Mechanism of Sodium Channel Block by Venlafaxine in Guinea Pig Ventricular Myocytes

MAJED KHALIFA, PASCAL DALEAU, and JACQUES TURGEON
Quebec Heart Institute, Laval Hospital, Faculty of Pharmacy, Laval University (M.K., J.T.); and Faculty of Medicine, Laval University (P.D., J.T.), Sainte-Foy, Canada

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ABSTRACT
Venlafaxine is a newly introduced antidepressant agent. The drug causes selective inhibition of neuronal reuptake of serotonin and norepinephrine with little effect on other neurotransmitter systems. Cases of seizures, tachycardia, and QRS prolongation have been observed following drug overdose in humans. The clinical manifestations of cardiac toxicity suggest that venlafaxine may exhibit cardiac electrophysiological effects on fast conducting cells. Consequently, studies were undertaken to characterize effects of venlafaxine on the fast inward sodium current \( I_{Na} \) of isolated guinea pig ventricular myocytes. Currents were recorded with the whole-cell configuration of the patch-clamp technique in the presence of \( Ca^{2+} \) and \( K^+ \) channel blockers. Results obtained demonstrated that venlafaxine inhibits peak \( I_{Na} \) in a concentration-dependent manner with an estimated \( IC_{50} \) of \( 8 \times 10^{-6} \) M. Inhibition was exclusively of a tonic nature and rate-independent. Neither kinetics of inactivation \( (\tau_{inac} = 0.652 \pm 0.020 \text{ ms}, \text{ under control conditions}; \quad \tau_{inac} = 0.635 \pm 0.050, \text{ in the presence of } 10^{-5} \text{ M venlafaxine}; \quad n = 5 \text{ cells isolated from five animals}) \), nor kinetics of recovery from inactivation of the sodium channels \( (\tau_{re} = 58.7 \pm 1.6 \text{ ms}, \text{ under control conditions}; \quad \tau_{re} = 54.4 \pm 1.8, \text{ in the presence of } 10^{-5} \text{ M venlafaxine}; \quad n = 10 \text{ cells isolated from six animals}) \), were significantly altered by \( 10^{-5} \) M venlafaxine. These observations led us to conclude that venlafaxine blocks \( I_{Na} \) following its binding to the resting state of the channel. Thus, the characteristics of block of \( I_{Na} \) by venlafaxine are different from those usually observed with most tricyclic antidepressants or conventional class I antiarrhythmic drugs.

Depression is a very common and disabling disease with important social and economic implications (Wells et al., 1989). Although many antidepressant agents are available for the management of this disorder, their efficacy is often limited because toxic events can be encountered. Their most serious adverse effects include the risk for life-threatening arrhythmias, especially in patients with preexisting cardiac disease or after overdose administration. Newly introduced antidepressive agents, including venlafaxine (Effexor), have improved compliance and response to drug treatment in various psychiatric disorders (Thase, 1996). Indeed, venlafaxine is perceived as a first-line agent in the treatment of depression because the drug possesses a better safety profile than some older antidepressant agents (Cunningham et al., 1994; Rudolph and Derivan, 1996; Ballenger, 1996; Van Gelder et al., 1998). Pharmacological action of venlafaxine involves inhibition of presynaptic reuptake of serotonin, norepinephrine, and, to a lesser extent, dopamine. Unlike the tricyclic antidepressant agents, venlafaxine does not have affinity for histamine, muscarinic, or \( \alpha_1 \)-adrenergic receptors (Grunder et al., 1996). Thus, it should not exhibit side effects traditionally associated with blockade of these receptors. Despite several studies evaluating venlafaxine efficacy and side effect profiles, there is limited information on its electrophysiological cardiovascular properties. Treatment with venlafaxine could be associated with some cardiovascular effects such as elevation of heart rate and blood pressure (Grunder et al., 1996; Rudolph and Derivan, 1996; Khan, 1998). Cases of seizures, hypotension, and sinus tachycardia also have been described in the setting of overdose administration (Fantaskey and Burkhart, 1995; Parsons et al., 1996; Dahl et al., 1996; Durback and Scharman, 1996; Kokan and Dart, 1996; Zhalkovsky et al., 1997; Peano et al., 1997; Rosen et al., 1997). In addition, widening of the QRS interval has been observed during treatment with venlafaxine in some patients. This observation led us to examine the cardiac electrophysiological properties of the drug by studying its effects on inward sodium current \( (I_{Na}) \), the major ionic current involved in the depolarization of cardiac ventricular myocytes and impulse propagation within the ventricles.

