Role of \(I_{\text{Kur}}\) in Controlling Action Potential Shape and Contractility in the Human Atrium

Influence of Chronic Atrial Fibrillation

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**Background**—The ultrarapid outward current \(I_{\text{Kur}}\) is a major repolarizing current in human atrium and a potential target for treating atrial arrhythmias. The effects of selective block of \(I_{\text{Kur}}\) by low concentrations of 4-aminopyridine or the biphenyl derivative AVE 0118 were investigated on right atrial action potentials (APs) in trabeculae from patients in sinus rhythm (SR) or chronic atrial fibrillation (AF).

**Methods and Results**—AP duration at 90% repolarization (APD\(_{90}\)) was shorter in AF than in SR (300±16 ms, \(n=6\), versus 414±10 ms, \(n=15\)), whereas APD\(_{20}\) was longer (35±9 ms in AF versus 5±2 ms in SR, \(P<0.05\)). 4-Aminopyridine (5 \(\mu\)mol/L) elevated the plateau to more positive potentials from −21±3 to −6±3 mV in SR and 0±3 to +12±3 mV in AF. 4-Aminopyridine reversibly shortened APD\(_{90}\) from 414±10 to 350±10 ms in SR but prolonged APD\(_{90}\) from 300±16 to 320±13 ms in AF. Similar results were obtained with AVE 0118 (6 \(\mu\)mol/L). Computer simulations of \(I_{\text{Kur}}\) block in human atrial APs predicted secondary increases in \(I_{\text{Kr}}\) and in the outward rectifiers \(I_{\text{Kr}}\) and \(I_{\text{Kur}}\), with smaller changes in AF than SR. The indirect increase in \(I_{\text{Ca,L}}\) was supported by a positive inotropic effect of 4-aminopyridine without direct effects on \(I_{\text{Ca,L}}\) in atrial but not ventricular preparations. In accordance with the model predictions, block of \(I_{\text{Kur}}\) with E-4031 converted APD shortening effects of \(I_{\text{Kur}}\) block in SR into AP prolongation.

**Conclusions**—Whether inhibition of \(I_{\text{Kur}}\) prolongs or shortens APD depends on the disease status of the atria and is determined by the level of electrical remodeling. (*Circulation*. 2004;110:2299-2306.)

**Key Words:** ion channels ■ potassium channel blockers ■ contraction ■ action potentials ■ fibrillation

The cardiac repolarization process is regulated by several outward currents, of which the ultrarapid delayed rectifier potassium current \(I_{\text{Kur}}\) is thought to play a major role. This current is absent in the ventricles and hence represents a suitable target for selectively modulating action potentials (APs) in the atria.\(^1\)\(^-\)\(^3\) The selective blocker of \(I_{\text{Kur}}\), 4-aminopyridine in low micromolar concentrations is expected to prolong the AP duration (APD).

However, experimental results in human atrial preparations from patients with sinus rhythm (SR) are inconsistent with shortening of APD in multicellular trabeculae\(^4\) and prolongation of APD in isolated atrial myocytes.\(^1\) Although block of \(I_{\text{Kur}}\) and the subsequent prolongation of the APD are expected to be beneficial in chronic atrial fibrillation (AF), the experimental proof is still lacking. Furthermore, AF itself induces shortening of APD and effective refractory period, known as electrical remodeling, that is associated with changes in expression and activity of the involved ion channels.\(^5\) Human \(I_{\text{Kur}}\) was found to be reduced by \(\approx 50\%\), whereas other groups reported no changes.\(^5\)

To predict the AP alterations associated with \(I_{\text{Kur}}\) block during chronic AF, Courtemanche et al\(^2\) simulated these changes in a model of human APs in AF and demonstrated that the reduction of \(I_{\text{Kur}}\) was associated with prolongation of APD. However, this article only predicted the changes without experimental verification.

Here, we studied the effects of \(I_{\text{Kur}}\) block with 4-aminopyridine and with the new \(I_{\text{Kur}}\) blocker, the biphenyl derivative AVE 0118, on APs in trabeculae from SR and AF patients. The impact of \(I_{\text{Kur}}\) block on other atrial currents was predicted by simulating APs in a modified Luo-Rudy model, and the predictions were tested experimentally by recording APs or force of contraction (F\(_c\)) in trabeculae or by measuring membrane currents in isolated atrial myocytes.
### Methods

#### Human Tissue Samples and Patient Characteristics

The study was approved by the ethics committee of the Dresden University of Technology (No. EK709799). Each patient gave written, informed consent.

