Tolperisone-Type Drugs Inhibit Spinal Reflexes via Blockade of Voltage-Gated Sodium and Calcium Channels

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ABSTRACT

The spinal reflex depressant mechanism of tolperisone and some of its structural analogs with central muscle relaxant action was investigated. Tolperisone (50–400 μM), eperisone, lanperisone, inaperisone, and silperisone (25–200 μM) dose dependently depressed the ventral root potential of isolated hemisected spinal cord of 6-day-old rats. The local anesthetic lidocaine (100–800 μM) produced qualitatively similar depression of spinal functions in the hemicord preparation, whereas its blocking effect on afferent nerve conduction was clearly stronger. In vivo, tolperisone and silperisone as well as lidocaine (10 mg/kg intravenously) depressed ventral root reflexes and excitability of motoneurons. However, in contrast with lidocaine, the muscle relaxant drugs seemed to have a more pronounced action on the synaptic responses than on the excitability of motoneurons. Whole-cell measurements in dorsal root ganglion cells revealed that tolperisone and silperisone depressed voltage-gated sodium channel conductance at concentrations that inhibited spinal reflexes. Results obtained with tolperisone and its analogs in the [3H]batrachotoxinin A 20-α-benzoate binding in cortical neurons and in a fluorimetric membrane potential assay in cerebellar neurons further supported the view that blockade of sodium channels may be a major component of the action of tolperisone-type centrally acting muscle relaxant drugs. Furthermore, tolperisone, eperisone, and especially silperisone had a marked effect on voltage-gated calcium channels, whereas calcium currents were hardly influenced by lidocaine. These data suggest that tolperisone-type muscle relaxants exert their spinal reflex inhibitory action predominantly via a presynaptic inhibition of the transmitter release from the primary afferent endings via a combined action on voltage-gated sodium and calcium channels.

2-Methyl-1-(4-methylphenyl)-3-(1-piperidinyl)-1-propanone hydrochloride (tolperisone) is an old, centrally acting muscle relaxant drug that is mainly used for treating muscle spasticities of neurological origin and painful muscle spasms due to rheumatologic conditions. Besides being an effective antispastic agent (Pratzel et al., 1996; Dulin et al., 1998), tolperisone also has analgesic activity in rodents (Sakaue et al., 2004) and in humans (Svensson et al., 2003). It possesses relatively few side effects in humans (Dulin et al., 1998). Other propiophenone muscle relaxants include 1-(4-ethylphenyl)-2-methyl-3-(1-piperidinyl)-1-propanone hydrochloride (eperisone), which is also a registered drug (Bose, 1999), and (−)-2-(R)-methyl-3-(1-pyrrolidinyl)-1-[4-(trifluoromethyl)phenyl]-propanone hydrochloride (lanperisone; Sakitama et al., 1997) and 1-(4-ethylphenyl)-2-methyl-3-(1-pyrrolidinyl)-1-propanone hydrochloride (inaperisone; Morikawa et al., 1992), two agents that had been tested in human phase III studies but not introduced into the clinical practice. 1-[4-(Fluorobenzyl)dimethylsilylmethyl]piperidine hydrochloride (silperisone), a sila analog of tolperisone (Farkas et al., 2005), has been shown in mice to have better separation between the desirable effects (i.e., reduction of abnormally increased muscle activity in various models) and anticipated undesirable effects (i.e., central nervous system depression and impairment of voluntary motor control) than currently available centrally acting muscle relaxant drugs. The development of this compound has been discontinued because of an unacceptable side effect found in the chronic toxicity studies.

Only few reports dealing with the mechanism of action of tolperisone-like compounds have been published. Ono et al. (1984) have shown that tolperisone and eperisone exert a
local anesthetic-like (membrane-stabilizing) action both on motoneurons and primary afferents in vivo as well as on peripheral nerves of rats in vitro. Tolperisone was found to inhibit action potential propagation on both A- and C-fibers of rat sciatic nerve (Quasthoff et al., 2003). The local anesthetic action of tolperisone and eperisone was implicated in their antinociceptive effects on acute pain in mice (Sakae et al., 2004). Thus, the effect of tolperisone seems to be similar to that of lidocaine (lignocaine; o-diethylamino-2,6-dimethyl-ylacetanilide), which is known to inhibit voltage-dependent sodium currents. Indeed, molecular modeling studies revealed that tolperisone can bind to the same site to which lidocaine can bind (Fels, 1996). In a two-electrode voltage-clamp study in Xenopus oocytes, Quasthoff et al. (2003) found an inhibition of both Na\textsubscript{1.6} (tetrodotoxin (TTX)-sensitive) and Na\textsubscript{1.8} (TTX-resistant) recombinant sodium channels by tolperisone. Similar to lidocaine, both silperisone (Durung and Koppenhöfer, 2001) and tolperisone (Hinck and Koppenhöfer, 2001) inhibited sodium currents of frog-isolated Ranvier nodes. The results of the latter study, however, suggest a significant involvement of potassium channels as well in the mediation of tolperisone’s action; therefore, the authors concluded that tolperisone cannot be regarded as having a lidocaine-like action, because the latter drug has negligible effect on potassium channels. Furthermore, voltage-clamp studies in snail neurons (Novales-Li et al., 1989) demonstrated an inhibition of voltage-dependent calcium currents by tolperisone and some of its analogs. The close chemical similarity of eperisone, lanperisone, and inaperisone (and to some extent silperisone) to tolperisone suggests a similar mode of reflex inhibitory action.

