Potent hERG channel inhibition by sarizotan, an investigative treatment for Rett Syndrome

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ABSTRACT

Rett Syndrome (RTT) is an X-linked neurodevelopmental disorder associated with respiratory abnormalities and, in up to ~40% of patients, with prolongation of the cardiac QTc interval. QTc prolongation calls for cautious use of drugs with a propensity to inhibit hERG channels. The STARS trial has been undertaken to investigate the efficacy of sarizotan, a 5-HT\(_{1A}\) receptor agonist, at correcting RTT respiratory abnormalities. The present study investigated whether sarizotan inhibits hERG potassium channels and prolongs ventricular repolarization. Whole-cell patch-clamp measurements were made at 37°C from hERG-expressing HEK293 cells. Docking analysis was conducted using a recent cryo-EM structure of hERG. Sarizotan was a potent inhibitor of hERG current (I\(_{hERG}\); IC\(_{50}\) of 183 nM) and of native ventricular IKr from guinea-pig ventricular myocytes. 100 nM and 1 μM sarizotan prolonged ventricular action potential (AP) duration (APD\(_{90}\)) by 14.1 ± 3.3% (\(n=6\)) and 29.8 ± 3.1% (\(n=5\)) respectively and promoted AP triangulation. High affinity I\(_{hERG}\) inhibition by sarizotan was contingent upon channel gating and intact inactivation. Mutagenesis experiments and docking analysis implicated F557, S624 and Y652 residues in sarizotan binding, with weaker contribution from F656. In conclusion, sarizotan inhibits IKr/IhERG, accessing key binding residues on channel gating. This action and consequent ventricular AP prolongation occur at concentrations relevant to those proposed to treat breathing dysrhythmia in RTT. Sarizotan should only be used in RTT patients with careful evaluation of risk factors for QTc prolongation.

1. Introduction

Rett Syndrome (RTT) is a severe X-chromosome-linked developmental disorder characterized by cognitive and motor skill deficits, together with autonomic spectrum features, seizures and microencephaly [1–3]. The condition is strongly associated with autonomic dysfunction, manifested in respiratory difficulties (including hyperventilation, breath-holding and air swallowing) and abnormal heart rate control [1,3]. Patients with RTT are almost exclusively female; males exhibit more severe respiratory and heart rate abnormalities and most die within a year of birth [2]. RTT is usually caused by mutations in the X-linked transcriptional regulator gene that encodes methyl-CpG-binding protein 2 (MECP2) [2,4–7]. MECP2 gene mutations were identified in >95% of individuals with RTT [8]. Approximately 26% of deaths in RTT are sudden and unexpected [9]. A proportion of RTT patients exhibit prolongation of the rate-corrected QT (QTc) interval and T wave abnormalities [10–14], which appear to be independent of electrolyte abnormalities [11]. In 1994 Sekul and colleagues reported lengthened QTc intervals and T wave abnormalities in 41% of girls with RTT compared to age-matched healthy controls [10]. The proportion of QTc interval/T wave abnormalities increased with increasing severity of disease [10]. A subsequent study of a cohort of 34 RTT patients showed a prolonged QTc interval in 9 patients and an upper borderline value in 10 patients; QTc prolongation was present in the absence of electrolyte abnormalities [11]. Examination of 74 females with RTT syndrome and 10 with an atypical RTT variant with preserved speech found QTc prolongation in 55% of girls with classic RTT compared to 20% with the atypical variant [12].

Similar to humans, both mouse and primate models of MECP2 linked RTT manifest QTc interval prolongation [13–16]. Experiments on 2–3-month old Mecp2\(^{null/\text{y}}\) mice have revealed these to exhibit longer QTc intervals than those from wild-type (WT) mice, in the
absence of any obvious structural or contractile abnormality [13]. Whole-cell patch-clamp recordings from isolated ventricular myocytes from MeCP2mut/V mice showed no change in peak sodium current (INa) elicited on step depolarization to ~20 mV, but showed an increased persistent, late sodium current component, INa,Lat [13]. Thus, prolonged QT intervals in RTT may result from enhanced ventricular INa,Lat [13].