Right atrial appendages were obtained from 34 patients with SR and 18 patients with chronic AF (AF > 6 months, Table 1). Significant differences between the 2 groups were found for underlying heart disease and pulmonary hypertension. AF patients more often received digitalis and diuretics, and β-blockers and lipid-lowering drugs were prescribed more frequently in SR patients. Ventricular trabeculae (n = 10) originated from left and right ventricles from 2 explanted end-stage failing hearts.

#### Electrophysiological Recordings

Atrial APs were recorded with conventional intracellular microelectrodes in right atrial trabeculae (microelectrode tip resistance, 10 to 25 MΩ; 1-ms stimulus, 25% above threshold intensity). The bath solution contained (in mmol/L): NaCl 127, KCl 4.5, MgCl₂ 1.5, CaCl₂ 1.8, glucose 10, NaHCO₃ 22, and NaH₂PO₄ 0.42, equilibrated with O₂/CO₂ (95:5) at 37°C, pH 7.4. A computer-aided system (developed at the University of Szeged, Hungary) was used for generating stimuli and data acquisition of various AP parameters. After equilibration for 1 hour, control APs were recorded for 20 minutes before 4-aminopyridine or AVE 0118 was cumulatively added, with 20 minutes of recording between concentration increments.

Human myocytes were isolated from atrial appendages as previously described. I_Ca,L and I_k were measured with conventional voltage-clamp technique as previously described. Mean cell capacitance was 101 ± 6.5 pF (n = 29).

#### Measurement of Fc

Pairs of right atrial or ventricular trabeculae were mounted in organ baths filled with 50 mL of buffer (composition in mmol/L: NaCl 126.7, KCl 5.4, CaCl₂ 1.8, MgCl₂ 1.05, NaHCO₃ 22.0, NaH₂PO₄ 0.42, EDTA 0.04, and glucose 5.0, equilibrated with O₂/CO₂ [95:5] at 37°C, pH 7.4). The bath solution contained 200 mmol/L (–)-propranolol to exclude effects mediated through β-adrenoceptors. The preparations were paced (0.5 Hz, 5-ms stimulus, 10% above threshold intensity) and were stretched to 80% of the length associated with maximum developed force. After an equilibration period of 30 minutes, the effects of 4-aminopyridine or AVE 0118 on Fc were determined by cumulatively increasing concentrations every 20 minutes.

#### Action Potential Simulations

For simulating the shapes of human atrial APs, we modified mathematical models described in the literature. The incorporated membrane currents and transporters and factors controlling intracellular ion concentrations are listed in the Appendix (see online-only Data Supplement), which also contains specific kinetic parameters, constants of ion currents, and the equations used for current calculations. Maximum current conductances of I_Ca,L, I_K, I_Na,L and I_Na,K were adapted to simulate the characteristic AP shapes. For AP simulation in chronic AF, original current data were taken from the literature and, when not available, amplitudes were extrapolated from changes in channel expression.

As an approximation, APs were assumed to be spatially uniform, ie, conduction within the preparation was neglected. Changes of membrane potential were calculated for space-clamp conditions as follows: d(V_m)/dt = (I_{Na,L} + I_{K} + I_{Ca,L} + I_{K,1} + I_{K,2} + I_{K,3} + I_{I_F} + I_{Na,K,puj} + I_{Na,K} + I_{Na,K,puj})/C_{m}.

#### Statistical Analysis

Differences between continuous data were compared by unpaired Student t test or 1-way ANOVA. Frequency data were analyzed with χ² statistics. Data are mean ± SEM. A value of P < 0.05 was considered statistically significant.

#### Results

**Effect of 4-Aminopyridine on AP Configuration in SR and AF**

Resting membrane potentials were −75 ± 1 mV in SR (n = 15) and significantly more negative in AF (−80 ± 3 mV, n = 6, P < 0.05). In accordance with our previous results, APD₉₀ at 20% of repolarization (APD₉₀) was shorter in SR (5 ± 2 ms) than in AF (35 ± 9 ms, P < 0.05), whereas APD₉₀ was longer in SR (414 ± 10 ms) compared with AF (300 ± 16 ms, P < 0.05).

