(−)-(1R,2R)-3-(3-Dimethylamino-1-ethyl-2-methyl-propyl)-phenol Hydrochloride (Tapentadol HCl): a Novel µ-Opioid Receptor Agonist/Norepinephrine Reuptake Inhibitor with Broad-Spectrum Analgesic Properties

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ABSTRACT
(−)-(1R,2R)-3-(3-Dimethylamino-1-ethyl-2-methyl-propyl)-phenol hydrochloride (tapentadol HCl) is a novel µ-opioid receptor (MOR) agonist (Kᵢ = 0.1 μM; relative efficacy compared with morphine 88% in a [³⁵S]guanosine 5’-3-O-(thio)triphosphate binding assay) and NE reuptake inhibitor (Kᵢ = 0.5 μM for synaptosomal reuptake inhibition). In vivo intracerebral microdialysis showed that tapentadol, in contrast to morphine, produces large increases in extracellular levels of NE (+450% at 10 mg/kg i.p.). Tapentadol exhibited analgesic effects in a wide range of animal models of acute and chronic pain [hot plate, tail-flick, writhing, Randall-Selitto, mustard oil colitis, chronic constriction injury (CCI), and spinal nerve ligation (SNL)], with ED₅₀ values ranging from 8.2 to 13 mg/kg after i.p. administration in rats. Despite a 50-fold lower binding affinity to MOR, the analgesic potency of tapentadol was only two to three times lower than that of morphine, suggesting that the dual mode of action of tapentadol may result in an opiate-sparing effect. A role of NE in the analgesic efficacy of tapentadol was directly demonstrated in the SNL model, where the analgesic effect of tapentadol was strongly reduced by the α₂-adrenoceptor antagonist yohimbine but only moderately attenuated by the MOR antagonist naloxone, whereas the opposite was seen for morphine. Tolerance development to the analgesic effect of tapentadol in the CCI model was twice as slow as that of morphine. It is suggested that the broad analgesic profile of tapentadol and its relative resistance to tolerance development may be due to a dual mode of action consisting of both MOR activation and NE reuptake inhibition.

Activation of opioid receptors, particularly the µ-opioid receptor (MOR), is one of the main options for the treatment of moderate-to-severe pain. MOR agonists are very effective against acute pain; however, they may be less effective against chronic pain of neuropathic or inflammatory origin, or they may have an unsatisfactory therapeutic window. MOR agonists are very effective against chronic pain of neuropathic or inflammatory origin, or they may have an unsatisfactory therapeutic window. Activation of opioid receptors, particularly the µ-opioid receptor (MOR), is one of the main options for the treatment of moderate-to-severe pain. MOR agonists are very effective against acute pain; however, they may be less effective against chronic pain of neuropathic or inflammatory origin, or they may have an unsatisfactory therapeutic window. It is suggested that the broad analgesic profile of tapentadol and its relative resistance to tolerance development may be due to a dual mode of action consisting of both MOR activation and NE reuptake inhibition.

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ABBREVIATIONS: MOR, µ-opioid receptor; 5-HT, 5-hydroxytryptamine (serotonin); ANOVA, analysis of variance; CCI, chronic constriction injury; CYP2D6, cytochrome P450 2D6; DOR, δ-opioid receptor; GTPγS, guanosine 5’-3-O-(thio)triphosphate; HPLC, high-pressure liquid chromatography; KOR, κ-opioid receptor; MPE, maximal possible effect; NE, norepinephrine; SNL, spinal nerve ligation; tapentadol HCl, (−)-(1R,2R)-3-(3-Dimethylamino-1-ethyl-2-methyl-propyl)-phenol hydrochloride.
opioids. The different, complementary mechanisms of action may additively or even synergistically enhance the analgesic efficacy and/or attenuate the side effects of MOR agonists by reducing the requirement for MOR activation. The facilitation of monoaminergic transmission in descending pain inhibitory pathways in the spinal cord seems to be an important mechanism because compounds that block the reuptake of norepinephrine (NE) and/or serotonin (5-hydroxytryptamine [5-HT]) are efficacious in the treatment of chronic pain conditions (Carter and Sullivan, 2002; Tzschentke, 2002) and can enhance the analgesic effect of morphine (Oasipov et al., 1982). This is of particular relevance because neuropathic pain is generally considered to be relatively unresponsive to opioids (Mao et al., 2000) and/or difficult to treat effectively because of MOR-related side effects (Martin and Eisenach, 1982).

Attempts to circumvent this problem initially led to the development of tramadol. Tramadol is an atypical, racemic opioid that combines weak MOR activation with inhibition of NE and/or serotonin (Mao et al., 2000) and/or difficult to treat effectively because of MOR-related side effects (Martin and Eisenach, 2001). The inhibition resides mainly in the MEs and the opioid that combines weak MOR activation with inhibition of because of MOR-related side effects (Martin and Eisenach, 2002).