ABBREVIATION: \( I_{Na} \), sodium current.
Materials and Methods

Experiments were performed in accordance with institutional guidelines of Laval University on animal use in research. Animals were housed and maintained in compliance with the Guide to the Care and Use of Experimental Animals of the Canadian Council on Animal Care.

Cell Preparation and Electrophysiological Measurements.

Experiments were performed on single ventricular myocytes obtained from adult guinea pig hearts by use of an enzymatic dissociation technique described in Daleau et al. (1995). A small aliquot of dissociated cells was placed in a 0.5-ml chamber mounted on the stage of an inverted microscope (model CK2; Olympus). Cells were allowed to adhere to the coverslip at the bottom of the chamber and were superfused continuously with the external solution containing 20 mM NaCl, 110 mM CsCl, 2 mM MgCl₂, 2 mM CaCl₂, 3 mM CoCl₂, 10 mM HEPES, 10 mM glucose, and 10 mM tetraethylammonium. The presence of cobalt in the extracellular solution is expected to allow full recovery from inactivation. The peak amplitude of $I_{Na}$ was 8 ± 2 nA at a holding potential of −20 mV from a holding potential of −120 mV. Estimated IC₅₀ for block of $I_{Na}$ was 8 ± 6 M. A total of 27 cells was used (the number of animals from which cells were isolated is indicated in parentheses) and is distributed as follows: 4 (2), 5 (2), 10 (6), 5 (3), and 3 (2), respectively, for venlafaxine (10⁻⁶, 3 · 10⁻⁶, 10⁻⁵, 3 · 10⁻⁵, and 10⁻⁴ M).

Concentration gradient of sodium and temperature were reduced to improve recordings of $I_{Na}$.

Data Storage and Analysis. Currents were filtered at 5 kHz by a four-pole Bessel filter (−3 dB/octave) and sampled at 20 kHz with a 12-bit analog-to-digital converter (TL-1 DMA; Axon Instruments, Inc.) A nonlinear least-square equation was used to fit exponential functions to experimental data. Exponentials were of the form $y = Ae^{\beta(t - C)}$, where $A$ is the amplitude, $\beta$ is the time constant, and $C$ is the residual constant. Boltzmann equations were of the form $y = 1/(1 + e^{E_m - E_\text{1/2}}/k)$, where $E_m$ is the membrane potential, $E_{1/2}$ is the membrane potential at the midpoint of the curve, and $k$ is the slope factor.

Statistics. Data are expressed as means ± S.E. Statistical significance ($P < .05$) of difference between two means was judged with paired or unpaired Student’s $t$ test as appropriate.

Results

Experiments performed in isolated guinea pig ventricular myocytes with the patch-clamp technique demonstrated that venlafaxine (10⁻⁶–10⁻⁴ M) caused a significant decrease in peak $I_{Na}$ in all cells ($n = 27$ from 15 animals) exposed to the drug. Figure 1 illustrates a typical example of sodium current recordings elicited by 30-ms pulses to −20 mV from a holding potential of −120 mV under control conditions, in the presence of venlafaxine 10⁻⁵ M and after 5-min washout. A progressive near complete recovery of current was observed after removal of the drug. Sodium currents recorded in the presence of venlafaxine were normalized to that recorded under control conditions, and appropriate fittings showed no significant changes in kinetics of inactivation of the currents ($\tau_{\text{inac}} = 0.652 ± 0.020$ ms, under control conditions; $\tau_{\text{inac}} = 0.636 ± 0.050$, in the presence of venlafaxine 10⁻⁵ M; $n = 5$ cells isolated from five animals). Decrease in $I_{Na}$ was concentration-dependent with an estimated IC₅₀ of 8 · 10⁻⁶ M (Fig. 2).

To elucidate the mechanism of action of venlafaxine on cardiac sodium current, we performed additional protocols exploring modifications of INa characteristics in the presence of the drug at a concentration of 10⁻⁵ M ($\approx$IC₅₀) and compared current elicited under control conditions to that observed in the presence of the drug.