For better understanding of the mechanism of suppressant action of tolperisone and its analogs on spinal reflexes, the effects of these agents on the spinal reflex machinery between the stimulated dorsal root and the ventral root conveying efferent discharges were studied in the rat spinal cord both in vitro and in vivo, in comparison with the local anesthetic lidocaine. The sodium channel blocking effects of these compounds were characterized in electrophysiological experiments on dorsal root ganglion (DRG) cells, in a functional assay using fluorescent membrane potential dyes, in cerebellar cultures, and in a radioligand binding assay using brain cortical synaptosomal preparation. Their effect on voltage-gated calcium channels was also analyzed.

Materials and Methods

Materials. Silperisone HCl, eperisone HCl, tolperisone HCl, inaperisone HCl, lanperisone HCl, and pipercuronium bromide were synthesized at Gedeon Richter Ltd. (Budapest, Hungary). N-Methyl-D-aspartate (NMDA) was purchased from Sigma-Aldrich (Boston, MA). Scorpion venom (Leiurus quinquestriatus from North Africa), bovine serum albumin, choline chloride, sucrose, and HEPES were purchased from Sigma-Aldrich (St. Louis, MO), and TTX was from Latoxan (Valence, France). [\textsuperscript{3}H]Bathochromotoxin A 20-\textalpha-benzoate ([\textsuperscript{3}H]BTX; specific activity, 50 Ci/mmol) was obtained from PerkinElmer Life and Analytical Sciences (Boston, MA). Methyl-D-aspartate (NMDA) was purchased from Sigma-Aldrich (St. Louis, MO), and TTX was from Latoxan (Valence, France). [\textsuperscript{3}H]Bathochromotoxin A 20-\textalpha-benzoate ([\textsuperscript{3}H]BTX; specific activity, 50 Ci/mmol) was obtained from PerkinElmer Life and Analytical Sciences (Boston, MA). Scorpion venom (Leiurus quinquestriatus from North Africa), bovine serum albumin, choline chloride, sucrose, and HEPES were purchased from Sigma-Aldrich (Budapest, Hungary). Acetone was purchased from Fluka (Buchs, Switzerland). Salts and other chemicals for artificial cerebrospinal fluid (ACSF) and electrode-filling solutions were purchased from Sigma-Aldrich. Culture medium components were obtained from Invitrogen (Carlsbad, CA). The fluorometric imaging plate reader membrane potential assay kit (blue) was purchased from Molecular Devices (Sunnyvale, CA).

For intravenous infusion, Rindex solution (68 mM NaCl, 3.5 mM KCl, 1.25 mM CaCl\textsubscript{2}, 0.5 mM MgCl\textsubscript{2}, and 555 mM glucose) was purchased from Human Ltd. (Budapest, Hungary). The anesthetic solution for in vivo studies contained 0.25% α-chloralose and 10% urethane (both from Sigma-Aldrich) dissolved in distilled water. The cannula for blood pressure monitoring was filled with saline containing 200 IU/mL heparin (Gedeon Richter Ltd.).

Animals. Wistar rats (bred at Gedeon Richter Ltd. or purchased from Toxicoop, Budapest, Hungary or Harlan, Indianapolis, IN) were used in all the studies. For the in vitro experiments, spinal cords and DRG cells were isolated from 6-day-old male rat pups. Male rats weighing 280 to 320 g were used for the in vivo experiments. The animal room was thermostated at 21 ± 1°C and illuminated artificially from 6:00 AM to 6:00 PM. The rats had free access to food and water. All of the procedures conformed to the guidelines of the National Institutes of Health for the care and use of laboratory animals and were approved by the Institutional Ethical Committee.

Isolated Hemisected Spinal Cord Preparation in Vitro. Rat pups weighing 13 to 16 g were anesthetized with ether and then placed on crushed ice to cool down the spinal cord until the respiration of the animal stopped. The spinal cord was removed and hemisected along the midline. Hemisected were transferred into a storage chamber, and they were incubated at room temperature (23–26°C) in standard ACSF (124 mM NaCl, 3.5 mM KCl, 1.23 mM NaH\textsubscript{2}PO\textsubscript{4}, 2 mM CaCl\textsubscript{2}, 2 mM MgCl\textsubscript{2}, 26 mM NaHCO\textsubscript{3}, and 10 mM glucose) bubbled with carbogen (95% O\textsubscript{2} and 5% CO\textsubscript{2}) for at least 30 min. One hemisec was placed into the recording chamber and perfused at 10 ml/min with ACSF at 26°C (regulated) if not stated otherwise. Glass suction electrodes were used both for stimulation and recording. Dorsal root stimulation-evoked ventral root potentials (DR-VRPs) were recorded from the L5 dorsal root. The L5 dorsal root was stimulated with square-wave anodic current pulses (0.2 mA; 0.1 ms; supramaximal for all recorded potential components) at a frequency of 2 min\textsuperscript{-1}. However, before and at appropriate times after drug applications, the input-output relationship (curve) was also determined using gradually increasing current intensities (0.01–0.2 mA). Evoked compound action potentials (afferent fiber potentials; AFPs) were recorded from the spinal cord surface with a glass suction electrode attached to the adjacent L4 dorsal root. In these experiments, a distance of at least 5 mm was kept between the site of stimulation and the dorsal root entry zone.