The chemistry program that was engaged yielded compounds with this desired novel dual activity. The present article presents the preclinical profile of one of these nonnarcotic compounds, (-)-(1R,2R)-3-(3-dimethylamino-1-ethyl-2-methyl-propyl)-phenol hydrochloride (tapentadol HCl) (Fig. 1), with respect to its in vitro characteristics and its analgesic, antihyperalgesic, and antiallodynic properties in rat and mouse models of acute and chronic pain.

Materials and Methods

Animals

For the in vitro studies was obtained from male Sprague-Dawley specific pathogen-free and Wistar specific pathogen-free rats (200 g) and male Firbright-white guinea pigs (200–250 g) (Charles River, Sulzfeld, Germany). In vivo studies were conducted with male NMRI mice (20–35 g) and Sprague-Dawley rats (130–180 g) (Charles River; Iffa Credo, Brussels, Belgium; and Janvier, Le Genest St. Isle, France) (pain models) and with male Wistar rats (280–350 g) (Harlan, Horst, The Netherlands) (microdialysis). Animals were housed under standard conditions (room temperature 20–24°C, 12-h light/dark cycle, relative air humidity 45–70%, 15 air changes/h, air movement <0.2 m/s) with food and water available ad libitum, with the exception of the time of the experiment. All animals were used only once in all pain models, with the exception of the neuropathy models, in which they were tested repeatedly with a washout period of at least 1 week between tests. There were at least 5 days between delivery of the animals and the test day or surgery. Animal testing was performed in accordance with the recommendations and policies of the International Association for the Study of Pain (Zimmermann, 1983) and the German Animal Welfare Law. All study protocols were approved by the local government committee for animal research, which is also an ethics committee (in vitro and in vivo pain studies) and the animal care committee of the Faculty of Mathematics and Natural Science of the University of Groningen (microdialysis).

In Vitro Studies

Receptor Binding. Incubations with rat membrane suspensions from brain without cerebellum for MOR; brain without pons, medulla oblongata, and cerebellum for s-opioid receptor (DOR); and brain without pons, medulla oblongata, cerebellum, and cortex for k-opioid receptor (KOR) were carried out to equilibrium. Blanks to quantify nonspecific binding were obtained by saturating the binding sites with naloxone (10−8 M for MOR, 10−6 M for DOR, and 10−4 M for KOR). All incubations were run in triplicate and terminated by rapid filtration under mild vacuum (Brandel cell harvester type M-24 R; Brandel Inc., Gaithersburg, MD) and 2 washes of 5-mL buffer using FP-100 Whatman GF/B filter mats (Whatman Schleicher and Schuell, Keene, NH). The radioactivity of the samples was counted after a stabilization and extraction period of at least 15 h by use of the scintillation fluid Ready Protein (Beckman Coulter, Krefeld, Germany). For further details regarding DOR and KOR binding studies, see Frink et al. (1996).

The human MOR binding assay was run in microtiter plates (Costar 3632; Corning Life Sciences, Acton, MA) with wheat germ agglutinin-coated scintillation proximity assay beads (GE Health-
care, Chalfont St. Giles, Buckinghamshire, UK). A cell membrane preparation of Chinese hamster ovary-K1 cells transfected with the human MOR (RB-HOM) was purchased from PerkinElmer Life and Analytical Sciences (Beltsville, MD). [³H]Naloxone (PerkinElmer Life and Analytical Sciences, Brussels, Belgium) was used as a ligand for the MOR binding studies. As assay buffer for the binding studies, 50 mM Tris-HCl, pH 7.4, supplemented with 0.05% sodium azide was used. The final assay volume of 250 µl per well included 1 nM [³H]naloxone as a ligand and either test compound in dilution series or 25 mM unlabeled naloxone for determination of unspecific binding. The test compounds were diluted with 25% dimethyl sulfoxide in H₂O to yield a final 0.5% dimethyl sulfoxide concentration, which served as a respective vehicle control. The assays were started by the addition of the beads (1-mg beads per well), which had been preloaded for 15 min at room temperature with human MOR membranes (23.4 µg/250 µl of final assay volume per well). After short mixing, the assays were run for 90 min at room temperature. The microtiter plates were then centrifuged for 20 min at 500 rpm, and the signal rate was measured by means of a 1450 MicroBeta Trilux liquid scintillation counter (PerkinElmer Life and Analytical Sciences–Wallac Oy, Turku, Finland). Half-maximal inhibitory concentration (IC₅₀) values reflecting 50% displacement of [³H]naloxone-specific receptor binding were calculated by nonlinear regression analysis. Individual experiments were run in duplicate and were repeated three times in independent experiments.

Transporter Binding. Human recombinant NE and 5-HT transporter membranes were obtained from PerkinElmer Life and Analytical Sciences. The assays were performed in 96-well microtiter plates (PP; Costar 3632; Corning Life Sciences), essentially according to the product information given by the manufacturer (total assay volume: 250 µl). After incubation, the microtiter plate was filtered through a Unifilter GF/B microtiter plate (PerkinElmer Life and Analytical Sciences) and washed with ice-cold 50 mM Tris, 0.9% NaCl, pH 7.4, by use of a Brandel Cell Harvester MPXRI-96T. The Unifilter GF/B plate was dried at 55°C for 1 h. Afterward, a back seal (PerkinElmer Life and Analytical Sciences) was added. The signal rate was measured by means of a 1450 MicroBeta Trilux liquid scintillation counter.