There are currently no specific treatments for breathing abnormalities in RTT. However, in mouse models of RTT, the investigational drug sarizotan (5-HT1A agonist, D2 partial agonist) has been found to correct this phenotype, as QTc prolongation carries a risk of respiratory, cognitive or motor deficits in the syndrome do not exist with UK Home Office legislation. Briefly, guinea-pigs (300–600 g) were killed in accordance with the UK Home Office legislation. Isolated myocytes were stored in low calcium solution (150 μM) at room temperature. For recording, an aliquot of the cell suspension was transferred into a chamber mounted on the microscope and left to settle for several minutes, before being exposed to normal Tyrode solution. Only cells with clear rod-shape and striated appearance were chosen for recording.

2.4. Electrophysiological recordings

Whole-cell patch-clamp experiments were performed using an Axopatch-1D amplifier and Digidata 1322A or 1440A (Molecular Devices, USA). Protocols were generated, and data recorded online with pClamp 8.0 or 10.0 (Molecular Devices, USA). The digitization rate was 10–20 kHz. Patch-pipettes (A-M Systems, USA) were pulled using a vertical electrode puller (Narishige PP-83, Japan), and heat-polished to a final resistance of 2–3 MΩ (Narishige MF-83, Japan). Capacitance and series resistance were routinely compensated, with series resistance compensation of ~70%. Conventional whole-cell patch-clamp recordings were made to measure hERG current (IhERG) from HEK 293 cells expressing WT or mutant hERG channels, and native delayed rectifier potassium current (IKr) from guinea-pig ventricular myocytes. Guinea-pig action potentials (APs) were recorded using perforated-patch with 400 μg/ml amphotericin B in pipette solution. All measurements were performed at 37°C. A standard voltage-protocol (lower trace of Fig. 1A) was applied from a holding potential of ~−80 mV to measure IhERG. The protocol incorporated a brief (50 ms) pre-pulse from −80 to −40 mV prior to the +20 mV test command, in order to quantify the instantaneous current at −40 mV. Comparison between this instantaneous current and the peak outward IhERG tail amplitude on repolarization to −40 mV enabled the accurate measurement of IhERG tail amplitude [31,32]. The sweep start-to-start interval was 12 s. The protocol used to investigate voltage-dependence of inhibition of IhERG by sarizotan was like that shown in Fig. 1A, but with test voltages between −40 and +40 mV. Action potential voltage clamp (AP clamp) experiments employed a human epicardial ventricular AP waveform (Fig. 2A) from the ten Tusscher et al ventricle model [33] identical to that used in prior experiments from our laboratory (e.g. [31]). AP commands were applied every 3 s and online leak subtraction was performed using a P4 protocol [34]. An ‘envelope of tails’ protocol (lower traces in Fig. 3A) was used to investigate the development of inhibition of IhERG by sarizotan with time following membrane depolarization. From holding of ~−80 mV, cell membrane potential was depolarized to +20 mV in steps of incrementing duration from 10 ms to 810 ms; the amplitude of IhERG tails on repolarization to −40 mV reflected the extent of IhERG activation produced during the pulses to +20 mV. The protocol used to investigate IhERG ‘availability’ is shown in Fig. 4A. From ~80 mV, the membrane potential was stepped to +40 mV for 500 ms; this was then followed by 2 ms repolarization steps to potentials ranging from −140 to +50 mV; membrane potential was then stepped back to +40 mV for 100 ms. The amplitude of current transients elicited by the second step to +40 mV was used to assess IhERG availability. The protocol to measure IKr was comprised of a brief step from −80 to −40 mV (to inactivate fast Na channels), followed by a 500 ms step to +20 mV and repolarization to −40 mV to observe IKr tails (lower trace of Fig. 2B) [35]. The sweep start-to-start interval was 10 s. Action potentials from
guinea-pig myocytes were elicited in current-clamp mode, by brief (5 ms) durationsuprathreshold depolarizing current pulses at a stimulation frequency of 0.1 Hz.