### Table 1. Characteristics of Patients in SR and Chronic AF

<table>
<thead>
<tr>
<th></th>
<th>SR</th>
<th>AF</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>34</td>
<td>18</td>
</tr>
<tr>
<td>Sex, M/F</td>
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<td>11/7</td>
</tr>
<tr>
<td>Age, y</td>
<td>68 ± 2</td>
<td>64 ± 4</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>29 ± 1</td>
<td>26 ± 1*</td>
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<tr>
<td>CAD, n</td>
<td>26</td>
<td>3*</td>
</tr>
<tr>
<td>AVID/MVD, n</td>
<td>5</td>
<td>10*</td>
</tr>
<tr>
<td>CAD + AVID/MVD, n</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Hypertension, n</td>
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<td>13</td>
</tr>
<tr>
<td>Pulmonary hyp, n</td>
<td>3</td>
<td>10*</td>
</tr>
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<td>8</td>
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<tr>
<td>Hyperlipidemia, n</td>
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<td>9</td>
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<tr>
<td>LVEF, %</td>
<td>61 ± 3</td>
<td>58 ± 3</td>
</tr>
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<td>LVEDP, mm Hg</td>
<td>14 ± 1</td>
<td>14 ± 2</td>
</tr>
<tr>
<td>LA, mm</td>
<td>38 ± 2</td>
<td>51 ± 4*</td>
</tr>
<tr>
<td>LVEDD, mm</td>
<td>51 ± 3</td>
<td>57 ± 3</td>
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<tr>
<td>Nitrates</td>
<td>19</td>
<td>3*</td>
</tr>
<tr>
<td>Lipid-lowering drugs</td>
<td>26</td>
<td>4</td>
</tr>
</tbody>
</table>

*P < 0.05 values from nonpaired Student t test for continuous variables and from χ² test for categorical variables.
In the presence of 4-aminopyridine (5 μmol/L), the potentials of the notch and dome (SR) and of the plateau shoulder (AF) were shifted to more positive values, leading to a significant increase in APD$_{20}$ from 5 to $11002 \pm 2$ ms in SR ($P < 0.05$) and from $35 \pm 9$ to $78 \pm 5$ ms in AF ($P = 0.002$, Figure 1, A and B). The final repolarization phase was accelerated in both groups; however, APD$_{90}$ was shortened from $414 \pm 10$ to $350 \pm 10$ ms in SR ($P < 0.0001$) but was prolonged from $300 \pm 16$ to $320 \pm 13$ ms in AF ($P = 0.006$; Figure 1, C and D), suggesting that the directions of APD$_{90}$ changes are different in SR and AF. The effects of 4-aminopyridine were reversible on washout.

In SR preparations, the mean notch potential, ie, the minimum potential after the initial rapid repolarization phase, was shifted by 4-aminopyridine (5 μmol/L) from $23 \pm 2$ to $4 \pm 2$ mV with $100 \mu$mol/L 4-aminopyridine ($P = 0.0001$), and the respective dome potential was changed from $18 \pm 1$ to $0 \pm 2$ mV ($P < 0.001$). Nonlinear curve fitting resulted in EC$_{50}$ values of $15 \mu$mol/L 4-aminopyridine for elevation of notch potential and $14 \mu$mol/L for elevation of dome potential (Figure 2C). In AF, the effect of 4-aminopyridine on the plateau potential was also concentration-dependent, with an EC$_{50}$ value of $28 \mu$mol/L in 1 experiment (Figure 2, B and D).

Model Simulations of APs in SR and AF: Block of $I_{Kur}$

Inserting experimentally estimated parameters into the mathematical model of human atrial APs (see Appendix) provided the spike-and-dome shape typical for tissue from SR patients (compare Figures 1A and 3). Selective inhibition of $I_{Kur}$ by 4-aminopyridine was simulated by setting the current to 20%
of its regular value in SR (see Table 2). The model reproduced the observed shifts of notch-and-dome potentials to more positive values (Figure 3) and shortened APD90. Block of \( I_{Kur} \) induced a series of indirect effects on other currents because of their voltage and time dependence during the course of a free-running action potential. The model predicted peak \( I_{Ca,L} \) to increase by 37% at the elevated plateau potential (Figure 3) and increases in the outward potassium currents \( I_{K1} \) and \( I_{K2} \) by 80% and 50%, respectively.