The first 200 ms of DR-VRP was analyzed. Responses were band-pass-filtered (0.02 Hz–10 kHz), amplified, and fed into a PC via an A-D converter (Digidata 1200; Molecular Devices, Sunnyvale, CA; sampling rate, 10 kHz). A custom-made computer program (Stimulat) controlled both stimulation and data acquisition and performed the on-line data analysis. Evoked potentials were displayed and stored for later evaluation. Different components of the ventral root reflex response were separated according to their poststimulus latencies and durations. The drugs were added into the ACSF only when the measured parameters had become stable. Drug effects were determined when a steady-state inhibition had developed, which was dependent on the drug used (typically after 60–90 min of perfusion).

Standard Surgery for the in Vivo Studies in Spinal Animals. The method was essentially similar to that described previously in more detail (Parkas and Ono, 1995). Rats anesthetized with a mixture of chloralose (25 mg/kg i.p.) and urethane (1 g/kg i.p.) were used. The vagal nerves were severed, and the common carotid arteries were ligated bilaterally at the cervical region. Blood pressure was monitored via a cannula in the carotid artery. The femoral vein was also cannulated to allow intravenous injections. A tracheal cannula was inserted, and the animals were artificially ventilated throughout the experiment. The spinal cord was infiltrated with lidocaine (1%; 50 μl) and transected at the C1 level. The animals were fixed in a spinal stereotaxic frame, and a dorsal laminectomy was performed on vertebrae L1–L6. A pool was formed from the skin of the back and filled with warm paraffin oil. Rectal and oil pool temperatures were...
maintained at 36 ± 0.2°C using two heating lamps. During the experiment, Rindex solution was infused (10–20 ml·kg⁻¹·h⁻¹) to maintain the mean arterial blood pressure of spinal animals at around 60 mm Hg.

In Vivo Spinal Reflex Study. Ventral and dorsal roots below L4 were cut bilaterally, L5 dorsal and ventral roots on both sides were isolated, and an ipsilateral pair of them was placed on bipolar silver wire hook electrodes. The dorsal root was stimulated by single impulses (stimulus strength, supramaximal voltage; pulse width, 0.05 ms; and frequency, 10/min). The first 10 ms of the ventral root reflex recorded using a differential amplifier was displayed, stored, and evaluated using the Stimulat software.

Study of Afferent Nerve Conduction in Vivo. In addition to the standard surgery, the right sciatic nerve was exposed in the femoral-popliteal region and placed on a bipolar silver wire electrode. A pool was formed from the skin of the back and of the leg and filled with warm paraffin oil. The sciatic nerve was stimulated by single square-wave impulses (stimulus strength, supramaximal for all A-fibers; i.e., 5–30 V; pulse width, 0.1 ms; and frequency, 10/min). The proximal end of L5 dorsal root transected at the dorsal root entry zone was placed on a silver wire bipolar hook electrode and crushed between the two hooks for monophasic recording of the arriving compound action potential of the afferent nerve fibers.

Motoneuron Excitability Test in Vivo. Excitability of the motoneuron soma and that of the primary afferent fibers was measured similarly to the technique described by Ono et al. (1979). Anesthetized animals were paralyzed with pipercuronium bromide (100 μg/kg starting dose + 50 μg·kg⁻¹·h⁻¹ in infusion). A tungsten microelecetrode, insulated with the exception of its tip, was inserted into the L5 motoneuron pool, which was stimulated by negative pulses (stimulus strength, 0.2–0.5 mA; pulse width, 0.05 ms; and frequency, 10/min). The compound action potential evoked by direct stimulation of motoneurons (MN; first peak) and the potential caused by (mono)synaptic activation of motoneurons (MS; second peak) were recorded from the L5 ventral root. The antidromic action potential, which reflects excitability of the primary afferent fibers (PAFs), was recorded in the presence of 5.0 nM [3H]BTX, 1 μM tetrodotoxin, 4.0 μg/ml amphotericin B, 100 U/ml penicillin G, and 100 μg/ml streptomycin, and they were plated onto poly-D-lysine-coated 96-well plates (1–2 × 10⁵ cells/well). Cultures were incubated at 37°C in a humidified atmosphere of 5% CO₂ and 95% air and used for the measurement after 7 days in vitro. Membrane potential was monitored using the flurometric imaging plate reader membrane potential assay kit (Molecular Devices) and FlexStation II (Molecular Devices), a plate reader fluorimeter with integrated eight-channel fluid addition capability. Cells were loaded with the fluorescent dye (100 μM) by incubating the plate for 20 to 60 min at 37°C. After loading, 50 μM of ACSF (control) or 50 μM of 4 × concentrated test compound solution (dissolved in ACSF) was added to each well, and the plate was incubated at 37°C for an additional 10 min. Fluorescence measurements were carried out at 37°C. The dye was excited at 530 nm, and emission was sampled at 565 nm at 1.4-s intervals. After recording baseline for 15 s, 50 μM of 4 × concentrated veratridine solution was added to the cells using the pipetter of FlexStation, and fluorescence was monitored for an additional 105 s. This 2-min protocol was executed column by column on the whole plate. The concentration of veratridine (defined as EC₅₀) was determined on each experimental day by performing dose-response measurements with veratridine using cells from the same plating. Cells were loaded with the fluorescent dye (100 μM) by incubating the plate for 20 to 60 min at 37°C. After loading, 50 μM of ACSF (control) or 50 μM of 4 × concentrated test compound solution (dissolved in ACSF) was added to each well, and the plate was incubated at 37°C for an additional 10 min. Fluorescence measurements were carried out at 37°C. The dye was excited at 530 nm, and emission was sampled at 565 nm at 1.4-s intervals. After recording baseline for 15 s, 50 μM of 4 × concentrated veratridine solution was added to the cells using the pipetter of FlexStation, and fluorescence was monitored for an additional 105 s. This 2-min protocol was executed column by column on the whole plate. The concentration of veratridine (defined as EC₅₀) was determined on each experimental day by performing dose-response measurements with veratridine using cells from the same plating. Raw fluorescence data were expressed as ΔF/IP values (fluorescence change normalized to baseline). The effects of blockers at various concentrations were quantified as percentage of inhibition of the control veratridine response.