2.5. Computational docking

Computational docking was conducted using the open pore cryo-EM structure of hERG [PDB: 5VA1] [36], as recently described [27] using GOLD following the methods described in [37]. Free side chain flexibility was allowed during docking for selected residues within the potential drug bindingsite within the hERG pore to accommodate and optimize drug interactions. The potential binding site was centred above the β-carbon of the side chain A Tyr-652 side chain and a radius of 10 or 12 Å was selected to allow the sarizotan molecule to sample configurational space within the chain A hydrophobic pocket and also the surrounding parts of the hERG pore. Due to the large number of

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**Fig. 1.** (A) Upper traces show $\mathbf{i}_{\text{hERG}}$ in control solution and in the presence of 100 nM and 10 μM sarizotan; voltage protocol shown as lower trace. Inset shows recordings from a separate experiment, showing partial reversibility of 1 μM sarizotan. Cross-over of washout and control $\mathbf{i}_{\text{hERG}}$ tails is consistent with ‘foot-in-the door’ inhibition. (B) Concentration-response relation for $\mathbf{i}_{\text{hERG}}$ inhibition. Mean fractional block of $\mathbf{i}_{\text{hERG}}$ is shown plotted against corresponding drug concentration. Replicate numbers at each concentration shown in brackets. IC$_{50}$ and nH values given in “Results” text. (C) Representative traces of $\mathbf{i}_{\text{hERG}}$ in control (black) and 100 nM sarizotan (grey) at selected potentials during protocol like that in A, but with test potentials between −40 and +40 mV. (D) Mean fractional block of $\mathbf{i}_{\text{hERG}}$ tails by 100 nM sarizotan plotted against test voltage (n = 7). Activation relations for control and sarizotan are shown superimposed ($V_{0.5}$ and $k$ values in the main text).

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**Fig. 2.** (A) Representative traces of $\mathbf{i}_{\text{hERG}}$ in control and 100 nM elicited by ventricular AP clamp (AP shown superimposed). (B) Representative traces of guinea-pig ventricular deactivating $\mathbf{i}_{\text{k}}$ tails (elicited on repolarization to −40 mV following 500 ms command to +20 mV) in control, 1 μM sarizotan and 10 μM E-4031. Sarizotan was applied in these experiments for 3–5 min and 1 μM E-4031 for 1 min. (C) Ventricular APs (elicited at 0.1 Hz) in control solution, after 100 nM and 1 μM sarizotan and following washout. Mean AP duration at 25% and 90% repolarization (APD$_{25}$ and APD$_{90}$) values are given in the main text.
Fig. 3. (A) Upper traces show representative current traces elicited by the envelope of tails protocol shown in as lower traces. Left hand panel shows data in Control, right hand panel shows data in 100 nM sarizotan. (B) Mean (n = 5) IhERG, blocking time-course at +20 mV derived from application of the envelope of tails protocol. Protocol was applied in control, cells then rested in sarizotan for 3–5 min, and protocol was reapplied to ascertain fractional block values. The inset shows the protocol with a high gain insert to show more clearly the steps of short duration early during the protocol. Fractional block data at different time-points were fitted with an exponential to ascertain the time constant value given in the Results text.

Fig. 4. (A) Protocol used to investigate IhERG ‘availability’. From a −80 mV, the membrane potential was stepped to +40 mV for 500 ms; this was then followed by 2 ms repolarization steps to potentials ranging from −140 mV to +50 mV, membrane potential was then stepped back to +40 mV for 100 ms (inset shows portion of protocol encompassing the transition to and from repolarizing steps). The amplitude of current transients elicited by the second step to +40 mV was used to assess IhERG availability. (B) Representative traces in control. Selected traces are shown for clarity. Numbers indicate corresponding voltage of preceding 2 ms repolarization step. (C) Representative traces at 100 nM sarizotan. (D) Plots against voltage of normalized current transient amplitude in control and in 100 nM sarizotan (n = 7 cells); the inactivation V0.5 and k values were derived from fits with standard Boltzmann function and are given in the Results text.
rotamers sampled during docking 300,000 generations of the genetic algorithm was used; the ChemPLP scoring function was used to select low energy score docking poses from a set of 100 docking runs for each of the sarizotan enantiomers.