The characteristic triangular shape of APs in AF was reproduced by setting conductances of \( I_{K1}, I_{Ca,L}, I_{Kur}, I_{Kur}, \) and \( I_{Kur} \) to values of reported ion current densities or channel expression (Figures 1B and 3; see Reference 5 and Table 2). The effect of 4-aminopyridine was simulated by setting the maximum conductance of \( I_{Kur} \) to 20% of the AF control value and computing membrane currents in the course of the resulting AP. The simulation produced a shift of the plateau potential and an overall prolongation of APD20 and APD90 (Figure 3). The accompanying indirect changes of other currents were qualitatively similar to those in SR but were substantially smaller in size.

**Experimental Verification of Model Predictions \( I_{Ca,L}, I_{Kur} \)**

The model predicted an increase of \( I_{Ca,L} \) by block of \( I_{Kur} \). 4-Aminopyridine did not modulate \( I_{Ca,L} \) in atrial myocytes (peak current density during clamp steps from -80 to +10 mV: 5.5±1.3 pA/pF before and 5.1±1.0 pA/pF after 100 \( \mu \text{mol/L} \) 4-aminopyridine, \( n=8 \) cells from 6 SR patients; \( P=\text{NS} \)). Similar results, although at lower basal \( I_{Ca,L} \), were obtained in atrial myocytes from AF patients (data not shown). 4-Aminopyridine (100 \( \mu \text{mol/L} \)) had no effect on \( I_{K1} \) (data not shown).

To test for indirect effects of block of \( I_{Kur} \) on \( Ca^{2+} \) entry via \( I_{Ca,L} \), we measured \( F_\text{c} \) as an indirect indicator of \( I_{Ca,L} \) activity (Figure 4A). In SR trabeculae, 4-aminopyridine (100 \( \mu \text{mol/L} \)) enhanced \( F_\text{c} \) from 4.5±0.7 to 7.3±1.1 mN (\( n=8/6 \) trabeculae/patients), \( P<0.05 \). The EC50 for 4-aminopyridine obtained by curve fitting was 52 \( \mu \text{mol/L} \) (Figure 4B). With 1 mmol/L 4-aminopyridine, \( F_\text{c} \) increased maximally (8.8±1.3 mN), corresponding to 58±3% of the \( F_\text{c} \) developed by 8 mmol/L CaCl2 (14.9±1.6 mN). As expected, basal \( F_\text{c} \) was lower (1.3±0.4 mN, \( n=9/5, P<0.001 \)) and the effect of 4-aminopyridine on \( F_\text{c} \) was smaller in AF than in SR. \( F_\text{c} \) increased at 1 mmol/L 4-aminopyridine to 2.9±0.9 mN, corresponding to 28±8% of that obtained by 8 mmol/L CaCl2 (10.9±1.6 mN, \( P=\text{NS} \) versus SR). The EC50 value was 36 \( \mu \text{mol/L} \). The positive inotropic effects were not affected by (-)-propranolol and hence were independent of enhanced neurotransmitter release.\(^{15}\) If the effect of 4-aminopyridine on \( F_\text{c} \) was a result of the blockade of \( I_{Kur} \), it should be absent in ventricular preparations, in which \( I_{Kur} \) cannot be measured.\(^{15}\) Indeed, 4-aminopyridine (0.3 \( \mu \text{mol/L} \) to 1 mmol/L) did not affect \( F_\text{c} \) in ventricular trabeculae (Figure 4, C and D), excluding a direct effect of 4-aminopyridine on \( Ca^{2+} \) release or contractile machinery.

According to the model prediction in SR, the shortening of APD90 by block of \( I_{Kur} \) is expected to be induced by an increase in \( I_{K1} \). Block of \( I_{K1} \) with E-4031 (1 \( \mu \text{mol/L} \)) prolonged APD90, although the effect did not reach the level of statistical significance (\( P=0.3661, n=5 \), Figure 5, A and C). In the presence of E-4031, 4-aminopyridine (25 \( \mu \text{mol/L} \)) no longer shortened but rather prolonged APD90 from 412±33 ms (\( n=5, P=0.2217 \) versus control, \( P=0.0249 \)) and significantly elevated the notch and plateau potentials from -30±2 to -19±3 mV (\( n=5, P<0.005 \)) and from -27±2 to -14±3 mV (\( n=5, P<0.001 \)), respectively. These effects were reproduced in the model simulation by reducing the conductance of \( I_{K1} \) by 95% and that of \( I_{Kur} \) by 90% (Figure 5B).