[^H]BTX Binding. Rat cerebrocortical synaptosomes were prepared as described by Catterall et al. (1981) with minor modifications. In brief, the cortices of 7- to 8-week-old male rats were dissected and homogenized in 10 volumes of ice-cold sucrose buffer (150 μM NaCl, 1.5 mM MgCl₂, 3 mM CaCl₂, 5 mM HEPES Na, 0.01 mM EGTA, pH 7.25). The homogenate was centrifuged at 10,000g (15 min; 4°C), and the resultant supernatant was retained (15 min; 4°C), and the resultant supernatant was retained. Aliquots (100 μl) equal to approximately 6 to 8 mg/ml protein were used in [^H]BTX binding experiments. Binding assays were performed in the presence of 5.0 nM [^H]BTX, 1 μM tetrodotoxin, 4.0 μg/ml scorpion toxin, and various concentrations of the added drugs at 37°C for 60-min incubation time. Nonspecific binding was deter-
determined in the presence of 300 μM aconitine. The reaction was terminated by rapid filtration using a UniFilter-96 GF/B (PerkinElmer Life and Analytical Sciences). The filtration plates were washed five times with ice-cold wash buffer containing 5 mM HEPES, 130 mM choline chloride, 0.8 mM MgSO$_4$, 1.8 mM CaCl$_2$, and 0.01% bovine serum albumin. Radioactivity trapped on a 96-well filtration plate was measured by liquid scintillation spectrometry in 40 μl of Microscint 20 scintillation cocktail (PerkinElmer Life and Analytical Sciences) using a TopCount NXT microplate scintillation and luminescence counter (PerkinElmer Life and Analytical Sciences).

**Statistics.** Data are presented as mean ± S.E.M. For IC$_{50}$ determinations, sigmoidal fitting to parametric data were applied using Origin 6.0 (OriginLab Corp., Northampton, MA).

## Results

**Isolated Hemisected Spinal Cord in Vitro.** A typical DR-VRP (Fig. 1A) consisted of a biphasic population spike (monosynaptic reflex; MSR; time to peak, 7.0 ± 0.4 ms) superimposed on the early phase of a tonic, long-lasting potential shift, reaching a maximum at 10 to 15 ms following the stimulation of the dorsal root. This latter potential basically represents population excitatory postsynaptic potential (EPSP) of motoneurons (Siarey et al., 1992). Nevertheless, small waves attributable to asynchronous firing of motoneurons were often discernibly superimposed on this tonic potential. When the stimulus intensity dependence of the evoked response was investigated (Fig. 1B, control curves), current intensities causing half-maximal activation of MSR, EPSP, and late EPSP were 0.05, 0.045, and 0.03 mA, respectively, whereas 0.2 mA was enough to maximally activate all components. This latter intensity, which was used in the experiments where drugs were tested, caused only negligible activation of C-fibers (not illustrated). Thus, C-fibers do not seem to participate in the generation of the first 180 ms of DR-VRP, including its highly NMDA antagonist-sensitive “tail part” (80–180 ms; Kocsis et al., 2003). This conclusion is in agreement with that of Thompson et al. (1992), who also found a predominant role of A-type afferent fibers in DR-VRP. Increasing the stimulus intensity above supramaximal for Aδ did not result in further increase in any of these response components.

Tolperisone (50–400 μM), eperisone, lanperisone, iniperisone, and silperisone (25–200 μM) as well as lidocaine (200–800 μM) caused concentration-dependent depression of all studied components of DR-VRP (Fig. 2). As illustrated by the action of silperisone in a representative experiment (Fig. 1A), MSR and the tail of EPSP were the most sensitive parameters, whereas the early part of EPSP was apparently less attenuated. Apart from responses just above the threshold, the depression afforded by different doses of silperisone was not dependent on the stimulus strength. Namely, maximum responses of the input-output curves were attenuated, rather than a rightward shift of the curve (Fig. 1B). Hence, these depressant drug effects were unlikely to be the consequence of an elevated excitation threshold of primary afferent axons at the site of stimulation.

Tolperisone, silperisone, and lidocaine all dose dependently inhibited AFP in the concentration range that also depressed EPSP. To be able to make a precise comparison between drug effects on AFP and synaptic responses, we recorded the two activities in the same hemisected spinal cord preparation. To eliminate the interference caused by spiking of motoneurons (MSR), we recorded the EPSP-related component at an elevated temperature, at which excitability of motoneurons in the hemisected spinal cord preparation was depressed (Brooks et al., 1955). Elevation of the temperature of the bathing solution from 26 to 32 ± 1°C depressed MSR, allowing us to record the main component of the incoming AFP (Fig. 3A) and a nearly pure EPSP-related potential (Fig. 3B) simultaneously. Figure 3 shows that lidocaine was clearly more effective in blocking nerve conduction than EPSP, whereas silperisone had an opposite preference regarding the two potentials. Tolperisone was in between the two other drugs, having similar efficacies to block EPSP and AFP.