2.6. Data analysis

Data are presented as mean ± SEM. Statistical analysis and fits to data sets were performed using Microsoft Excel (Microsoft Corporation, USA), Origin 7.0 (OriginLab, USA), Prism 7.04 (Graphpad Software Inc., USA) and Clampfit of pClamp 10.7 (Molecular Devices, USA). Data distribution was tested using the Kolmogorov–Smirnov normality test. Comparisons were made using paired t-test, unpaired t-test; Wilcoxon signed rank test, or one-way ANOVA followed by a Tukey post-test as appropriate; P < .05 was taken as significant. The following standard eqs. (24,26) were used to fit particular data-sets:

- Fractional block of $I_{hERG}$ was determined using an equation of the form:

$$\text{Fraction block} = 1 - \left( \frac{I_{\text{residual}}}{I_{\text{control}}} \right)$$

(1)

where $I_{hERG}$ control represents current amplitude prior to drug application and $I_{hERG}$ residual represents the unblocked current remaining following drug exposure.

- Concentration-response data were fitted with a Hill equation of the form:

$$\text{Fractional block} = \frac{1}{1 + 10^h((\log(C_{50} - X))}$$

(2)

where Fractional block refers to the degree of inhibition of $I_{hERG}$ by a given concentration of sarizotan ($X$, the logarithm of concentration); $C_{50}$ is [sarizotan] producing half-maximal inhibition of $I_{hERG}$, and $h$ is the Hill coefficient for the fit.

- Voltage-dependent activation parameters were derived from current-voltage (I-V) relations for $I_{hERG}$ tail currents, fitted with a Boltzmann equation of the form:

$$I = I_{\text{max}} / (1 + \exp((V_{0.5} - V_i)/k))$$

(3)

where $I$ is tail current magnitude at $-40$ mV following a voltage test potential ($V_i$); $I_{\text{max}}$ is the maximal tail current during the voltage protocol; $V_{0.5}$ is the voltage at which $I_{hERG}$ is half maximally activated, and $k$ is the slope factor for the relation.

Continuous plots of $I_{hERG}$ activation were produced by inserting the values for $V_{0.5}$ and $k$ obtained from Eq. (3) into the equation:

$$\text{Activation variable} = \frac{1}{1 + \exp((V_{0.5} - V_i)/k)}$$

(4)

where the terms have similar meanings to those described above for Eq. (3).

- $I_{hERG}$ blocking time-course from application of the envelope of tails protocol was fitted with a single-exponential equation:

$$\text{Fractional block} = Y_e + (\text{Plateau} - Y_e) \times (1 - \exp(-x/t))$$

(5)

where Fractional block refers to the degree of inhibition of $I_{hERG}$ at a pulse duration `$t$'; the fractional block starts at $Y_e$, then goes to Plateau; and $t$ is the time constant of development of $I_{hERG}$ inhibition.

- Voltage dependence of $I_{hERG}$ availability (inactivation) was determined by fitting normalized current transients with the equation:

$$I/I_{\text{max}} = 1-1/(1 + \exp((V_{0.5} - V_i)/k))$$

(6)

where the normalized current ($I/I_{\text{max}}$) is a ratio of a current ($I$) at a membrane potential/voltage ($V_i$) and the maximal current ($I_{\text{max}}$) during the voltage protocol ($-140$ to $+50$ mV); $V_{0.5}$ is the potential at which $I_{hERG}$ was half maximally inactivated, and $k$ is the slope factor for the relation.

3. Results

3.1. Potency and voltage dependence of sarizotan inhibition of $I_{hERG}$

Sensitivity of $I_{hERG}$ to sarizotan was evaluated using a previously described voltage protocol (lower trace in Fig. 1A) [23,24]. In the example shown the $I_{hERG}$ tail was inhibited by 37% at 100 nM and by 96% at 10 μM sarizotan. The inset shows partial reversibility of the response to sarizotan (1 μM). A total of 5 concentrations were tested and a mean concentration-response plot was constructed (Fig. 1B), yielding an $IC_{50}$ of 183 ± 51 nM, with a Hill coefficient of (nH) of 0.58 ± 0.10. Sarizotan action on $I_{hERG}$ tails following different test potentials was assessed using a similar protocol, but with test voltages between −40 and +40 mV. Representative current traces are shown in Fig. 1C. $I_{hERG}$ tail block by 100 nM sarizotan was evaluated following the different command voltages and plotted as shown in Fig. 1D. Tail currents in control and drug following the different test potentials were fitted with a Boltzmann function and mean derived $V_{0.5}$ and $k$ values then used to construct activation plots, superimposed in Fig. 1D. Voltage dependent activation was leftward shifted in sarizotan compared to control ($V_{0.5}$ in sarizotan of −29.9 ± 2.3 mV and in control of −24.2 ± 1.9 mV, $P < .05$; $k$ in sarizotan of 6.1 ± 0.8 and in control 5.7 ± 0.3, $P > .84$, n = 7; Wilcoxon matched-pairs signed rank test for both). The progressive changes in extent of $I_{hERG}$ block by sarizotan coincided with the steep phase of $I_{hERG}$ activation, consistent with activation-depending inhibition [26]. Over potentials (between +10 and +40 mV) at the top of the voltage-dependent activation relation there was no significant change in the extent of fractional inhibition, suggesting that voltage-dependence of inhibition independent of channel gating did not occur.