**Effect of the \( I_{Kur} \) Blocker AVE 0118 on AP in SR and AF**

The effects of \( I_{Kur} \) inhibition were verified with the new \( I_{Kur} \) blocker AVE 0118 (6 \( \mu \text{mol/L} \)). AVE 0118 revealed the typical changes in AP shape as found with low concentrations of 4-aminopyridine (5 \( \mu \text{mol/L} \)), ie, elevation of the plateau potential from -16.3±4.1 to -6.7±2.4 mV (\( n=9, P<0.001 \)) in the presence of 6 \( \mu \text{mol/L} \) AVE 0118, and shortening of APD90 from 343±14 to 328±17 ms (\( P=0.066 \)) in SR. In AF, the plateau amplitude increased from -2.4±3.6 to 8.8±3.6 mV (\( n=6, P<0.001 \)), and APD90 increased from 260±14 to 280±13 ms (\( P<0.05 \); Figure 6).
Discussion

The concept of block of $I_{Kur}$ as a therapeutic target in AF is widely accepted, despite inconsistent experimental and theoretical evidence for changes in APD. Here, we report that selective block of $I_{Kur}$ shortens APD of human atrial trabeculae from SR but prolongs APD in AF. Changes in APD in SR and AF were consistent with secondary current changes as predicted by a modified Luo-Rudy model and were verified experimentally.

Effects of Block of $I_{Kur}$ on Shapes of Atrial APs in SR and AF

In low concentrations, 4-aminopyridine is a selective blocker of $I_{Kur}$. In earlier work, we found that 4-aminopyridine blocks $I_{Kur}$ and $I_{to,f}$ in human atrial myocytes with IC$_{50}$ values of 8 $\mu$mol/L and 1 mmol/L, respectively. Similar values were published by others (ie, 49 $\mu$mol/L for $I_{Kur}$ and 1.9 mmol/L for $I_{to,f}$).

Block of repolarizing outward current is expected to prolong APD; however, we observed shortening in SR preparations instead. In the literature, shortening, prolongation, and even no effect at all have been reported. How can these inconsistencies be reconciled? The shape of the cardiac AP is the result of the balanced activity of several ion currents. Provided that 4-aminopyridine at the concentrations used is in fact selective for $I_{Kur}$ block, APD shortening in SR must be associated with alterations in additional currents. In this context, the pronounced elevation of the action potential plateau may provide an important clue because enhanced amplitude of $I_{Ca,L}$ at more positive potentials could activate repolarizing outward currents that would shorten APD.

In AF, block of $I_{Kur}$ resulted in the expected APD prolongation. The characteristic triangular AP shape in AF compared with the spike-and-dome configuration in SR is a result of electrical remodeling that comprises changes in several ion currents.
conductances. The densities of $I_{\text{Ca,L}}$ and $I_{\text{to,f}}$ are reduced by $\approx 70\%$,\textsuperscript{16,17} and $\approx 60\%$,\textsuperscript{16,18,19} respectively, and inward rectifier $I_{\text{K}}$ is increased by $\approx 100\%$\textsuperscript{14,16,18,20}. From these considerations, it follows that selective block of $I_{\text{kur}}$ (or any other current) will perturb the balance of ion channel activation differently in AF and SR and may result in different patterns of secondary effects.

**Computer Simulations: Indirect Effects of 4-Aminopyridine on $I_{\text{Ca,L}}$**

To predict individual current changes secondary to selective block of $I_{\text{kur}}$, we used a computer model of AP simulation. For this purpose, ion conductances in the Luo-Rudy model\textsuperscript{9} were set to the experimentally observed values reported

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**Figure 4. Effect of 4-aminopyridine on $F_c$ in isolated human atrial and ventricular preparations.**

A. Original recordings of $F_c$ with increasing concentrations of 4-aminopyridine (300 nM to 1 mM) for atrial trabeculae from an SR patient (top) and an AF patient (below). B. Concentration-dependent effects of 4-aminopyridine on $F_c$ in atrial preparations from SR (open squares) and AF (open circles) patients (EC$_{50}$=52 $\mu$M/L, SR, and EC$_{50}$=36 $\mu$M/L, AF). Maximum contractile responses were tested with high extracellular Ca$^{2+}$ (8 mM/L) at end of each experiment. C. Original recordings of $F_c$ in time-matched controls (TMC, top) and with 4-aminopyridine (0.3 $\mu$M/L to 1 mM/L) of human ventricular trabeculae (below). D. Concentration-dependent effects of 4-aminopyridine on $F_c$ in human ventricular preparations.

