by 3 and 10 μmol/L Ivabradine

| Channel          | Fractional Inhibition (%) | Ivabradine 3 μmol/L | Ivabradine 10 μmol/L |
|------------------|---------------------------|---------------------|----------------------|
| WT hERG ([K+]e of 4 mmol/L) | 56.0±3.3 (5) | 79.5±0.9 (6) |
| S624A hERG ([K+]e of 4 mmol/L) | 20.6±1.2 (6) *** | 47.5±3.6 (6) *** |
| Y652A hERG ([K+]e of 4 mmol/L) | 12.4±1.5 (6) *** | 28.4±1.7 (6) *** |
| WT hERG ([K+]e of 94 mmol/L) | 39.1±1.6 (5) ** | 64.8±1.3 (5) *** |
| F656A hERG ([K+]e of 94 mmol/L) | 7.05±2.2 (5) *** | 10.5±3.1 (5) *** |

Data are presented as mean±SEM. Numbers in parentheses next to fractional block percentages denote number of replicates (N value). WT hERG with a [K+]e of 4 mmol/L was the control for S624A and Y652A hERG (all assessed using the standard voltage protocol shown in Figure 1; ***P<0.0001 vs WT, 1 way ANOVA with Dunnett’s post-test). WT hERG with a [K+]e of 4 mmol/L was the control for F656A hERG (both assessed using inward IhERG tails in high [K+]e, see Figure 6; ***P<0.0001 for F656A vs its WT control; unpaired t test). Inhibition of WT IhERG at 4 and 94 mmol/L [K+]e, assessed respectively through measurement of outward and inward IhERG tails, were compared with one another using an unpaired t test (**P<0.01; ***P<0.0001 at 3 and 10 μmol/L, respectively, shown for ‘WT hERG ([K+]e of 94 mmol/L’). hERG indicates human Ether-á-go-go-Related Gene; I510A, current hERG; WT, wild-type.
ivabradine inhibition of HCN4, with docking simulations to open WT HCN4 channels identifying the drug adopting a bent configuration and stacking interactions between the benzazepinone and benzocyclobutane moieties of the drug and Y506 and F509 aromatic side chains.\(^4^2\) Hydrophobic interactions between I510 and Y506 influence the orientation of Y506 toward the center of the closed channel pore.\(^4^2\) Both Y652A and F656A mutations greatly attenuate hERG block by ivabradine (Figure 6). The folded compact conformation adopted by ivabradine in our hERG docking simulations allowed the 2 aromatic rings to form multiple π-π interactions with the aromatic side chains of both Y652 and F656, thus mirroring reported docking observations for open WT HCN4.\(^4^2\)

Thus, our findings provide molecular insight into why ivabradine has a similar potency for hERG as it does for HCN4. However, we do not exclude the possibility that other shared, but yet to be identified, features (eg, lipid association near the channel pore) may also contribute to the similar ivabradine potency against the 2 channels.

**Limitations**

This study combines data from in vitro experiments on recombinant human (hERG) potassium channels with ventricular repolarization data from perfused hearts from an animal model. The use of intact perfused guinea-pig hearts enabled...
effects of ivabradine on both apical and basal ventricular MAPD to be assessed, as well as drug effects on electrical restitution and effective refractory period to be established. Although such experiments are not possible to perform on isolated healthy human hearts and so require approaches such as those adopted here, data from animal models must be extrapolated to humans with caution. For example, the pacing rate cycle length used in this study is somewhat faster than would occur at human resting heart rates. The preparation also shares limitations common to ex vivo preparations that are removed from the normal hormonal and autonomic influences present in vivo. It is noteworthy, however, that in a previous investigation of the utility of guinea-pig paced Langendorff perfused hearts for assessing cardiovascular liability of drugs, 81% (17 of 21) of drugs associated with QT prolongation in the clinic were correctly identified in the guinea-pig perfused heart model, suggestive that this approach is largely reliable. Additionally, the results of our perfused heart experiments in respect of repolarization and restitution can most usefully be considered alongside \( I_{\text{hERG}} \) \( IC_{50} \) data and estimated safety margin in attempting to gauge safety/risk. Another potential limitation of our experiments was the inability to study ivabradine concentrations higher than 0.5 \( \mu \)mol/L in perfused hearts due to sinus arrest. Some previous studies have not observed sinus arrest at higher ivabradine concentrations. However, the use of different species (rabbit, mouse), experimental solutions (in both), or preparations (a reduced guinea-pig atrial preparation in as opposed to intact heart) precludes direct comparison with our study.

Conclusions

Ivabradine prolongs ventricular repolarization and alters electrical restitution properties in perfused guinea-pig hearts. \( hERG/IKr \) channel blockade by ivabradine has the potential to contribute to the overall actions of the drug at some plasma concentrations, with tissue accumulation or with impaired repolarization reserve. Ivabradine shows poor pharmacological selectivity between \( hERG \) and \( HCN \) channels: our data indicate that ivabradine is similarly potent against \( hERG \) as reported previously for \( HCN4 \), and there are close similarities in blocking mechanism/binding determinants for the 2 channels. This has implications for the future design of \( HCN \)-selective bradycardic agents based on an ivabradine-like template.

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Disclosures

None.

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