3.2. Effects of sarizotan on ventricular action potentials and $I_{Kr}$

Fig. 2A shows effects of 100 nM of sarizotan on $I_{hERG}$ elicited by a ventricular AP waveform. Peak repolarizing current occurred at −38.6 ± 1.6 mV in control and −35.2 ± 2.7 mV in sarizotan ($P > .05$, paired t-test; n = 7). It was reduced by 33.0 ± 3.2% in sarizotan ($P > .05$, cf standard protocol (35.4 ± 2.6%; n = 9) unpaired t-test). We evaluated block of native ventricular $I_{Kr}$ using a protocol comprised of a brief step from −80 to −40 mV (to inactivate fast Na channels), followed by a 500 ms step to +20 mV and repolarization to −40 mV to observe $I_{Kr}$ tail. 1 μM sarizotan suppressed deactivating tail current amplitude by 66.2 ± 1.9% (n = 7). As shown in Fig. 2B, with subsequent application of a high concentration of E-4031 after sarizotan there was no residual tail current, confirming that under these conditions deactivating outward current tails were carried by $I_{Kr}$. We also monitored the peak inward L-type Ca$^{2+}$ current ($I_{Ca,L}$) at the start of the +20 mV step of this protocol and observed only a small (18.4 ± 3%; n = 7) reduction in that current with 1 μM sarizotan (not shown). Fig. 2C shows the effect of 100 nM and 1 μM sarizotan on ventricular AP duration (APD). 100 nM sarizotan prolonged action potential duration at 25% repolarization (APD$_{25}$) by 3.1 ± 1.8% and action potential duration at 90% repolarization (APD$_{90}$) by 14.1 ± 3.3% (n = 6), whilst 1 μM sarizotan prolonged APD$_{25}$ by 3.8 ± 1.2% and APD$_{90}$ by 29.8 ± 3.1% (n = 5). AP triangulation [38] was measured as the APD$_{25}$ to APD$_{90}$ difference. This was 100.7 ± 7.6 ms in control, 126.4 ± 10.7 ms in 100 nM sarizotan and 173.9 ± 9.9 ms in 1 μM sarizotan (P < .01 vs control for both; one-way ANOVA with Tukey post-test). Significant triangulation was also observed when measured as APD$_{30}$-APD$_{90}$ difference (see Table 1). Thus, sarizotan both prolonged ventricular APD and increased AP triangulation.

3.3. Time dependence and effect of sarizotan on $I_{hERG}$ inactivation

Time-dependence of $I_{hERG}$ block was explored using two
Table 1  Effects of sarizotan exposure on ventricular AP repolarization parameters.

<table>
<thead>
<tr>
<th></th>
<th>Control (n = 6)</th>
<th>Sarizotan 100 nM (n = 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>APD0 (ms)</td>
<td>114.8 ± 17.7</td>
<td>121.4 ± 17.8</td>
</tr>
<tr>
<td>APD90 (ms)</td>
<td>137.9 ± 20.1</td>
<td>142.9 ± 19.4</td>
</tr>
<tr>
<td>APD25 (ms)</td>
<td>189.1 ± 21.9</td>
<td>204.7 ± 23.9</td>
</tr>
<tr>
<td>APD50 (ms)</td>
<td>206.4 ± 21.6</td>
<td>224.3 ± 21.3</td>
</tr>
<tr>
<td>APD75 (ms)</td>
<td>275.1 ± 21.7</td>
<td>304.0 ± 21.3</td>
</tr>
<tr>
<td>APD90/APD0 (ms)</td>
<td>100.6 ± 9.0</td>
<td>126.4 ± 10.7</td>
</tr>
<tr>
<td>APD90/APD50 (ms)</td>
<td>81.1 ± 7.4</td>
<td>105.0 ± 9.5</td>
</tr>
</tbody>
</table>

