Inhibition of the Cardiac L-Type Calcium Channel Current by Antidepressant Drugs

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Received October 2, 2007; accepted November 28, 2007

ABSTRACT

Antidepressants inhibit many membrane receptors and ionic channels, including the L-type calcium channel. Here, we investigated the inhibition of calcium current (I_{Ca}) by antidepressants in enzymatically isolated rat ventricular myocytes using whole-cell patch clamp. The molecular mechanism of inhibition was studied by comparing the voltage and state dependence of antidepressant inhibition of I_{Ca} to the respective properties of calcium antagonists, and by studying the effect of (±)-1,4-dihydro-2,6-dimethyl-5-nitro-4-(2-[trifluoromethyl]phenyl)-3-pyridine carboxylic acid methyl ester (Bay K8644) or diltiazem on the inhibitory potency of the antidepressants. All selected antidepressants inhibited calcium currents reversibly and concentration-dependently. At a stimulation frequency of 0.33 Hz, the antidepressants imipramine, clomipramine, desipramine, amitriptyline, maprotiline, citalopram, and dibenzepin blocked I_{Ca}, with IC_{50} values of 8.3, 11.6, 11.7, 23.2, 31.0, 64.5, and 364 μM. The antidepressant drugs shifted steady-state inactivation curves of I_{Ca} to negative voltages. The extent of the shift was similar to that induced by diltiazem or verapamil, but it was significantly smaller than that induced by felodipine. The use-dependent component of the antidepressant-induced block was similar to that of diltiazem, and it was significantly more and less, respectively, than those of felodipine and verapamil. In the presence of Bay K8644, antidepressants were more effective in inhibiting I_{Ca}. However, the inhibitory effect of antidepressants was also augmented by diltiazem, suggesting that these drugs do not compete with diltiazem for a single binding site. These data suggest that antidepressants exert their inhibitory action on cardiac L-type calcium channels by a specific interaction at a receptor site similar to, but distinct from, the benzothiazepine site.

Antidepressants of different chemical structure and mechanism of action are used in the therapy of major depression (DeVane, 1998). Due to their unspecific mode of action, they produce many side effects, cardiotoxicity being among the most serious effects (Glassman, 1998). Tricyclic antidepressants are known to inhibit calcium currents in heart myocytes (Isenberg and Tamargo, 1985; Delpón et al., 1991) and in neurons (Ogata et al., 1989; Choi et al., 1992). They also modulate binding of dihydropyridines and that of diltiazem and gallopamil to the calcium channel (Schaeffer et al., 1991; Rehavi et al., 1993), and calcium antagonists of the verapamil type were shown to affect binding of [3H]imipramine (Rehavi et al., 1988). However, no attempt was made to specify the mechanism of the interaction between the antidepressant drugs and the L-type calcium channel. Antidepressants affect diverse membrane receptors and transport systems (Hall and Ogren, 1981; White et al., 1990; Habuchi et al., 1991; Rana et al., 1993; Wooltorton and Mathie, 1993), as do many other amphiphilic molecules, including calcium antagonists, in the high (micromolar) concentration range (e.g., Hargreaves et al., 1996; Rauer and Grissmer, 1996). Thus, understanding the degree of specificity of these drugs and the mechanisms involved in the drug-receptor interaction is of general importance. In the present work, we study the mechanism of the inhibitory effects of a series of antidepressants on L-type calcium channels. We have used seven antidepressants (Fig. 1): imipramine and its closely related derivatives clomipramine and desipramine; the less structurally related tri- and tetracyclic drugs amitriptyline, maprotiline, and dibenzepin; and the very different citalopram (a selective serotonin reuptake inhibitor), to test whether the effects of antidepressants on the L-type calcium current (I_{Ca}) are determined by their specific molecular characteristics. All these drugs are widely used in the therapy of major depression.