Synaptosomal NE and 5-HT Uptake Inhibition. Methods were according to Frink et al. (1996). Rats were killed by decapitation. The tissue (hypothalamus for NE uptake, medulla oblongata and pons for 5-HT uptake) was homogenized in ice-cold 0.32 M sucrose (100 mg of tissue/1 ml) and centrifuged at 4°C for 10 min at 1000g. Subsequent centrifugation of the supernatant at 17,000g for 55 min yielded a pellet (P₇₀), which was resuspended in 0.32 M glucose (0.5 ml/100 mg original weight). Incubations were run in triplicate. The synaptosomal suspension (50 µl) containing approximately 200 µg of protein for NE and 5-HT uptake transporters was added to 850 µl of incubation medium containing the drug to be tested and preincubated for 5 min at 37°C under an atmosphere of 5% CO₂ in O₂. Accumulation was started by the addition of the radioactive substrate to yield a concentration of 0.1 µM in a final volume of 1 ml. Uptake was stopped after 30 s in the case of [³H]NE and 60 s in the case of [³H]5-HT immediately following by filtration through FP-100 Whatman GF/B filter mats using a Brandel cell harvester. Filters were washed with 5 ml of incubation medium and then extracted with Ready Protein (Beckman Coulter) for at least 15 h and counted for radioactivity. The incubation medium contained 119 mM NaCl, 3.9 mM KCl, 0.51 mM CaCl₂, 0.65 mM MgSO₄, 15.6 mM Na₂HPO₄, 3.4 mM NaH₂PO₄, 10 mM glucose, 0.57 mM ascorbic acid, and 0.0156 mM imipramine. The pH was adjusted to 7.4 by the addition of NaOH (23°C). Values were corrected for accumulation of tritium at 0°C.

The uptake was also measured in 96-well microtiter plates (PP; Costar 3632; Corning Life Sciences). In this case, the volume was scaled down to 250 µl, and incubation was at room temperature. These conditions (without 5% CO₂ in O₂) are suitable for high-throughput screening campaigns. The incubation period for [³H]NE and [³H]5-HT uptake lasted 7.5 and 5 min, respectively. Blanks to quantify the nonspecific uptake were run in the presence of nioxetine (10 µM) for [³H]NE and fluoxetine (100 µM) for [³H]5-HT uptake. Thereafter, the 96 samples were filtered through a Unifilter GF/B microtiter plate and washed with 200 ml of incubation buffer by use of a Brandel Cell Harvester MPXRI-96T. The Unifilter GF/B plate was dried at 55°C for 1 h. Afterward, a back seal (PerkinElmer Life and Analytical Sciences) was fixed on the plate, and 35 µl of scintillation fluid per well (Ultima Gold; PerkinElmer Life and Analytical Sciences) was added. After fixation of a top seal (PerkinElmer Life and Analytical Sciences), the radioactivity was determined (after an equilibration period of approximately 5 h) in a 1450 MicroBeta Trilux liquid scintillation counter.

Agonist-Stimulated [³⁵S]GTP/S Binding. The [³⁵S]Guanosine 5’-3-O-(thio)triphosphate (GTP/S) assay was carried out as a homogeneous scintillation proximity assay as described by Gillen et al. (2000), with the following modifications. It was run in microtiter plates (Costar 3632; Corning Life Sciences), in which each well contained 1.5 mg of wheat germ agglutinin-coated scintillation proximity assay beads (GE Healthcare) in a final volume of 200 µl. To test the agonistic activity of test compounds on human recombinant MOR-expressing cell membranes from Chinese hamster ovary-K1 cells (PerkinElmer Life and Analytical Sciences), 10 µg of membrane proteins per assay were incubated with 0.1 nM [³⁵S]GTP/S (GE Healthcare) and different concentration of agonists in buffer containing 20 mM HEPES, pH 7.4, 100 mM NaCl, 10 mM MgCl₂, 1 mM EDTA, 1 mM dithiothreitol, 1.28 mM Na₂S₇O₇ and 1 µM GDP for 120 min at 25°C. The microtiter plates were then centrifuged for 10 min at 2100 rpm in a GS6 microtiter plate centrifuge (Beckman Coulter) to sediment the beads. The bound radioactivity was determined after a delay of 15 min by means of a 1450 MicroBeta Trilux liquid scintillation counter. The enhancement of [³⁵S]GTP/S binding above the basal activity was used to determine the potency (EC₅₀) and the relative efficacy (percentage of maximal efficacy) of test compounds versus the reference compound morphine, which was set at 100%.