APD refers to action potential duration and subscripted numbers refer to point after start of repolarization at which duration was measured (values are given for 25%, 50%, 75%, 90% of complete repolarization).

** denotes statistical significance of P < .01 versus control; paired t-test.

complementary approaches. The first of these utilized a protocol comprised of a long (10 s) duration depolarization from −80 to 0 mV [39], which was applied first in control solution and then in 100 nM sarizotan, after resting the cell at −80 mV in sarizotan for ~3 min (representative traces are shown in supplemental Fig. S1A). As shown in Fig. S1B, a substantial component of the block observed at 10 s at 0 mV occurred by 100–200 ms into the depolarizing command, indicating that block was evident quickly on membrane depolarization. However, as highlighted previously in this journal, this protocol is less suited to examination of block over comparatively shorter than longer periods following membrane depolarization [40]. Consequently, we also employed an envelope of tails protocol (with depolarizing commands to +20 mV of differing duration, shown as lower traces in Fig. 3A, with representative currents shown as the upper traces) [35,40,41]. This was applied in control, the cell then rested for ~3 min during exposure to 100 nM sarizotan, and then reapplied. Fractional inhibition of the tail currents following the different duration voltage commands was then determined and plotted against test pulse duration as shown in Fig. 3B (n = 5). There was little or no block with very short voltage commands, and block increased progressively over ~200 ms. A single exponential fit to these data gave a blocking τ of 34.4 ms. These results demonstrate that sarizotan’s action was contingent upon channel gating with little or no block of resting channels.

Fig. 4A shows the protocol used to evaluate voltage dependent availability of IhERG, from which inactivation V0.5 and k values were obtained [42,43]. Fig. 4B and C respectively show representative traces, focusing on the portion of the protocol including brief repolarizing steps (to produce differing extents of IhERG availability) and the subsequent outward IhERG transients during the final step of the protocol. Plots of IhERG availability (Fig. 4D) were constructed as described previously [42] and Boltzmann fits used to obtain inactivation V0.5 and k values (V0.5 in sarizotan of −45.3 ± 5.0 mV and in control of −57.9 ± 4.5 mV; P > .05, n = 7 paired t-test; k in sarizotan of 23.1 ± 1.1 and in control of 26.3 ± 1.9, P > .05, n = 7; paired t-test). Time-course of inactivation was evaluated for current following a brief conditioning pulse to −120 mV and was not significantly altered by sarizotan (τ values of 1.74 ± 0.43 and 1.93 ± 0.22 ms in control and sarizotan respectively; P > .05; paired t-test; data not shown).

3.4. Molecular basis of sarizotan action

The effects of targeted hERG mutations on inhibition of IhERG by 1 μM and 10 μM sarizotan action were established. The NS88K mutation to the S5-Pore linker region markedly reduces IhERG inactivation and attenuates blockade of a range of agents that rely on intact inactivation to bind to the channel [32,44]. IhERG inhibition by both 1 μM and 10 μM sarizotan was significantly attenuated by this mutation, indicating that an intact inactivation process is needed for high affinity sarizotan binding. Representative traces for the S624A mutation (located in the pore helix/base of selectivity filter) and Y652A mutation (located in the S6 helix) are also shown in Fig. 5A, with attenuation of block by 1 μM sarizotan. Fig. 5B summarises effects of these mutations plus S6 F656 V and S5 F557 I mutations, both of which also attenuated drug action. Supplemental Table S1 provides estimates of the changes in binding energy for sarizotan introduced by the mutations studied.