ABBREVIATIONS: I_{Ca}, calcium current; BTZ, benzothiazepine; TTX, tetrodotoxin; IBMX, 3-isobutyl-1-methylxanthine; ANOVA, analysis of variance; DHP, dihydropyridine; Bay K8644, (±)-1,4-dihydro-2,6-dimethyl-5-nitro-4-(2-[trifluoromethyl]phenyl)-3-pyridine carboxylic acid methyl ester.
depression. We show that all the studied antidepressants inhibit L-type calcium channel current specifically and in a use- and voltage-dependent manner. Our results suggest that the antidepressants exert their inhibitory action at a binding site that has similar properties to the benzothiazepine (BTZ) receptor of the L-type calcium channel but is distinct from it.

Materials and Methods

Isolation of Myocytes. Ventricular myocytes were isolated from male Wistar rats (200–250 g) as described previously (Zahradník and Palade, 1993). Cell isolation routinely yielded 50 to 70% of rod-shaped, viable, calcium-tolerant cells. The experimental protocol was approved by the State Veterinary and Food Administration of the Slovak Republic, and all animal procedures complied with the appropriate animal care regulations.

Calcium Current Measurements. The $I_{\text{Ca}}$ was recorded using standard whole-cell patch clamp (Hamill et al., 1981). The myocytes were placed into the perfusion channel (volume 50 μl) allowing rapid (<1 s) and complete exchange of external solutions. Sodium current was inhibited using −50-mV holding potential and 20 μM tetrodotoxin (TTX) in the external solution, and potassium currents were blocked by replacing K+ with Cs+ in both external and internal solution. The standard pulse protocol for recording calcium currents consisted of a continuous train of 70-ms-long voltage pulses elicited every 3 s from a holding potential of −50 mV. Calcium channels were kept in phosphorylated state by including 50 μM cAMP to the internal solution and 10 μM 3-isobutyl-1-methylxanthine (IBMX; a membrane-permeant phosphodiesterase inhibitor) into the external solution. These conditions were chosen to standardize cell status by reducing the variability of calcium currents due to variable phosphorylation level of calcium channels in isolated myocytes (Zahradník and Palade, 1993), to reduce calcium current rundown (Ono and Fozzard, 1992), and to eliminate the consequences of eventual inter- actions of the studied drugs with the phosphorylation/dephosphorylation pathways. Experiments were carried out at 20 to 24°C.

Solutions for Patch-Clamp Recordings. The external solution contained 135 mM NaCl, 5.4 mM CsCl, 0.33 mM NaH2PO4, 1 mM CaCl2, 0.02 mM TTX, and 0.01 mM IBMX, pH 7.3. This solution was also used as the vehicle for the drugs. The internal solution contained 135 mM CsCl, 10 mM CaCl2, 10 mM HEPES, 1 mM EGTA, 3 mM MgSO4, 3 mM ATP, and 0.05 mM cAMP, pH 7.3.

Data Analysis. Whole-cell currents were measured with the EPC-7 patch-clamp amplifier (List Medical Electronics, Darmstadt, Germany), they were filtered at 2 kHz, and they were digitized at 5 kHz by the LabMaster interface (Scientific Solutions, Mentor, OH) using pClamp version 5.5.1 (Axon Instruments, Foster City, CA). Series resistance (≥2.5 MΩ) was compensated electronically by ±50%.

Results

The effect of the antidepressants on the peak amplitude of $I_{\text{Ca}}$ was investigated using the standard pulse protocol. In the typical experiment of Fig. 2A, application of progressively higher concentrations of desipramine led to a concentration-dependent inhibition of $I_{\text{Ca}}$. The IC50 value for desipramine in this particular experiment was 11.0 μM. The inhibition of $I_{\text{Ca}}$ proceeded rapidly, and it was reversible. All antidepressants tested in this study provided qualitatively similar results. Although inhibition by the antidepressants required higher drug concentrations than inhibition by the calcium antagonists felodipine, verapamil, and diltiazem (Zahradní-
ková et al., 2007), their concentration dependence was of the same form as that of the calcium antagonists, and full inhibition could be achieved at a sufficiently high drug concentration. The concentration dependence of antidepressant action on calcium currents is illustrated in Fig. 3. The fast and concentration-dependent inhibitory action of antidepressants suggests that their effect might be caused by interaction with a specific receptor site on the L-type calcium channel.