**Figure 5. Effect of block of $I_{\text{kur}}$ by 4-aminopyridine in presence of $I_{\text{Kr}}$ block with E-4031.** A. Original AP registration in SR; C, control AP (solid line), 20 minutes after E-4031 (1 $\mu$M/L, short dashes), and 20 minutes after 4-aminopyridine (25 $\mu$M/L) in presence of E-4031 (long dashes). B, Simulated AP; C, control, after reducing $g_{\text{max}}$ of $I_{\text{Kr}}$ to 5% (dashed line) and $g_{\text{max}}$ of $I_{\text{kur}}$ to 10% of control value. C, Means of APD$_{90}$ (left), notch potential (middle), and plateau potential (right) for atrial trabeculae from SR patients ($n=5$, *$P<0.05$).
recently for human AF. The model simulated the characteristic AP shapes. For selective block of \( I_{Kr} \) in SR APs, the model produced a more pronounced spike-and-dome configuration. The shift of the plateau to more positive potentials was associated with enhanced \( I_{Ca,L} \) activation in the model (although 4-aminopyridine had no direct effects on \( I_{Ca,L} \)) and is expected to increase systolic \( Ca^{2+} \) influx during a free-running AP. Indeed, 4-aminopyridine significantly increased \( F_c \) in atrial trabeculae in a concentration-dependent manner (see Figure 4) in SR and AF, respectively. Although the positive inotropic effect was much smaller in AF, it is considered to be clinically interesting, because atrial contractility is already impaired in AF\(^2\) and all other drugs currently used in the treatment of AF, e.g., \( \beta \)-adrenoceptor blockers or calcium channel blockers, have a negative inotropic effect.

**Computer Simulations: Indirect Effects of 4-Aminopyridine on \( I_{Kr} \)**

Secondary enhancement of outward currents as an explanation for APD shortening in SR by block of \( I_{Kr} \) was also predicted by the model. As the likely candidates, the model identified \( I_{Kr} \) and \( I_{Ks} \). Because of its slow activation kinetics, \( I_{Kr} \) will not play a major role in the course of the short atrial APs. Conversely, the impact of \( I_{Ks} \) was examined experimentally: pharmacological block of \( I_{Ks} \) in trabeculae from SR un masks the APD-prolonging effect of \( I_{Kr} \) block (see Figure 4) in SR and AF, respectively. Although the positive inotropic effect was much smaller in AF, it is considered to be clinically interesting, because atrial contractility is already impaired in AF\(^2\) and all other drugs currently used in the treatment of AF, e.g., \( \beta \)-adrenoceptor blockers or calcium channel blockers, have a negative inotropic effect.

**TABLE 2. Maximum Conductances, \( g_{\text{max}} \), of the Main Currents Incorporated in the Mathematical Model for Action Potential Simulation**

<table>
<thead>
<tr>
<th>Current</th>
<th>SR</th>
<th>AF</th>
<th>Percent Change From SR</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_{Ca,L} )</td>
<td>( 7.2 \times 10^{-2} )</td>
<td>( 2.3 \times 10^{-2} )</td>
<td>(-68% )</td>
</tr>
<tr>
<td>( I_{Ks} )</td>
<td>( 1.8 \times 10^{-2} )</td>
<td>( 8.64 \times 10^{-3} )</td>
<td>(-52% )</td>
</tr>
<tr>
<td>( I_{Kr} )</td>
<td>( 1.6 \times 10^{-1} )</td>
<td>( 6.24 \times 10^{-2} )</td>
<td>(-61% )</td>
</tr>
<tr>
<td>( I_{K1} )</td>
<td>( 6.0 \times 10^{-2} )</td>
<td>( 6.0 \times 10^{-2} )</td>
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</tr>
<tr>
<td>( I_{Kr} )</td>
<td>( 5.0 \times 10^{-2} )</td>
<td>( 5.0 \times 10^{-2} )</td>
<td>Unchanged</td>
</tr>
<tr>
<td>( I_{K1} )</td>
<td>( 4.9 \times 10^{-2} )</td>
<td>( 9.6 \times 10^{-2} )</td>
<td>(+98% )</td>
</tr>
<tr>
<td>( I_{KCa} )</td>
<td>( 1.5 \mu \text{m} )</td>
<td>( 2.5 \mu \text{m} )</td>
<td>(+67% )</td>
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</table>