In Vivo Studies

In Vivo Intracerebral Microdialysis. These experiments were performed at Brains-on-Line (Groningen, The Netherlands). Surgery and microdialysis. Rats were anesthetized using 2.5% isoflurane (400 mg/min N₂O; 600 mg/min O₂). Lidocaine (10% m/v) was used for local anesthesia. The animals were fixed in a stereotaxic frame (David Kopf Instruments, Tujunga, CA), and home-made I-shaped probes were inserted into the ventral hippocampus (diameter length, 4 mm). Microdialysis probes were inserted according to Paxinos and Watson (1982) and secured with dental cement and screws. Coordinates of implantation were: posterior −5.3 mm, lateral +4.8 mm, and ventral −8.0 mm.

Experiments were performed 24 to 48 h after surgery. On the day of the experiment, animals were connected with flexible polyetheretherketone tubing to a microperfusion pump (Harvard Apparatus Inc., Holliston, MA) and perfused with artificial cerebrospinal fluid containing 147 mM NaCl, 3.0 mM KCl, 1.2 mM CaCl₂, and 1.2 mM MgCl₂ at a flow rate of 1.5 µl/min. Microdialysis samples (15-min fractions) were collected in mini-vials containing 7.5 µl of 0.02 M acetic acid, mixed, and placed in a chilled automatic injection apparatus (Gilson 231 autoinjector; Gilson, Villiers Le Bel, France).

Upon termination of the animals, brains were removed and fixed in 4% m/v solution of paraformaldehyde. The position of the probe was verified according to Paxinos and Watson (1982) by making coronal sections of the brain.

Analysis. NE was analyzed using high-pressure liquid chromatography (HPLC) with electrochemical detection. The HPLC pump
The age of MPE was calculated according to the formula: 
\[
\frac{\text{[reaction time after drug injection]}}{\text{[reaction time with vehicle]}} \times 100
\]

where 0 and 2 were the cut-off time (120 s).

Tail-Flick. The tail-flick test was carried out in rats using a modification of the method described by D'Amour and Smith (1941). The tail-flick latency, defined by the time (in seconds) to withdraw the tail from a radiant heat source (bulb, 8 V/50 W), was measured at a cut-off time of (120 s).

Tail-Flick latency was defined as the nociceptive response during the exposure to the heat stimulus. The percent-maximal possible effect (MPE) was defined as the lack of a nociception and calculated as \% MPE according to the formula: 
\[
\frac{[\text{reaction time after drug injection}]}{[\text{reaction time with vehicle}]} \times 100
\]

where 0 and 2 were the cut-off time (120 s).

Behavioral Studies

Experimental Procedures. Animals were assigned randomly to treatment groups. Different doses and vehicle were tested in a randomized fashion. Although the operators performing the behavioral tests were not formally “blinded” with respect to the treatment, they were not aware of the study hypothesis or the nature of differences between drugs. Models were selected to cover a range of different types and etiologies of pain.

Hot Plate. The hot plate test was adapted from Eddy and Leimbach (1953). The device consisted of an electrically heated surface and an open Plexiglas tube (17 cm high \( \times \) 22 cm diameter) to confine the animals to the heated surface. The temperature was kept at 48.0 ± 0.5°C. Mice were placed on the hot plate, and the time until either licking of the hind paw or jumping occurred was recorded with a stopwatch. Animals were tested before and 30 min after drug administration. The predrug latencies were between 17 and 45 s. The maximal possible effect (MPE) was defined as the lack of a nociceptive response during the exposure to the heat stimulus. The percentage of MPE was calculated according to the formula: 
\[
\frac{[\text{reaction time after drug injection}]}{[\text{reaction time with vehicle}]} \times 100
\]

where 0 and 1 were the latencies obtained before and after drug injection and 2 was the cut-off time (120 s).

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Spinal Nerve Ligation. The spinal nerve ligation (SNL) model of neuropathic pain was adapted from Kim and Chung (1992). Under pentobarbital anesthesia (Narcoren, 60 mg/kg i.p.), the left L6 and L7 spinal nerves were exposed by removing a small piece of the paravertebral muscle and a part of the left spinal process of the L5 lumbar vertebra. The L6 and L7 spinal nerves were then carefully isolated and tightly ligated with silk (NC-silk black, USP 5/0, metric 1; B. Braun Melsungen AG, Melsungen, Germany). After checking hemostasis, the muscle and the adjacent fascia were closed with sutures, and the skin was closed with metal clips. After surgery, animals were allowed to recover for 1 week. For the assessment of mechanical allodynia, which was stable for at least 5 weeks, the rats were placed on a metal mesh covered with a plastic dome and were allowed to habituate until exploratory behavior ceased. The threshold for mechanical allodynia was measured with an electronic von Frey filament (1–32 mN), and scored withdrawal reactions (16 mN).