**State Dependence of the Inhibitory Action.** Inhibition of $I_{\text{Ca}}$ by calcium antagonists is known to be accompanied by a shift of the calcium current inactivation ($I_{\text{Ca}}$ availability) curve to negative voltages (Sanguinetti and Kass, 1984; Uehara and Hume, 1985), resulting in increase of drug potency with membrane depolarization. To assess the effect of antidepressants on $I_{\text{Ca}}$ availability, we measured $I_{\text{Ca}}$ in response to test voltage pulses to $-11001$ mV, applied every 10 s from a holding potential of $-11002$ mV. The test pulses were preceded by 5-s prepulses to a set of inactivating voltage levels (ranging between $-11002$ and $-11003$ mV) separated from the test pulse by a 15-ms sojourn at $-11002$ mV. Typical currents recorded with this protocol in the absence and presence of 20 $\mu$M amitriptyline are shown in Fig. 2B. Peak amplitudes of currents were normalized relative to the maximal amplitude in each experiment (Fig. 2C), and the data were fitted with the Boltzmann equation with a midpoint $V_{0.5}$ and a slope parameter $k$. Antidepressants evoked a negative shift of $V_{0.5}$ of the $I_{\text{Ca}}$ availability curve, reversible on washout of the drugs. The values of the shifts in $V_{0.5}$ and $k$ for the antidepressants and for the representatives of the three

**Fig. 2.** Concentration and voltage dependence of antidepressant action. A, onset, concentration dependence and washout of the inhibition of calcium current by antidepressants. The myocyte was first exposed to control solution. During the periods indicated by horizontal lines, the myocyte was exposed to progressively higher concentrations of desipramine, applied by fast perfusion. Then, the myocyte was perfused with drug-free solution again. The values of $I_{\text{Ca}}$ are plotted as a function of time. Top, current traces recorded at the times indicated (solid symbols, bottom) are shown. B, voltage dependence of $I_{\text{Ca}}$ inhibition by antidepressants. Currents were evoked by depolarizations to 0 mV, preceded by 5-s prepulses to the indicated potentials in the absence (left) and presence (right) of 20 $\mu$M amitriptyline. The inhibition of $I_{\text{Ca}}$ by the drugs is more apparent after larger depolarizing prepulses. C, effect of antidepressants on the $I_{\text{Ca}}$ availability curve. The peak currents from B were normalized and plotted as a function of voltage. In the presence of 20 $\mu$M amitriptyline (open symbols), the $I_{\text{Ca}}$ availability curve is shifted to the left with respect to the control curve (solid symbols).

**Fig. 3.** Concentration dependence of the studied antidepressants. The peak currents from experiments such as those in Fig. 2A were normalized and plotted as a function of drug concentration. Different symbols represent different antidepressants: solid squares, circles, and triangles stand for imipramine, desipramine, and clomipramine, respectively; open squares, circles, and triangles stand for amitriptyline, maprotiline, and citalopram, respectively; and the semisolid squares stand for dibenzepin. Solid lines represent the theoretical concentration dependences, parameters of which are given in Table 2. The Hill coefficients were not significantly different from $n_H = 1$ nor from each other.
TABLE 1
State dependence of antidepressant effects