Values are in mS/\( \mu \text{F} \) except as noted. For simulations of AF action potentials, channel conductances were adapted to correspond to the reported changes in current density or were extrapolated from changes in mRNA and protein levels.\(^5\)

The model simulation of the human atrial SR AP reproduces the experimentally observed APD shortening that is induced by \( I_{Kr} \) block. However, this experimental finding is reproduced only when \( I_{Kr} \) is set to sufficiently high values (Table 2). If low values are used (see, for instance, Nygren et al\(^3\)), APD either is prolonged\(^3\) or remains unaffected.\(^2\) Although the large conductance of \( I_{Kr} \) assumed in our model was not proved with current measurements, the APD-prolonging effect of \( I_{Kr} \) block by E-4031 (Figure 5) points to a prominent role of this current in atrial repolarization, supported also by current measurements of \( I_{Kr} \) in human atrium.\(^2\) In the presence of \( I_{Kr} \) block, \( I_{Ks} \) inhibition further prolonged APD. We therefore assume that in multicellular trabeculae, \( I_{Kr} \) was fully available for repolarization. In conscious dogs, the \( I_{Kr} \) blocker ibutilide prolonged atrial monophasic APs and effective refractory period,\(^2\) providing evidence for a prominent \( I_{Kr} \) contribution.

Because \( I_{Ca,L} \) is reduced in AF, block of \( I_{Kr} \) cannot produce much indirect increase in \( I_{Ca,L} \), and therefore the plateau is only slightly elevated. Because of enhanced \( I_{Kr} \) in AF, rapid and strong induction of the repolarization process abbreviates the time window for activation of \( I_{Kr} \) and thus reduces its repolarizing potency. All interacting factors together will produce an AP-prolonging effect of \( I_{Kr} \) block, which possibly represents the antiarrhythmic potency of putative \( I_{Kr} \) blockers.

**Study Limitations**

The majority of patients donating tissue samples suffered from coronary artery disease. Therefore, AP measurements from SR trabeculae may not be considered to be fully representative of APs from trabeculae of a healthy population. In addition, the patients’ medications may have additional effects. The large variability in action potential shapes may represent this inhomogeneity of the material.

Early repolarization is controlled not only by \( I_{Kr} \) but also by \( I_{K1} \). Although low concentrations of 4-aminopyridine are selective for block of \( I_{Kr} \), a contribution of \( I_{K1} \) block cannot be excluded at larger concentrations. In the absence of selective blockers for \( I_{K1} \), model simulations are useful for estimating the consequences of \( I_{K1} \) block on atrial AP. Like \( I_{Kr} \) block, reduced basal conductance of \( I_{K1} \) shifted the notch potential to more positive values and abbreviated APD\(_{90}\) in...
SR and only slightly prolonged APD\textsubscript{90} in AF. In contrast to 
\( I_{\text{Kur}} \) block, selective block of \( I_{\text{Kur}} \) did not elevate the dome 
potential or enhance the spike-and-dome configuration (data 
not shown). The rapid \( I_{\text{Kur}} \) inactivation most likely limits 
indirect enhancement of \( I_{\text{Kur}} \) if \( I_{\text{Kur}} \) is blocked.

Conclusions
We hypothesize that \( I_{\text{Kur}} \) is a major determinant in controlling 
action potential shape and therefore also contractility in the 
human atrium. The antiarrhythmic potency of \( I_{\text{Kur}} \) inhibitors is 
determined largely by the level of electrical remodeling of the 
diseased atrium. Although the antiarrhythmic effectiveness of 
\( I_{\text{Kur}} \) blockers is significantly attenuated in chronic AF,\textsuperscript{26} 
selective \( I_{\text{Kur}} \) blockers may be more potent in prolonging atrial 
refractory period in chronic AF than in SR and may therefore 
be more efficient in terminating AF than in maintaining SR.

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