Fig. 5 Ci and Scii show results of in silico docking of sarizotan within the pore of the recently determined cryo-EM hERG channel structure [36]. Sarizotan could bind within the pore below the selectivity filter, with a hydrophobic aromatic part of the drug projecting into one of the hydrophobic pockets identified in the EM structure that are found at the interface between the pore helix (PH) and S5 and S6 helices (Fig. 5 Ci). In this configuration sarizotan made π-π stacking interactions with F557 and Y652 aromatic side chains, and the polar amino and pyridine nitrogens lay below the C-terminal end of the pore helix with possible direct or water-mediated interactions with the T623 and S624 hydroxyl side chains (Fig. 5 Ci); interactions with F656 in this configuration were minimal. This docking pose is consistent with the mutagenesis data summarized in Fig. 5B. The specific binding interactions between sarizotan and S624, Y652 and F557 are further highlighted in the stereo view in supplemental Fig. S2.

4. Discussion

4.1. Sarizotan interaction with the hERG channel

This study demonstrates that sarizotan inhibits both IhERG and native IKr at sub-micromolar concentrations (IC50 for IhERG block of 183 nM), prolongs ventricular APD90 and increases ventricular AP tri-angulation, which is a marker of proarrhythmic risk [38]. The observed potency of sarizotan inhibition of IhERG can usefully be considered in the context of IC50 values obtained in our laboratory under similar experimental conditions for established IhERG inhibitors. Thus, using the standard protocol shown in Fig. 1A, we have previously obtained IhERG IC50 values for the canonical hERG/IzKp blockers E-4031 and dofetilide of 16 nM and 9.8 nM respectively and for the Class Ia antiarrhythmic quinidine of 620 nM [32,45]. Both dofetilide and quinidine are well established to be linked to QTc interval prolongation [19] and it is notable that sarizotan is a more potent inhibitor of IhERG than is quinidine under similar experimental conditions.

The WT IhERG data in this study show that sarizotan relies on hERG channel gating in order to access its binding site, whilst the NS88K mutant data demonstrate that an intact inactivation process is necessary for high affinity binding [32,44]. High affinity hERG channel inhibition most commonly involves drug interaction with S6 aromatic residues, with further supportive interactions with other residues on the S6 helices and located close to the selectivity filter/base of the pore helix [21,46]. Our mutagenesis and docking results indicate that sarizotan interacts with residues of the canonical drug binding site, though it is notable that mutation at Y652 led to a greater attenuation of inhibition than did mutation of F656. Recent studies have shown a role for the F557 S5 aromatic residue in IhERG block [27;47] and, here, mutation of F557 markedly reduced IhERG block by sarizotan. F557 lies partly within hydrophobic pockets recently identified in the cryo-EM structure of hERG [36]. Docking to this structure shows low-energy binding could occur in a configuration that places sarizotan near F557, S624 at the base of the selectivity filter and Y652. The original study that identified F557 as a potential binding determinant for hERG inhibitors did not directly compare effects of mutations at F557 and F656 experimentally [47]. In our prior study of a minimally structured high affinity hERG inhibitor, Cavalli-2, mutation at F656 had greater effects on blocking potency than mutation at either F557 or Y652 [27]. An independent study of a novel EGFR inhibitor FHND004 also found mutation at F656 to attenuate inhibition more than at F557 [48]. Sarizotan is notable in this regard as it is an IhERG inhibitor for which mutation of F557 produces a greater attenuation of inhibition than mutation at the canonical F656 binding residue. Interestingly, a very
recent independent study of the HCN channel inhibitor ivabradine has reported IhERG inhibition by that drug to be attenuated more by the F557L than F656C mutation [49].