<table>
<thead>
<tr>
<th>Drug</th>
<th>Concentration</th>
<th>$\Delta V_{0.5}$</th>
<th>$\Delta k$</th>
<th>$n$</th>
<th>Use Dependence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mu mol/l$</td>
<td>mV</td>
<td></td>
<td></td>
<td>%</td>
</tr>
<tr>
<td>Imipramine</td>
<td>10</td>
<td>$-7.4 \pm 0.9^{**}$</td>
<td>0.5 $\pm$ 0.3</td>
<td>3</td>
<td>41 $\pm$ 3</td>
</tr>
<tr>
<td>Clomipramine</td>
<td>20</td>
<td>$-4.1 \pm 0.9^{**}$</td>
<td>0.5 $\pm$ 0.2</td>
<td>5</td>
<td>33 $\pm$ 3</td>
</tr>
<tr>
<td>Desipramine</td>
<td>20</td>
<td>$-3.9 \pm 0.9^{**}$</td>
<td>0.5 $\pm$ 0.2</td>
<td>3</td>
<td>37 $\pm$ 3</td>
</tr>
<tr>
<td>Amtriptyline</td>
<td>20</td>
<td>$-3.5 \pm 0.4^{**}$</td>
<td>0.5 $\pm$ 0.3</td>
<td>3</td>
<td>39 $\pm$ 2</td>
</tr>
<tr>
<td>Maprotiline</td>
<td>20</td>
<td>$-2.4 \pm 0.4^{**}$</td>
<td>0.3 $\pm$ 0.3</td>
<td>3</td>
<td>29 $\pm$ 1</td>
</tr>
<tr>
<td>Citalopram</td>
<td>50</td>
<td>$-3.5 \pm 0.5^{**}$</td>
<td>0.2 $\pm$ 0.1</td>
<td>6</td>
<td>39 $\pm$ 3</td>
</tr>
<tr>
<td>Dibenzepin</td>
<td>500</td>
<td>$-6.4 \pm 1.2^{**}$</td>
<td>1.4 $\pm$ 0.4$^{**}$</td>
<td>4</td>
<td>32 $\pm$ 3</td>
</tr>
<tr>
<td>Felodipine</td>
<td>0.01</td>
<td>$-15.3 \pm 2.0^{**}$</td>
<td>4.8 $\pm$ 0.2$^{**}$</td>
<td>3</td>
<td>8 $\pm$ 3$^{**}$</td>
</tr>
<tr>
<td>Verapamil</td>
<td>0.5</td>
<td>$-4.3 \pm 0.3^{**}$</td>
<td>0.6 $\pm$ 0.2</td>
<td>4</td>
<td>87 $\pm$ 5$^{**}$</td>
</tr>
<tr>
<td>Diltiazem</td>
<td>1</td>
<td>$-4.9 \pm 1.0^{**}$</td>
<td>0.3 $\pm$ 0.2</td>
<td>5</td>
<td>47 $\pm$ 8</td>
</tr>
</tbody>
</table>

** $P < 0.01$ (paired t test).
†† Significantly less than other drugs (ANOVA; $P < 0.05$).
§§ Significantly more than other drugs (ANOVA; $P < 0.05$).
$^a$ Number of experiments.
$^b$ The average values of inactivation curve parameters under control conditions were $V_{0.5} = -25.4 \pm 0.8$ mV; $k = 3.9 \pm 0.1$ mV ($n = 21$).

The properties of the antidepressant-binding site on the calcium channel were further investigated by studying the inhibitory effects of antidepressants on calcium currents prestimulated by Bay K8644. Figure 5A shows typical responses of the L-type calcium channel, measured as $I_{Ca}$, to application of antidepressants (desipramine in the illustrated case) in the continuing presence of 300 nM Bay K8644. It can be seen that in
the presence of Bay K8644 desipramine induced a more pronounced decrease in $I_{Ca}$ than in the absence of the agonist. In the illustrated experiment, the IC$_{50}$ value for desipramine in the presence of Bay K8644 was 7.3 μM. The results of these experiments are compared in Table 2 (middle columns) to those performed in the absence of Bay K8644 (Table 2, leftmost column), together with the data of Zahradníková et al. (2007) that were obtained under the same conditions for the three types of calcium channel antagonists. The differences between the effect of Bay K8644 on the inhibitory potency of antidepressants and calcium antagonists were tested at concentrations of drugs that induced approximately 50% inhibition in the absence of Bay K8644.

### TABLE 2
Effect of Bay K8644 or diltiazem on parameters of the concentration dependence of $I_{Ca}$ inhibition by antidepressants and Ca$^{2+}$ antagonists