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solved in citrate solution, pH 4.6. Control animals received citrate solution. Diabetes was confirmed 1 week after injection by measurement of tail vein blood glucose levels with Hemoglukotest 20-800R glucose and a reflectance colorimeter (Roche Diagnostics, Mannheim, Germany). Animals with a blood glucose level of >17 mM were considered to be diabetic. Tests took place during weeks 3 and 4 after the induction of diabetes. At that time, the abnormal pain behavior was at a stable maximum (Courteix et al., 1993). Mechanical hyperalgesia was assessed using an algometer (Ugo Basile) by measuring withdrawal thresholds to an increasing pressure on the dorsal surface of the right paw via a cone-shaped pusher with a rounded tip (2 mm²). The cut-off was set at 250 g, and the behavioral readout was paw withdrawal, vocalization, or overt struggling. The reaction latencies were measured before and 15, 30, 45, and 60 min after administration of the test compounds. The value before administration of substance was used as 0% MPE, and 100% MPE represented full antihyperalgesic efficacy (i.e., cut-off).

**Antagonism in the Writhing Model.** Writhing was induced by i.p. injection of 0.35 ml of a 0.02% solution of phenylquinone according to the method described by Hendershot and Forssath (1959). The characteristic writhing responses, such as stretching, twisting a hind leg inward, or contraction of the abdomen, were observed and counted from 5 to 20 min after phenylquinone administration. During this time, the animals were placed individually in observation boxes. Recording of the writhing reactions (with the help of a pressure button counter) started 10 min after administration of the test compounds. Naloxone (0.001, 0.01, 0.1, and 1.0 mg/kg) was given 10 min before the respective agonist.

**Antagonism in the Spinal Nerve Ligation Model.** The experimental details were identical to those described above. In the antagonism experiments, yohimbine (2.15 mg/kg), naloxone (0.3 mg/kg), or vehicle was administered 5 min before tapentadol (10 mg/kg), morphine (6.81 mg/kg), or vehicle. Animals were tested before and 0.5, 1, and 3 h after drug administration. Drugs or vehicle were tested in weeks 1, 2, 3, 5, 8, 10, 12, 15, 17, 19, 22, and 23 of the treatment. Treatment of all groups continued until full tolerance (i.e., lack of significant antiallodynic effect) against tapentadol was reached, i.e., day 23. ED₅₀ values were determined in a separate group of chronic constriction injury (CCI) rats that was tested before and 15, 30, 45 and 60 min after drug administration. % MPE of each time point was calculated according to the formula: \(\frac{(|T_a - T_i| \times 100)}{T_i}\), where \(T_a\) and \(T_i\) were numbers of paw withdrawal reactions before and after drug administration, respectively.

**Data Analysis**

**In Vitro Studies.** IC₅₀ values were calculated using the computer software “Figure P” (version 6.0c; Biosoft, Cambridge, UK), and \(K_i\) values were obtained using the Cheng-Prusoff equation. Equilibrium dissociation constant (\(K_i\)) values were calculated using the computer software “Ligand” (version 4; Biosoft).

**In Vivo Studies.** Microdialysis. Four consecutive microdialysis samples with less than 40% variation were taken as baseline levels and set at 100%. Drug effects were expressed as percentage of the basal level (mean ± S.E.M.). Statistical analysis was performed using SigmaStat for Windows (SPSS Inc., Chicago, IL). Effects were compared versus vehicle using two-way ANOVA with repeated measures across all doses for each compound and transmitter and subsequently, where applicable, for each individual dose, followed by the Dunnet’s post hoc test. The level of statistical significance was set at \(p < 0.05\).

**Pain models.** Unless indicated otherwise in the preceding sections, data were analyzed by means of 1- or 2-factor ANOVA with or without repeated measures, depending on the experimental design. Significance of treatment, time, or treatment × time interaction effects was analyzed by means of Wilks’ Lambda statistics. In the case of a significant treatment effect, pairwise comparison was performed at the time of maximal effect by Fisher least significant difference test. Results were considered statistically significant if \(p < 0.05\). ED₅₀ values and 95% confidence intervals were determined at the time of the peak effect for each drug by semi-logarithmic regression analysis or according to Litchfield and Wilcoxon (1949). ED₅₀ values with nonoverlapping 95% confidence intervals were considered to be significantly different. Note that our definition of ED₅₀ value differs from the original strict mathematical definition in that our ED₅₀ values refer to the calculated dose that would yield 50% MPE in the test population, rather than the dose that would yield a given effect in 50% of the test population. Although this modified definition deviates from the formal mathematical definition, it is commonly used for the analysis of behavioral data.

**Group sizes were** \(n = 10\) for hot plate, tail-flick, writhing, Randall-Selitto, SNL, and CCI models; \(n = 7\) for mustard oil-induced colitis; \(n = 5\) to 10 for streptozotocin-induced diabetic polyneuropathy; and \(n = 3\) to 6 for microdialysis.

**Drugs and Chemicals.** The following drugs were used: tapentadol HCl (Grünenthal GmbH); morphine HCl and codeine phosphate (Merck AG, Darmstadt, Germany); naloxone HCl and yohimbine HCl (Sigma-Aldrich Laborchemikalien, Seelze, Germany); Narcoren (Merck KGaA, Darmstadt, Germany); sarpentadone HCl (Sigma-Aldrich Laborchemikalien). Mustard oil and streptozotocin were obtained from Sigma-Aldrich Laborchemikalien.