4.2. Implications of the study

The STARS trial involves administration of 2 or 10 mg sarizotan bidaily (over 24 weeks) to RTT patients aged ≥4 years, with a body weight of ≥10 kg, with a primary outcome measure of reduction of respiratory abnormalities [18]. Redfern et al [19] proposed a safety margin of 30 (hERG IC50/ plasma Cmax) for drugs undergoing clinical evaluation [50], which would correspond to a sarizotan plasma level of 6–7 nM (for the IhERG IC50 in this study). Oral administration of 2 and 10 mg of sarizotan to adult men produced peak total plasma concentrations of ~170 and 488 ng/ml (~442 nM and 1.27 μM, respectively [51]). Therefore, it is expected that peak total plasma levels of sarizotan in young RTT patients given 2 or 10 mg doses may fall within a comparable range. Although unbound levels may be substantially lower than total plasma drug levels, it is notable that sarizotan is lipophilic (logP value of 4.1; PubChem CID 6918388) and so could concentrate in lipid membranes. Feasibly, therefore, sarizotan administration could result in a safety margin of < 30. Thus, it is reasonable to conclude that hERG/IKr block is a potential risk of sarizotan administration to RTT patients. This would pose a particular safety concern in the subset of RTT patients with overt QTc prolongation [10–14]. Administration of sarizotan to primes is associated with production of metabolites (EMD148107, EMD329989, EMD50929) at concentrations 5–10 fold lower than that of the parent compound [52]. The propensity of these metabolites to inhibit hERG/IKr and delay repolarization remains to be established. Exclusion criteria for the STARS trial include a Friderici corrected QTc interval of >450 ms. However, in principle, individuals with a borderline QTc but impoverished repolarization reserve prior to drug administration could also be at significant risk. Moreover, as female sex is itself a risk factor for drug-induced long QT syndrome [53] long-term administration of sarizotan (post-puberty) in RTT patients would need to be undertaken with care. At present, there is no alternative selective treatment for the respiratory disturbances in RTT, thus it would be premature to conclude that sarizotan is unsuitable due to its hERG-activity, particularly given the risk posed by apnoeas themselves. It is noteworthy that severe breathing dysrhythmia is independently associated with QTc prolongation in RTT (OR = 2, P = .001) [54]. Studies in neurotypical individuals suffering from sleep apnoeas suggest a causal link [55–57] between frequent apnoeas and QTc prolongation, but this is yet to be determined in RTT. Recent analysis suggests that extent of QTc interval prolongation in RTT may vary between MECP2 mutations, with R255* mutations and large deletions being most strongly linked to QTc prolongation [58]. If this is borne out by further investigations with larger sample sizes, mutation

Fig. 5. (A) Representative traces showing effects of sarizotan on IhERG tail current for WT, N588K, S624A and Y652A hERG channels (shown as upper sets of traces) with expanded portion of voltage protocol shown as lower traces. (B) Bar charts showing mean fractional block of IhERG tails by 1μM and 10μM sarizotan for WT, N588K, S624A, F557L, Y652A and F656A hERG channels. Replicate numbers shown in brackets. * and ** are significance at P < .05 and P < .01 respectively (one-way ANOVA with Tukey post-test). (Ci) Low energy score configuration for R sarizotan (yellow space filling representation) docked into the cryo-EM structure of hERG [36]. Subunit A of the hERG pore is colored grey and the side chains shown are identified in Cii. The location of N588 in chain A is also shown. The selectivity filter is occupied by K+ ions in the 1 and 3 positions (purple spheres) and waters in the 2 and 4 positions. The S enantiomer of sarizotan (not shown) was similarly able to bind with a hydrophobic aromatic part of the drug projecting into a hydrophobic pocket. PH: pore helix. (Cii) Close up of the bound configuration for R sarizotan as in panel Ci showing side chains in the binding “pocket” [36] of chain A (grey sticks) and other side chains important for binding to hERG blockers and mentioned in the text. (For interpretation of the references to colour in this figure legend, the reader is referred to the online version of this article.)
type as well as severity of respiratory arrhythmia could aid patient selection for sarizotan treatment. Additionally, evaluation of the value of other compounds with 5-HT1A agonist activity as potential alternative RTT treatments [59] could usefully consider their hERG-blocking propensity (or lack thereof) alongside efficacy against respiratory dysrhythmia.

5. Perspectives

The results of this study demonstrate that sarizotan inhibits hERG/IKr, and delays ventricular repolarization at concentrations relevant to those being considered for the treatment of RTT. Given the paucity of alternative RTT treatments, if the drug is found to be beneficial for respiratory arrhythmias in RTT patients, the findings of this study indicate that treatment should commence under clinical supervision with close monitoring of ECG and electrolyte levels, with further caution to:

(i) use the lowest effective dose; (ii) avoid use in patients with existing LQTS or in combination with other QT-prolonging medications; and (iii) consider other risk factors for acquired LQTS [53].

Disclosures

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Appendix A. Supplementary data

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References