<table>
<thead>
<tr>
<th>Drug</th>
<th>Control IC$_{50}$ μmol/l</th>
<th>$n_{H}$</th>
<th>$n^*$</th>
<th>in 300 nmol/l Bay K8644 IC$_{50}$ μmol/l</th>
<th>$n$</th>
<th>in 1.5 μmol/l Diltiazem IC$_{50}$ μmol/l</th>
<th>$n^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imipramine</td>
<td>8.1 ± 0.6</td>
<td>1.02 ± 0.03</td>
<td>11</td>
<td>5.38 ± 0.42*</td>
<td>4</td>
<td>N.D.</td>
<td></td>
</tr>
<tr>
<td>Clomipramine</td>
<td>11.6 ± 0.5</td>
<td>1.09 ± 0.06</td>
<td>22</td>
<td>6.81 ± 0.73**</td>
<td>5</td>
<td>N.D.</td>
<td></td>
</tr>
<tr>
<td>Desipramine</td>
<td>11.7 ± 0.6</td>
<td>1.11 ± 0.07</td>
<td>10</td>
<td>6.93 ± 0.37**</td>
<td>3</td>
<td>9.30 ± 0.79*</td>
<td>4</td>
</tr>
<tr>
<td>Amitriptyline</td>
<td>22.2 ± 1.2</td>
<td>1.12 ± 0.08</td>
<td>11</td>
<td>11.95 ± 0.64**</td>
<td>6</td>
<td>15.7 ± 4.5*</td>
<td>4</td>
</tr>
<tr>
<td>Maprotiline</td>
<td>31.0 ± 2.8</td>
<td>1.06 ± 0.07</td>
<td>8</td>
<td>18.0 ± 1.8**</td>
<td>3</td>
<td>15.1 ± 2.1**</td>
<td>3</td>
</tr>
<tr>
<td>Citalopram</td>
<td>64.5 ± 3.3</td>
<td>1.08 ± 0.05</td>
<td>7</td>
<td>22.0 ± 1.3**</td>
<td>5</td>
<td>32.0 ± 4.7**</td>
<td>5</td>
</tr>
<tr>
<td>Dibenzepin</td>
<td>364 ± 12</td>
<td>1.14 ± 0.08</td>
<td>15</td>
<td>87 ± 11**</td>
<td>4</td>
<td>91 ± 31**</td>
<td>3</td>
</tr>
<tr>
<td>Felodipine*</td>
<td>0.011 ± 0.003</td>
<td>1.02 ± 0.10</td>
<td></td>
<td>0.165 ± 0.026††</td>
<td></td>
<td>N.D.</td>
<td></td>
</tr>
<tr>
<td>Verapamil§</td>
<td>0.246 ± 0.013</td>
<td>1.02 ± 0.04</td>
<td></td>
<td>0.737 ± 0.071††</td>
<td></td>
<td>N.D.</td>
<td></td>
</tr>
<tr>
<td>Diltiazem§</td>
<td>0.512 ± 0.041</td>
<td>1.07 ± 0.07</td>
<td></td>
<td>0.227 ± 0.014**</td>
<td></td>
<td>N.A.</td>
<td></td>
</tr>
</tbody>
</table>

N.A., not applicable; N.D., not determined.

* $P < 0.05$ and ** $P < 0.01$, significantly less than in control.

†† $P < 0.01$, significantly more than in control.

§ Number of experiments.

§§ Data from Zahradníková et al. (2007).
K8644. The apparent value of IC$_{50}$ of individual antidepressants was decreased by 45 to 75%, whereas the IC$_{50}$ value of diltiazem was decreased by ~50%, and the IC$_{50}$ values of verapamil and felodipine were increased 3 times and 15 times, respectively, in the presence of Bay K8644. The effect of Bay K8644 on the potency of antidepressants was not significantly different from its effect on the potency of diltiazem, whereas there was a statistically significant difference between the effect of Bay K8644 on the potency of verapamil and felodipine on one hand, and on the potency of antidepressants on the other hand.