**Standard application route for test compounds was** i.p., with the exception of the SNL antagonist experiments where tapentadol and morphine were administered i.v. In the visceral pain models (writhing, mustard oil) where i.p. injections are not feasible, drugs were administered i.v. For the in vivo studies, all drugs were dissolved in saline and injected at 1 ml/kg (microdialysis), 5 ml/kg (rat pain models), or 10 ml/kg body weight (mouse pain models).

For all drugs, the salt form has been omitted from the text. All doses indicated refer to the respective salt form as indicated in this paragraph.

**Results**

**In Vitro Data**

In opioid receptor binding studies, tapentadol bound to native rat MOR, DOR, and KOR, with \(K_i\) values of 0.096, 0.97, and 0.91 μM, respectively (Table 1). At the human recombinant MOR, tapentadol had a similar \(K_i\) of 0.16 μM (Fig. 2A) as at the native rat MOR. Tapentadol did not bind to the human recombinant ORL1 receptor (\(K_i > 100\) μM). In the human MOR [³⁵S]GTPγS binding assay, tapentadol showed agonistic activity, with an efficacy of 88% relative to morphine and with an EC₅₀ of 0.67 ± 0.15 μM (morphine: EC₅₀ = 0.022 ± 0.003 μM) (Fig. 3 A). Binding properties of the reference opioids, morphine and codeine, in rat assays are shown in Table 1.

In rat synaptosomal reuptake assays, tapentadol inhibited the NE reuptake transporter with a \(K_i\) of 0.48 ± 0.11 μM and...
the 5-HT reuptake transporter with a $K_i$ of $2.37 \pm 0.54 \mu M$ (Table 1; Fig. 3, B, C, and D, in comparison to reference compounds). Other uptake systems, like choline, GABA, adenosine, and dopamine, were not affected (data not shown). In human recombinant transporter binding assays, tapentadol had a $K_i$ for the NE transporter of $8.80 \pm 1.17 \mu M$ and a $K_i$ for the 5-HT transporter of $5.28 \pm 0.58 \mu M$ (Table 1; Fig. 2, B and C, in comparison to reference compounds).

Tapentadol was further tested in a range of assays for possible interactions with receptors, ion channels, and enzyme systems. The only (submicromolar) interactions that were found were with the rat sigma2 binding site ($K_i = 0.43 \pm 0.009 \mu M$).

### Table 1

<table>
<thead>
<tr>
<th>Rat Opioid Receptor Binding Assays</th>
<th>Rat Synaptosomal Monoamine Uptake Assays</th>
<th>Human Recombinant Monoamine Transporter Binding Assays</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[^{3}H]$Naloxone (MOR Antagonist)</td>
<td>$[^{3}H]$Cl-DPDPE (DOR Agonist)</td>
<td>$[^{3}H]$NE</td>
</tr>
<tr>
<td>Tapentadol</td>
<td>$0.96 \pm 0.009$</td>
<td>$0.48 \pm 0.11$</td>
</tr>
<tr>
<td>Morphine</td>
<td>$0.02 \pm 0.0001$</td>
<td>$&gt;100$</td>
</tr>
<tr>
<td>Codeine</td>
<td>$1.3 \pm 0.5$</td>
<td>$&gt;100$</td>
</tr>
<tr>
<td>Tapentadol-Glucuronide</td>
<td>N.D.</td>
<td>N.D.</td>
</tr>
<tr>
<td>Venlafaxine</td>
<td>N.D.</td>
<td>$0.45 \pm 0.03$</td>
</tr>
<tr>
<td>Fluoxetine</td>
<td>N.D.</td>
<td>$0.062 \pm 0.013$</td>
</tr>
<tr>
<td>Duloxetine</td>
<td>N.D.</td>
<td>$0.011 \pm 0.0025$</td>
</tr>
<tr>
<td>Nisoxetine</td>
<td>N.D.</td>
<td>$0.37 \pm 0.045$</td>
</tr>
<tr>
<td>Morphine</td>
<td>$0.009 \pm 0.009$</td>
<td>$8.80 \pm 1.17$</td>
</tr>
<tr>
<td>Codeine</td>
<td>$0.54 \pm 0.001$</td>
<td>$&gt;100$</td>
</tr>
<tr>
<td>Tapentadol-Glucuronide</td>
<td>N.D.</td>
<td>$&gt;100$</td>
</tr>
<tr>
<td>Venlafaxine</td>
<td>N.D.</td>
<td>$0.0017 \pm 0.00015$</td>
</tr>
<tr>
<td>Fluoxetine</td>
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</tr>
<tr>
<td>Duloxetine</td>
<td>N.D.</td>
<td>$0.011 \pm 0.0012$</td>
</tr>
<tr>
<td>Nisoxetine</td>
<td>N.D.</td>
<td>$0.17 \pm 0.02$</td>
</tr>
<tr>
<td>Morphine</td>
<td>$0.009 \pm 0.009$</td>
<td>$5.28 \pm 0.58$</td>
</tr>
</tbody>
</table>

N.D., not determined; pCl-DPDPE, [D-Pen²,pCl-Phe⁴,D-Pen⁵]-enkephalin; Cl-977, enandoline.