![Fig. 1. Recordings of sodium currents elicited by 30 ms pulses to −20 mV from a holding potential of −20 mV under control conditions, in the presence of 10⁻⁶ M venlafaxine and after washout of the drug.](image-url)

![Fig. 2. Concentration-dependent block of $I_{Na}$ elicited by 30 ms pulses to −20 mV from a holding potential of −120 mV. Estimated IC₅₀ for block of $I_{Na}$ was 8 · 10⁻⁶ M. A total of 27 cells was used (the number of animals from which cells were isolated is indicated in parentheses) and is distributed as follows: 4 (2), 5 (2), 10 (6), 5 (3), and 3 (2), respectively, for venlafaxine (10⁻⁶, 3 · 10⁻⁶, 10⁻⁵, 3 · 10⁻⁵, and 10⁻⁴ M).](image-url)
Time Course of Block Development. Block induced by venlafaxine $10^{-5}$ M was assessed with 8-Hz trains (30 pulses; 30-ms pulse duration). At each pulse, cells were depolarized from a holding potential of $-120$ mV to a test potential of $-20$ mV. In the absence of the drug, repetitive pulsing did not affect $I_{Na}$ magnitude. As well, in the presence of venlafaxine, maximal reduction of the current was reached instantaneously, showing block with no use-dependent characteristics. Similar results were found with 2.5-Hz trains of depolarizing pulses from different holding potentials to the same test potential of $-20$ mV (Fig. 3). In addition, block of $I_{Na}$ was rate-independent regardless of the holding potential tested ($-120$, $-130$, and $-140$ mV). Thus, no phasic block of $I_{Na}$ could be detected, venlafaxine causing only a tonic block on cardiac sodium current.

Kinetics of Recovery from Inactivation. Time course of recovery from sodium channel inactivation was characterized with the double-pulse protocol shown in the inset of Fig. 4. Steady-state sodium channel inactivation was achieved with a 100-ms conditioning pulse to $-20$ mV, and the time course of recovery was determined with a test pulse (30 ms to $-20$ mV from a holding potential of $-120$ mV) at different coupling intervals, ranging from 2 to 4000 ms. In Fig. 4, the peak current measured following each test pulse was normalized to matching control values and plotted as a function of the recovery time. Under control conditions as well as in the presence of venlafaxine, reactivation of $I_{Na}$ at $-120$ mV was monoeponential. Time constants were $58.7 \pm 6$ ms and $54.4 \pm 1.8$ ms ($n = 10$ cells isolated from six animals) under control conditions and in the presence of venlafaxine $10^{-5}$ M, respectively. These data suggest that venlafaxine reduces the amplitude of $I_{Na}$ without altering the time course of recovery from sodium channel inactivation.

Steady-State Inactivation of Sodium Channel. Sodium currents were measured during a 30-ms test pulse to $-20$ mV after a 2000-ms depolarization to different potentials varying between $-140$ and $-30$ mV (Fig. 5). Examples of sodium currents recorded in the absence and presence of venlafaxine ($10^{-5}$ M) are presented in Fig. 5A. The experimental values were well fit to a Boltzmann equation (Fig. 5B). Under control conditions, the mean values for $E_{1/2}$ and $k$ averaged $-76 \pm 2$ mV and $4.9 \pm 0.2$ mV, respectively ($n = 10$ cells isolated from six guinea pigs). Venlafaxine ($10^{-5}$ M) reduced the maximum available $I_{Na}$ by $51 \pm 9\%$ and significantly shifted the midpoint by $10 \pm 2$ mV toward more negative potentials ($-86 \pm 2$ mV, $n = 10$ isolated from six guinea pigs, $p < .05$). No significant changes in the slope factor of the inactivation curve were observed in presence of venlafaxine ($5.5 \pm 0.3$ mV, $n = 10$ isolated from six guinea pigs, $p > .05$).

Discussion

Results obtained in this study demonstrate that venlafaxine is a relatively potent cardiac sodium channel blocker. Inhibition of $I_{Na}$ by venlafaxine was concentration-dependent with an estimated $IC_{50}$ of $8 \cdot 10^{-8}$ M. Block of $I_{Na}$ by venlafaxine was essentially tonic; no use-dependent characteristics could be detected. Moreover, venlafaxine reduced $I_{Na}$ current without affecting the time course of recovery from sodium channel inactivation. These observations led us to conclude that venlafaxine blocks $I_{Na}$ by binding to the resting state of the channel.

One of the important observations made during this study was the demonstration that venlafaxine inhibits $I_{Na}$ by $\approx 50\%$ at a concentration of $10^{-6}$ M and also shifts the midpoint of $I_{Na}$ availability by $-10$ mV. Previous studies have reported a shift toward the negative potentials by $-0.41$ mV/min in the half-point of $I_{Na}$ availability with time (Hanck and Sheets, 1992b). This effect could not account for the entire shift caused by venlafaxine because effects were observed within 5 to 10 min upon exposure to the drug. Incomplete recovery of drug effects on $I_{Na}$ amplitude during the washout period could be partially explained by this effect.