**Interaction between Antidepressants and Diltiazem.**

The previously shown results demonstrate a high similarity in the mode of action of diltiazem and the studied antidepressants. Therefore, the possibility that antidepressants interact with the BTZ receptor site on the calcium channel was investigated by comparing the extent of antidepressant-induced inhibition of $I_{\text{Ca}}$ in the absence and presence of diltiazem. If diltiazem and antidepressants competed for a common binding site on the calcium channel, the presence of diltiazem would lead to a decrease of the apparent affinity of the channel to the antidepressants, i.e., to an increase in their IC$_{50}$ values. Concentrations of diltiazem that induced at least 50% inhibition were chosen, so that at least a 100% increase of the apparent value of IC$_{50}$ for a competing drug should be observed. Figure 5B shows a typical example of the time course of $I_{\text{Ca}}$ during such an experiment. The data for five of the antidepressants (desipramine, amitriptyline, maoprotoline, citalopram, and dibenzepin) are summarized in Table 2 (rightmost columns). It is clear from Fig. 5B and Table 2 that the effect observed is opposite to that expected for a competitive interaction: the antidepressant-evoked inhibition of $I_{\text{Ca}}$ is more pronounced in the presence than in the absence of diltiazem. In the illustrated experiment, 20 µM amitriptyline induced 60% inhibition of $I_{\text{Ca}}$, whereas in the absence of diltiazem the same concentration induced 47% inhibition on average. The higher decrease in $I_{\text{Ca}}$ was not caused by rundown, because after removal of amitriptyline and in the continuing presence of diltiazem, the current returned to 90% of the value before amitriptyline application, and after removing diltiazem block by 1-min-lasting hyperpolarization to $-80$ mV, $I_{\text{Ca}}$ increased to 110% of predrug control. In none of the experiments did diltiazem induce a decrease in the inhibitory potency of antidepressants. The increase in potency of antidepressants in the presence of diltiazem was significant for all antidepressants tested, when the apparent IC$_{50}$ values were compared. In the presence of diltiazem, the apparent IC$_{50}$ value of desipramine and amitriptyline was decreased by 25 to 35% and that of maprotiline, citalopram, and dibenzepin was decreased by >50% (Table 2). These results strongly suggest that the antidepressants do not act at the same binding site as diltiazem does.

**Discussion**

The principal finding of this work is that antidepressants inhibit cardiac calcium current by binding to a specific receptor on the L-type calcium channel. From the electrophysiological viewpoint, these drugs in every aspect resemble calcium antagonists. The shape of the concentration dependence curves and the rates of the onset and washout of inhibition at concentrations of the antidepressants close to their IC$_{50}$ values are similar to those of calcium antagonists (Uehara and Hume, 1985; Méry et al., 1996; Zahradníková et al., 2007). The inhibitory action of the antidepressants is dependent on the conformational state of the channel in a manner comparable with nondihydropyridine calcium antagonists, as demonstrated by the shift in the calcium channel availability curve.

The above-mentioned properties are shared with all types of calcium antagonists—dihydropyridines, phenylalkylamines, and benzoazepines (for review, see McDonald et al., 1994). The level of use dependence of the investigated antidepressants is intermediate, as is the case with diltiazem, i.e., they are significantly less use-dependent than verapamil, but significantly more so than the dihydropyridine felodipine (Table 1) (McDonald et al., 1994).

The study of the effect of Bay K8644 on the potency of the inhibitors showed direct evidence for interaction of antidepressants with a receptor allosterically coupled to the dihydropyridine binding site. Antidepressants share the property with diltiazem of strongly enhanced inhibitory potency in the presence of Bay K8644. These observations are in accordance with the previously observed antidepressant-induced increase of the Hill slope and binding affinity of the dihydropyridine felodipine to the calcium channel (Minarovic et al., 1996), which is typical for the benzothiazepines (Minarovic and Meszaros, 1998; also see Striessnig et al., 1986), but they contrast with the results of Murphy et al. (1983), who found no change in binding of $[^{3}H]$nitrendipine to smooth muscle membranes after application of clomipramine and nortriptyline at 25 µM concentrations.

Our direct measurements of the action of antidepressants on $I_{\text{Ca}}$ in cardiac myocytes in the presence of diltiazem show that these drugs do not directly compete with diltiazem, as opposed to the observation in neuronal membrane preparations (Schaeffer et al., 1991). The inability to observe competition between drugs in electrophysiological experiments is not inherent to the method used, since direct competition between drugs that act at the dihydropyridine receptor, i.e., Bay K8644 and felodipine, could be convincingly demonstrated using the same protocols (Zahradníková et al., 2007). Therefore, the antidepressant drugs most probably act at a site distinct from the benzothiazepine receptor.