**In Vivo Spinal Reflex Study.** A typical ventral root reflex response to stimulation of the dorsal root and its attenuation by silperisone are shown in Fig. 4A. We differentiated three characteristic components of the ventral root reflex potential (as described previously in Farkas and Ono, 1995): monosynaptic, disynaptic, and polysynaptic reflex (MSR, DSR, and PSR, respectively; Fig. 4A). Silperisone (10 mg/kg i.v.) attenuated all of the three components with a

![Fig. 1. Effects of silperisone on DR-VRP components in vitro.](image)

A. Inhibition of DR-VRP by increasing doses of silperisone (50–200 μM) added to the perfusing medium. The inset shows the same extended time scale to allow the observation of the changes in the monosynaptic reflex. B. Effect of 50 (●), 100 (▲), and 200 μM (▼) silperisone compared with control (■) on the stimulus strength dependence of the peak-to-peak amplitude of monosynaptic compound action potential (MSR AMPL) and on the integral of EPSP (EPSP INT.). Data are presented as mean ± S.E.M. from four experiments. Note that efficacy of silperisone was not dependent on the stimulus intensity, i.e., increasing the stimulus strength did not counteract the inhibition produced by silperisone.
were a bit greater for all of the three components. The profile of silperisone was also similar to that of the above-mentioned two compounds. However, its peak effect on MSR was slightly weaker. The profile of lidocaine was substantially different, because it produced relatively weaker depressant effect on MSR compared with that on PSR (Fig. 4B).

**Motoneuron Excitability Test in Vivo.** The effects of silperisone, tolperisone, and lidocaine on excitability of motoneurons and primary afferents were studied in three to five animals. Results are shown in Fig. 5. Characteristic potentials recorded from the dorsal and ventral roots following intraspinal focal electrical stimulation of the area of the motoneuron pool are shown in Fig. 5A.

Silperisone (10 mg/kg i.v.) depressed MN (direct excitability) by 15%, whereas MS (the synaptic response) decreased by 68% on average (Fig. 5). It exerted no effect on excitability of PAFs. The onset of the effect of silperisone was relatively slow, and the inhibition reached its maximum in 15 min. Tolperisone (10 mg/kg i.v.) reached a maximum effect of 24, 80, and 8% inhibition of MN, MS, and PAF, respectively, in 6 to 8 min, whereas lidocaine (10 mg/kg i.v.) produced more marked depression of MN and PAF (30 and 14%, respectively; Fig. 5D) than did tolperisone or silperisone. On the other hand, its depressant effect on MS (67%) was less pronounced compared with tolperisone, and it was similar to that of silperisone. Although these differences may seem small, they were highly reproducible when the different compounds were administered successively in the same experiment.

**Study of Afferent Nerve Conduction in Vivo.** Possible contribution of a local anesthetic-type inhibition of afferent nerve conduction to the reflex inhibition following systemic
administration of silperisone, tolperisone, and lidocaine (10–10 mg/kg i.v.) was investigated. AFPs recorded from the L4 dorsal root following stimulation of the sciatic nerve reflected evoked action potentials of A-fibers (no synchronized C-fiber-mediated components could be recorded under our experimental conditions). Silperisone and tolperisone left AFP practically unchanged (2.7 ± 0.5 and 5.0 ± 1.2% inhibitions of the peak, respectively; n = 6). Lidocaine exerted slight but consistent inhibitory effect on AFP amplitude (10.7 ± 1.7%).

Effects on Voltage-Gated Sodium and Calcium Currents. Sodium currents recorded from medium-sized (25–35 μm) dorsal root ganglion cells had an average maximal peak current amplitude of 3.9 ± 0.4 nA (43 cells). Because in pilot experiments we found that the sodium channel inhibitory effect of tolperisone-like compounds is highly membrane potential-dependent, the concentration-response relationships were investigated at a membrane potential, where approximately half of the channels were in an inactivated state (V_{H1/2}), i.e., at −80 mV. Thus, to decrease the variability of drug sensitivities among DRG neurons, cells with V_{H1/2} out of the range of −70 and −90 mV were not used for drug testing.

Tolperisone, silperisone, eperisone, and lidocaine inhibited peak sodium currents evoked by step depolarizations to 0 mV from a holding potential of −80 mV in a concentration-dependent manner (Fig. 6A). The inhibitory effect developed rapidly and was reversible. The IC_{50} values are listed in Table 1. Silperisone had a slightly higher potency to block sodium currents than the other three drugs.

The membrane potential dependence of the available current (sodium channel availability) was assessed by applying a voltage protocol in which membrane potential was held for 10 ms at different voltages, increasing from −130 to −10 mV in 10-mV steps preceding the test pulses to 0 mV. In Fig. 6B, the effect of tolperisone (200 μM) on the steady-state inactivation curve is shown. The peak amplitude of the resultant current was normalized to the value of the maximum available current (recorded at −130 mV) and plotted against the membrane potential. Tolperisone (200 and 400 μM) as well as silperisone (80 and 160 μM) and lidocaine (200 and 400 μM) caused concentration-dependent shifts of the control inacti-
sensitive calcium channels with an IC\textsubscript{50} of 218 μM (Fig. 7A).