*Less than 10% inhibition at 10 μM (at human recombinant MOR); data for reference compounds were in part published in Frink et al. (1996).
μM), muscarinic receptors (rat M₁ and human M₁–M₅, with $K_i$ values in the range of 0.47–1.19 μM), and the rat 5-HT₃ receptor ($K_i = 1.04$ μM). In the case of the muscarinic receptors, further characterization revealed that tapentadol behaved like a weak muscarinic antagonist in a human embryonic kidney (HEK-293) cell assay. With respect to the 5-HT3 receptor, tapentadol showed a dose-dependent antagonistic activity in a guinea pig colon bioassay (see Tzschentke et al., 2006).

Binding and functional studies with the major metabolite of tapentadol, tapentadol-O-glucuronide, did not reveal any pharmacological activity at opioid receptors, synaptosomal reuptake systems, and other binding sites (Table 1; data not shown).

**In Vivo Intracerebral Microdialysis**

Tapentadol (4.64–10 mg/kg i.p.) produced a clear, dose-dependent increase in extracellular levels of NE, with a maximal increase of 450% above baseline obtained at 10 mg/kg. Overall, ANOVA indicated a significant effect of tapentadol on extracellular NE levels [$F(2,15) = 5.44, p < 0.05$]. Whereas increases elicited by the lower dose (4.64 mg/kg) were not significant [$F(1,10) = 3.10, p > 0.05$], 10 mg/kg significantly increased NE levels [$F(1,10) = 6.03, p < 0.05$]. Extracellular levels of 5-HT were also increased significantly by tapentadol, albeit to a lesser extent than NE (up to 130% above baseline, at 10 mg/kg). Overall, ANOVA indicated a significant effect of tapentadol on extracellular 5-HT levels [$F(2,15) = 5.42, p < 0.05$]. As for NE, the effects of the lower dose (4.64 mg/kg) were not significant [$F(1,10) = 2.79, p > 0.05$], whereas the higher dose (10 mg/kg) elicited significant increases in 5-HT levels [$F(1,10) = 8.11, p < 0.05$] (Fig. 4).

Morphine (1–10 mg/kg i.p.) did not significantly affect extracellular levels of NE and 5-HT across the dose range tested [ANOVA, $F(3,17) = 1.37, p > 0.05$ for NE; $F(3,23) = 1.45, p > 0.05$ for 5-HT]. There was only a tendency toward decreased NE levels and increased 5-HT levels at the two lower doses tested (Fig. 4).

**Behavioral Tests**

$ED_{50}$ values (with 95% confidence limits) from all pain models are summarized in Table 2. Because of an extensive first-pass metabolism, tapentadol has a low oral absolute bioavailability of approximately 9% in rats. This is much lower than the oral absolute bioavailability of tapentadol in man (approximately 32%, which is comparable to that of morphine) (Tzschentke et al., 2006; unpublished data). Therefore, it was decided to use the i.p. route of administration to circumvent the problem of low oral availability of tapentadol in rats and potential underestimation of its potency and efficacy (relative to morphine) in humans.

**Hot Plate.** Tapentadol [$F(4,45) = 8.92, p < 0.0001$] and morphine [$F(4,45) = 12.35, p < 0.0001$] induced dose-dependent antinociception and reached full efficacy. Morphine was approximately two times more potent that tapentadol ($ED_{50} 4.7$ versus $11.8$ mg/kg i.p., respectively) (Fig. 5A).

**Tail-Flick.** Tapentadol [$F(4,45) = 18.21, p < 0.0001$] and morphine [$F(5,54) = 22.48, p < 0.0001$] induced dose-dependent antinociception and reached full efficacy. Morphine was approximately twice as potent as tapentadol ($ED_{50} 5.8$ versus $10.0$ mg/kg i.p., respectively) (Fig. 5B).

**Randall-Selitto.** Tapentadol [$F(4,45) = 28.35, p < 0.0001$] and morphine [$F(5,54) = 25.18, p < 0.0001$] produced dose-dependent antinociception and reached similar efficacy. Morphine was approximately twice as potent as tapentadol ($ED_{50} 5.6$ versus $10.1$ mg/kg i.p., respectively) (Fig. 6).

**Mustard Oil-Induced Visceral Pain.** Tapentadol showed a dose-dependent inhibition of different visceral pain parameters. Spontaneous visceral pain was inhibited with an $ED_{50}$ of 1.5 mg/kg i.v., referred allodynia as measured by means of 1 mN von Frey stimulation with an $ED_{50}$ of 3.8 mg/kg i., and referred hyperalgesia as measured by scoring.
the reaction toward 16 mN von Frey stimulation with an ED\textsubscript{50} of 3.9 mg/kg i.v. Morphine showed a similar efficacy as tapentadol, with a 1.5 to 4-fold higher potency (ED\textsubscript{50} 1.0 mg/kg i.v. for spontaneous visceral pain, 0.77 mg/kg i.v. for referred allodynia, and 0.86 mg/kg i.v. for referred hyperalgesia) (Fig. 7). The results of the ANOVAs for effects on spontaneous pain were as follows: tapentadol \(F(3,36) = 9.96, p < 0.0001\); morphine \(F(5,54) = 8.72, p < 0.0001\).