Results were reproduced in all cells tested. Although statistical analysis was realized on the number of cells (total number, 27), we suggest that the number of animals from which these cells were isolated (total number, 15) is enough to consider this sample size as adequate.

Venlafaxine has been shown to be effective in the treat-
 mechanism of a wide variety of psychological diseases (Guelfi et al., 1995; Ballenger, 1996; Rudolph and Derivan, 1996). Dose-response relationships were reported so that patients who do not respond to lower dosages (150–200 mg/day) are often titrated to higher dosages (up to 375 mg/day) (Nierenberg et al., 1994; Chiu and McCarthy, 1997). At therapeutic dosages, peak plasma concentrations vary between $2 \cdot 10^{-7}$ and $10^{-6}$ M (Klamerus et al., 1992; Patat et al., 1998). Consequently, block of sodium current could be observed in the upper range of these concentrations because 25% block of $I_{\text{Na}}$ was measured at a concentration of $10^{-6}$ M. Moreover, higher plasma concentrations ($3 \cdot 10^{-5}$ M) observed following overdose administration have been associated with QRS prolongation (Kokan and Dart, 1996).

Increased plasma concentrations of venlafaxine could be observed not only after overdose administration of the drug but also because of decreased clearance in some subjects. Indeed, the genetically determined cytochrome P-450 isoenzyme CYP2D6 is involved in the metabolism of venlafaxine. About 5 to 10% of the white population have an autosomal recessive trait for impaired ability to metabolize drugs via CYP2D6 and are described poor metabolizers (Brosen, 1990; Duman et al., 1997). Administration of venlafaxine to poor metabolizers places them at risk of accumulation of the drug to toxic concentrations because >50% of venlafaxine is eliminated through extensive first-pass metabolism by CYP2D6. Also, coadministration of venlafaxine with drugs that inhibit the activity of CYP2D6, such as some antiarrhythmic agents (Caporaso and Shaw, 1991), or the selective serotonin reuptake inhibitors (Brosen, 1990; DeVane, 1994; Hamelin et al., 1996), could provoke accumulation of the drug and predispose patients to proarrhythmia.

Block of sodium current by venlafaxine appears to be different from that described with tricyclic antidepressant agents and type I antiarrhythmic agents. Indeed, block of sodium current is often comprised of both tonic and use-dependent characteristics (Schaufl et al., 1975; Muir et al., 1982; Hondeghem, 1987; Kojima et al., 1989; Ogata and Narahashi, 1989; Krafte et al., 1994). In contrast, our results demonstrated that venlafaxine blocks sodium current in a use-independent manner. In addition, block did not change with hyperpolarization in the range of voltages tested. These observations led us to conclude that venlafaxine blocks $I_{\text{Na}}$ in its resting state. Finally, venlafaxine did not affect the time of recovery from sodium channel inactivation. Voltage dependence of channel availability was in full agreement with tonic block observed during previous experiments.

In conclusion, our results demonstrate that venlafaxine possesses direct cardiac electrophysiological effects by inhibiting $I_{\text{Na}}$ in ventricular myocytes. Although an extrapolation of data obtained from animal experiments to human must be taken with care, we speculate that reported effects of venlafaxine could explain QRS prolongation and proarrhythmia observed in some patients with increased plasma concentrations of the drug. We propose that better knowledge of the potential cardiac electrophysiological effects of venlafaxine may result in a safer use of the drug.

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References

Guelfi JD, White C, Hackett D, Guichoux JV and Magin G (1995) Effectiveness of

Fig. 5. A, an example of sodium current recorded during a 30-ms test pulse to $-20$ mV after a 2000 ms depolarization from different potentials varying between $-140$ and $-30$ mV under control conditions and in the presence of $10^{-5}$ M venlafaxine. Values of peak currents are reported and best-fit of Boltzmann equation (see Materials and Methods) are presented with solid lines (B). The dotted line represents the curve fit following normalization of the currents in the presence of venlafaxine. A clear shift of $10 \pm 2$ mV was observed in the presence of venlafaxine ($n = 10$ cells isolated from six guinea pigs).


Hanck DA and Sheets MF (1992a) Extracellular divalent and trivalent cation effects on sodium current kinetics in single canine cardiac Purkinje cells. *J Physiol (Lond)* **454**:267–298.


Send reprint requests to: Jacques Turgeon, Ph.D., Centre de Recherche, Hôtel Laval, 2725 Chemin Ste-Foy, Sainte-Foy, Quebec, G1V 4G5, PQ, Canada. E-mail: phajtu@hermes.ulaval.ca