In accordance with the data of Wu and Pan (2004), we found that L-type and P/Q-type calcium channels do not contribute considerably to the high-threshold voltage-activated calcium current in DRG cells, because neither nitrendipine (10 μM; n = 4) nor ω-agatoxin-IVA (0.1 μM; n = 9) blocked the current significantly (5 ± 1 and 4 ± 1% inhibition of calcium current amplitude, respectively), whereas ω-conotoxin-GVIA, a selective N-type calcium channel blocker (3 μM) inhibited both the ω-conotoxin-sensitive current component and also most of the drug-resistant (R-type) current (not illustrated).

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Silperisone concentration dependently inhibited voltage-sensitive calcium channels with an IC\textsubscript{50} of 218 ± 22 μM (determined in eight cells). In another set of experiments, the patch pipette-filling solution lacked creatine phosphate, creatine phosphokinase, and GTP, agents that facilitate the phosphorylation of intracellular proteins. In these experiments, the blocking effect was more prominent (IC\textsubscript{50} = 65 ± 9 μM; n = 8). Tolperisone had an IC\textsubscript{50} of 1062 μM in the presence of creatine phosphate, creatine phosphokinase, and GTP; thus, it was ~5-fold less potent than silperisone. No IC\textsubscript{50} values were determined with eperisone and lidocaine; thus, the calcium channel-inhibiting efficacies of drugs were compared at 320 μM (Fig. 7B). At their IC\textsubscript{50} concentrations for sodium channel blockade, tolperisone, eperisone, and lidocaine caused 22, 34, 36, and 7% diminution of calcium currents, respectively.

**Effects on [3H]BTX Binding and Veratridine-Induced Depolarization.** All of the studied compounds inhibited [3H]BTX binding in cortical synaptosomal preparation dose dependently. IC\textsubscript{50} values are listed in Table 1. At similar concentrations, the same compounds also reduced membrane depolarization evoked by the sodium channel activator/inactivation inhibitor veratridine (Table 1). Similar to the sodium current measurements, lidocaine proved to be the least effective also in these assays. The results of the [3H]BTX binding test are in good correlation with those of the veratridine depolarization assay, and the rank orders, with one exception, are in agreement with the orders found in the whole-cell current experiments. However, the potencies of the compounds in the former two assays are different from what was determined in the patch-clamp experiments. The discrepancy may be related to the fact that the former assays apply veratridine and BTX, respectively, which may alter the sensitivity of sodium channels to this type of blocking agents. Furthermore, different parameters (peak current or steady-state responses) were measured in the different assays.

### Discussion

Tolperisone and its analogs as well as lidocaine suppressed the spinal segmental reflex activity both in vitro and in vivo. Various presynaptic and postsynaptic events may be considered as possible site(s) of this inhibitory action. Using an intraspinal stimulation protocol, we found that tolperisone and silperisone decreased motoneuronal (postsynaptic) excitability but to a lesser extent than the local anesthetic lido-

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**TABLE 1**

<table>
<thead>
<tr>
<th>Compound</th>
<th>Current\textsuperscript{a}</th>
<th>[3H]BTX Binding</th>
<th>VER</th>
<th>MSR</th>
<th>EPSP Integral</th>
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<tr>
<td>Tolperisone</td>
<td>198 ± 21 (6)</td>
<td>40.9 ± 2.5 (7)</td>
<td>58.3 ± 2.4 (3)</td>
<td>62.7 ± 9.4 (7)</td>
<td>130.7 ± 10.4 (7)</td>
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<tr>
<td>Silperisone</td>
<td>111 ± 18 (10)</td>
<td>7.2 ± 0.8 (4)</td>
<td>14.2 ± 0.6 (3)</td>
<td>55.9 ± 1.5 (4)</td>
<td>72.5 ± 13.8 (4)</td>
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<tr>
<td>Eperisone</td>
<td>250 ± 93 (5)</td>
<td>21.7 ± 2.5 (3)</td>
<td>37.1 ± 1.8 (3)</td>
<td>43.3 ± 5.8 (5)</td>
<td>76.0 ± 9.4 (5)</td>
</tr>
<tr>
<td>Inaperisone</td>
<td>N.D.</td>
<td>34.6 ± 3.0 (3)</td>
<td>41.8 ± 3.5 (4)</td>
<td>29.6 ± 3.8 (7)</td>
<td>59.7 ± 7.4 (7)</td>
</tr>
<tr>
<td>Lapnerisone</td>
<td>N.D.</td>
<td>13.7 (1)</td>
<td>31.2 ± 2.9 (4)</td>
<td>33.0 ± 3.1 (6)</td>
<td>114.7 ± 15.1 (6)</td>
</tr>
<tr>
<td>Lidocaine</td>
<td>297 ± 86 (6)</td>
<td>132 ± 9 (4)</td>
<td>60.6 ± 6.2 (4)</td>
<td>186.2 ± 17.6 (6)</td>
<td>198.5 ± 42.8 (6)</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Sodium currents were measured by whole-cell patch clamp.