To give molecular interpretation to our findings, we extended the guarded modulated receptor model of the L-type calcium channel (Berjukow et al., 1999) to incorporate the simultaneous action of an agonist and a non-DHP antagonist. These authors have shown the importance of both, the preferential drug binding to inactivated channels and the slow rate of drug unbinding from noninactivated channels in the phenomenon of use dependence (Fig. 6A). In the depolarized state, drugs have high affinity to the channel, because of the high rate of drug binding in the open state and of drug trapping in the inactivated state. Unbinding of the drug occurs mainly upon recovery from inactivation. In polarized cells, occupation of the antidepressant site hinders unbinding of the drug from the DHP or BTZ site (Fig. 6, B and C), and vice versa, thus effectively increasing drug affinity and accounting for positive cooperativity. In other words, the rate constants from the ternary complexes are decreased in the closed states of the channel. In depolarized cells, when the channels reside in the open state(s), the interaction of antidepressants and the BTZ or DHP drugs with their respective
binding sites is stericly hindered. As a result, the association rate constants of the ternary complex receptor-antidepressant-BTZ or DHP drug are lower than the rate constants of binary drug-channel complexes in the open state(s) of the channel (Fig. 6, B and C), effectively decreasing drug affinity and accounting for negative cooperativity. It is conceivable that steady-state inhibition by antidepressants (moderately use-dependent compounds) is more dependent on the interaction of the drugs with the closed and recovering channel than with the open channels, and thus positive cooperativity prevails during steady-state stimulation.

We have shown here that all of the investigated antidepressants block the L-type calcium currents in a concentration-dependent manner. The potency of the drugs ranged over 2 orders of magnitude. Because of the voltage and use dependence of antidepressant action (Table 1), their concentration dependence will be affected by changes in the holding potential, test pulse duration, and stimulation frequency. In addition, the level of calcium channel phosphorylation may affect binding of the antidepressants, in analogy to the observed effects of β-adrenergic stimulation on inhibition of calcium current by the dihydropyridines (Legsey et al., 1997). Our estimates of drug potency are in good agreement with the single concentration data for imipramine obtained by others (Isenberg and Tamargo, 1985; Delpón et al., 1991; Hamplová-Pechlová et al., 2002). This difference might have been due to differences in experimental conditions (cultured versus acutely isolated cells), differences in the phosphorylation status of the cells, or the use of Ba2+ as the charge carrier in their experiments.

The inhibitory potency of the studied antidepressants was not clearly related to their chemical structure, i.e., it did not decrease with increasing structural disparity from the most potent imipramine. The least related drug, citalopram, was more than 6 times more potent than the tricyclic dibenzepin. The relationship between IC50 and drug lipophilicity is also not direct: The three structurally similar drugs, desipramine, imipramine, and clomipramine, have similar potency (IC50 values of 11.7, 8.1, and 11.6 μM, respectively), but their experimentally determined log P at pH 7.4 varies from 1.5 (desipramine) to 2.5 (imipramine) to 3.3 (clomipramine) (Hansch et al., 1987). In contrast, the calculated lipophilicities of the lipophilic core of these drugs are less different (3.73, 3.73, and 4.25, respectively). We have determined that the pKd values of these three drugs under the conditions of our experiments are 9.0, 7.8, and 6.7, respectively. This means that although more than 95% of desipramine is ionized at pH 7.4, almost 75% of imipramine and less than 50% of clomipramine is ionized under the same conditions. Therefore, one could speculate that for drugs with similar structure, the lipophilicity of the drug core is determining their IC50 value, i.e., both charged and uncharged forms of the drugs are equally effective. The distance between the carbon atoms of the lipophilic ring structure with the alkylamine moiety, and the partially ionized amine nitrogen is similar in all drugs (5.02 ± 0.01 nm), except the least potent dibenzepin (3.82 nm). On the basis of these data, we suggest that the drugs interact with a binding site that is within the membrane, but close enough to the external side of the membrane to allow interaction of both charged and uncharged drugs having at least two carbons between the amine/ammonium group and the lipophilic ring.

Acknowledgments

We acknowledge the late Prof. J. Pogády (Psychiatric Hospital, Pezinok, Slovak Republic) for suggesting this study and M. Danišová for technical assistance. We acknowledge the generous gifts of citalopram from Lundbeck and of felodipine from Astra Hae äsele.

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