\textsuperscript{b} N.D., not determined; VER, veratridine-evoked depolarization determined by microfluorimetry.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Current\textsuperscript{a}</th>
<th>[3H]BTX Binding</th>
<th>VER</th>
<th>MSR</th>
<th>EPSP Integral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tolperisone</td>
<td>198 ± 21 (6)</td>
<td>40.9 ± 2.5 (7)</td>
<td>58.3 ± 2.4 (3)</td>
<td>62.7 ± 9.4 (7)</td>
<td>130.7 ± 10.4 (7)</td>
</tr>
<tr>
<td>Silperisone</td>
<td>111 ± 18 (10)</td>
<td>7.2 ± 0.8 (4)</td>
<td>14.2 ± 0.6 (3)</td>
<td>55.9 ± 1.5 (4)</td>
<td>72.5 ± 13.8 (4)</td>
</tr>
<tr>
<td>Eperisone</td>
<td>250 ± 93 (5)</td>
<td>21.7 ± 2.5 (3)</td>
<td>37.1 ± 1.8 (3)</td>
<td>43.3 ± 5.8 (5)</td>
<td>76.0 ± 9.4 (5)</td>
</tr>
<tr>
<td>Inaperisone</td>
<td>N.D.</td>
<td>34.6 ± 3.0 (3)</td>
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\textsuperscript{a} N.D., not determined; VER, veratridine-evoked depolarization determined by microfluorimetry.

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**Mechanism of Tolperisone-Type Drugs**

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Fig. 6. Effect of tolperisone on voltage-gated sodium channels in DRG cells. A, current traces from bottom to top were recorded in the presence of 0, 40, 80, 160, 320, and 640 μM tolperisone in a representative experiment. The applied voltage command protocol is shown above the traces. B, effect of tolperisone on the steady-state inactivation characteristics. Tolperisone (200 μM; □) shifted the control (■) inactivation curve and decreased the maximum current at high negative potentials. The normalized curve (○) indicates a pronounced parallel leftward shift in the current availability curve of the control curve. Data are presented as mean ± S.E.M. from seven cells.
drug, and $I_H$ is the percentage inhibition of current peak amplitude at a holding potential of -130 mV. The number of observations is shown in parentheses.

<table>
<thead>
<tr>
<th>Compound</th>
<th>$\Delta V_{H2}$</th>
<th>$I_H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 Tolperisone</td>
<td>-19 ± 3 (7)</td>
<td>33 ± 12 (4)</td>
</tr>
<tr>
<td>400 Tolperisone</td>
<td>-22 ± 3 (6)</td>
<td>41 ± 9 (6)</td>
</tr>
<tr>
<td>80 Silperisone</td>
<td>-6 ± 1 (7)</td>
<td>13 ± 2 (6)</td>
</tr>
<tr>
<td>160 Silperisone</td>
<td>-8 ± 1 (7)</td>
<td>32 ± 7 (6)</td>
</tr>
<tr>
<td>200 Lidocaine</td>
<td>-13 ± 2 (7)</td>
<td>14 ± 4 (6)</td>
</tr>
<tr>
<td>400 Lidocaine</td>
<td>-17 ± 2 (9)</td>
<td>27 ± 7 (7)</td>
</tr>
</tbody>
</table>

caine. The compound action potential recorded from the dorsal root represents excitability of primary afferents. From the ventral root, two successive potentials could be recorded: the first spike was the consequence of direct electrical stimulation (nonsynaptic excitation of the motoneurons; MN), whereas the second spike was due to MS activation of motoneurons (Ono et al., 1984; Farkas and Ono, 1995).

Lidocaine was also the most effective among the three compounds in decreasing the excitability of primary afferent terminals and the conduction of afferent volley (AFP). These presynaptic events have a great impact on the quantity of transmitter substances (primarily glutamate) released from the terminals. A decreased transmitter release results in a depression of EPSP. To analyze precisely the relationship between depression of the afferent nerve conduction and synaptic transmission, dose-response studies were performed with simultaneous recording of AFP and DP-VRP. Although tolperisone, silperisone, and lidocaine all attenuated both AFP and EPSP, silperisone preferentially depressed EPSP, whereas lidocaine possessed a more pronounced depressant action on AFP. The profile of tolperisone was between that of the two other drugs, namely, it equally inhibited AFP and EPSP.

In summary, lidocaine had significantly greater depressant effects on the direct electrical excitability of motoneurons and primary afferents than silperisone, whereas their efficacies to inhibit the synaptic transmission were similar. The profile of tolperisone was between that of the two other drugs.

Among the compounds studied, silperisone had the slowest rate of onset of effect (not shown). Since an apparently complete steady state usually could not be achieved with silperisone even within 90 min, this could cause slight underestimation of its potency. As shown by Fig. 2, inaperisone was the most potent in attenuating both MSR and the early part (peak) of EPSP. However, it was equally potent to eperisone and silperisone in attenuating the “tail” and consequently the whole area under the curve of EPSP. Tolperisone and lanperisone were somewhat less potent than the above-mentioned drugs, but their patterns of actions were similar. Lidocaine was the least potent, especially in depressing the early part of EPSP. However, it was relatively potent in attenuating the tail (Fig. 2), which is in agreement with the results of Nagy and Woolf (1996) obtained in a similar model.

Thus, in spite of the fact that lidocaine had marked effects on AFP and excitability of presynaptic terminals, it was less efficient in depressing synaptic transmission compared with tolperisone and especially with silperisone. This suggests that the latter drugs may have additional inhibitory actions on EPSP generation.

In our in vitro model, EPSP could be abolished by coadministration of the $\alpha$-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid antagonist GYKI 52466 and the NMDA antagonist 2-amino-5-phosphonovalerate (Kocsis et al., 2003). However, according to our former (unpublished) studies, neither tolperisone nor silperisone had any affect on $\alpha$-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid or NMDA receptors, suggesting that the depressant effect on EPSP reflects a presynaptic action on the release of the excitatory transmitter rather than an action on postsynaptic glutamate receptors. Neither did the two drugs affect GABA-A receptors in binding experiments.

Voltage-gated sodium channels are regarded as one of the most important sites of action of lidocaine (Hille, 1977; Clare et al., 2000). The effect of lidocaine on sodium channels can explain both the depression of excitability and synaptic transmission observed at the spinal segmental level. Our present results clearly indicate that tolperisone and its analog share this feature of lidocaine, which is in agreement with the findings of Ono et al. (1984), Hinck and Koppenhofer (2001), During and Koppenhofer (2001), and Quasthoff et al. (2003). The lack of clear correlation between the blocking potencies of these drugs in the tests for sodium channels and those for depression of spinal reflex transmission in vitro (Table 1) may be related to differences between the compounds regarding the diffusibility inside the spinal tissue and/or to differences in activities on other channels.
The coupling between the afferent volley and the transmitter release can be modulated effectively by antagonists of certain subtypes of voltage-gated calcium channels as well (Burnashev and Rozov, 2005). Tolperisone slightly blocked these channels at sodium channel blocking concentrations. However, silperisone and eperisone were more potent in this regard, whereas lidocaine had only weak effect on calcium channels. This might underlie the stronger effect of silperisone on EPSP than on AFP compared with tolperisone.

As suggested by the results with silperisone, under certain experimental conditions, which may affect the phosphorylation states of channel proteins, the potency of tolperisone-like drugs to inhibit calcium channels may be even higher. Therefore, we suggest that the effect of tolperisone and particularly silperisone and eperisone on $\text{Ca}^{2+}$ channels contributes to their presynaptic action on transmitter release.

Regarding the significance of sodium channel blockade in the reflex inhibitory action of tolperisone-like compounds, it must be kept in mind that the resting membrane potential of large TTX-sensitive DRG neurons that are involved in the mediation of somatic spinal reflexes and regulation of the muscle tone at spinal segmental level is usually between $-60$ and $-70 \text{mV}$ (Caffrey et al., 1992; Liu et al., 2000; Xing et al., 2001). In this membrane potential range, the steady-state inactivation curve of these sodium channels displays a steeply changing phase. Thus, even minor depolarization of the membrane results in the inactivation of a significant portion of sodium channels resulting in a weaker current (due to decreased channel availability). Under these conditions, the incoming action potentials can trigger smaller calcium influx, resulting in decreased transmitter release from the primary afferent terminals. Such changes in the membrane potential occur during presynaptic inhibition in the spinal cord fibers under normal physiological conditions due to the GABA-A-mediated depolarization of the presynaptic primary afferent terminal.

Spinal presynaptic inhibition (for reviews, see Schmidt, 1971; Levy, 1980) is thought to be decreased in some states of spasticity, yielding an imbalance between facilitatory and inhibitory influences on segmental spinal neuronal circuits involved in reflex transmission (Nielsen and Hultborn, 1993; Delwaide and Pennisi, 1994). Shifting the steady-state inactivation curve of sodium channels toward more negative potentials may compensate for the weakened physiological presynaptic inhibition and thus may be an efficient therapeutic strategy to restore the balance. The sodium channel blocking effect of tolperisone-like drugs in DRG cells is state-dependent and results in a shift in the steady-state inactivation curve toward the hyperpolarized potentials in addition to some depression of the maximum current at high negative potentials. This feature is manifested as a preferential action on depolarized membranes. A state-dependent block of sodium channels is a common feature of several anticonvulsants, such as phenytoin, carbamazepine, and lamotrigine (Clare et al., 2000). This means that these drugs bind preferentially to the inactivated and open states of the sodium channel $\alpha$ subunit (Wang et al., 2004). A sustained hyperexcitable and depolarized state of spinal neurons has been recently reported in a spasticity model (Bennett et al., 2003; Li and Bennett, 2003, 2004a,b) reminiscent of human spasticity disorders. Thus, we propose that the state-dependent action of tolperisone and its analogs on sodium channels may result in a selective inhibition of the function of those neurons that are involved in spasticity disorders. This feature may underlie the relative lack of motor side effects of tolperisone in clinical practice (Dulin et al., 1998) and the relative lack of impairment of normal motor control caused by tolperisone-like drugs, which was observed in conscious mice (Farkas et al., 2005). Although a majority of the present results were obtained in spinal preparations, we do not claim that the proposed mechanism of the muscle relaxant action of tolperisone-like drugs is restricted to the spinal cord level. Actually, the effects of these agents on central nervous system (cortical and cerebellar) preparations suggest that supraspinal mechanisms might also be affected.

Baclofen acting via GABA-B receptors, benzodiazepines potentiating GABA-A receptor-mediated primary afferent depolarization, and tizanidine stimulating a2 receptors are centrally acting muscle relaxants that all act via an inhibition of transmitter release by a presynaptic action (Farkas et al., 1989; Delwaide and Pennisi, 1994). Our results indicate that a state-dependent blockade of sodium channels combined with an inhibition of calcium channels by tolperisone-like drugs offers another efficient way of treating spasticity disorders with less risk of motor side effects.

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