**Spinal Nerve Ligation.** Tapentadol \([\text{tapentadol} \ F(4,45) = 12.17, p < 0.0001]\) and morphine \([\text{morphine} \ F(4,45) = 29.87, p < 0.0001]\) showed dose-dependent inhibition of mechanical allodynia. Morphine was approximately twice as potent as tapentadol (ED\textsubscript{50} 4.6 versus 8.2 mg/kg i.p., respectively) (Fig. 8A). Baseline withdrawal thresholds were 22.7 g for ligated animals and 57.1 g for sham animals.

**Streptozotocin Model.** Mechanical hyperalgesia was dose-dependently inhibited by tapentadol \([\text{tapentadol} \ F(3,36) = 68.85, p < 0.0001]\) and morphine \([\text{morphine} \ F(3,36) = 30.46, p < 0.0001]\), and both drugs reached full efficacy. Morphine was approximately three times as potent as tapentadol (ED\textsubscript{50} 3.0 versus 8.9 mg/kg i.p.) (Fig. 8B). The baseline withdrawal threshold was 94.0 g for diabetic animals.

**Antagonism in the Writhing Model.** In a pilot experiment (to determine equianalgesic doses for subsequent antagonism experiments), tapentadol and morphine induced a dose-dependent inhibition of writhing reactions with ED\textsubscript{50} values of 0.7 and 0.4 mg/kg i.v., respectively. When equianalgesic doses of tapentadol (3.16 mg/kg i.v.) and morphine (0.681 mg/kg i.v.) were combined with increasing doses of naloxone, the antinociceptive effect of morphine was more potently reduced than that of tapentadol at any given naloxone dose (Fig. 9). Naloxone antagonized the morphine effect with an ED\textsubscript{50} of 0.007 mg/kg i.v. (0.001–0.023) and the tapentadol effect with an ED\textsubscript{50} of 0.099 mg/kg i.v. (0.046–0.269). Two-factor ANOVA indicated a highly significant difference between treatment conditions (tapentadol versus morphine groups): \(F(1,90) = 15.60, p < 0.001\).

In an attempt to parallel the antagonism studies conducted...
in the SNL model (see below), we also used the α₂ adrenoceptor antagonist yohimbine in the writhing model. However, these experiments yielded no meaningful results. Yohimbine produced strong side effects in phenylquinone-treated mice, thus preventing measurement of writhing reactions.

Antagonism in the Spinal Nerve Ligation Model. When equieffective doses of tapentadol (10 mg/kg i.v.) and morphine (6.81 mg/kg i.v.) were combined with naloxone (0.3 mg/kg i.p.), the antiallodynic effect of tapentadol was reduced from 72 to 42% MPE at the peak effect time of 30 min [interaction: F(1,36) = 0.77, p > 0.05, nonsignificant], whereas the antiallodynic effect of morphine was reduced from 83 to 25% MPE [interaction: F(1,36) = 16.79, p < 0.001]. On the other hand, yohimbine (2.15 mg/kg i.p.) showed a clear reduction of the antiallodynic effect of tapentadol from 81 to 19% MPE [interaction: F(1,36) = 6.74, p < 0.05], whereas only a small reduction was seen in the combination with morphine from 80 to 54% MPE [interaction: F(1,36) = 3.02, p > 0.05, nonsignificant] (Fig. 10).

Tolerance Development in the Chronic Constriction Injury Model. In a pilot experiment (to determine equianalgesic doses for subsequent antagonism experiments), tapentadol and morphine dose-dependently inhibited cold allodynia with ED₅₀ values of ~13 and 7.1 mg/kg i.p., respectively. Subsequently, tolerance was induced by daily administration of 6.81 mg/kg i.p. tapentadol or 6.81 mg/kg i.p. morphine. Complete tolerance to morphine was obtained at day 10, whereas complete tolerance to tapentadol was not reached until day 23 (Fig. 11) [treatment: F(2,39) = 34.05, p < 0.0001; time: F(12,28) = 50.73, p < 0.0001; treatment × time: F(24,56) = 10.54, p < 0.0001]. Baseline numbers of withdrawal reactions on day 1 before the first administration were 37.9, 37.6, and 37.5 for vehicle, tapentadol, and morphine groups, respectively.

Discussion

Tapentadol was characterized as a MOR agonist and NE transporter inhibitor in receptor binding assays and in functional MOR and NE synaptosomal reuptake assays. The in-
In vivo intracerebral microdialysis with probes located in the ventral hippocampus was performed in awake rats. Pilot studies with the selective NE reuptake inhibitor reboxetine and the selective 5-HT reuptake inhibitor citalopram confirmed that this brain region is sensitive to both NE and 5-HT reuptake inhibitors (see Cremers et al., 2007; unpublished data). Tapentadol induced a clear increase in extracellular NE levels in the analgesic dose range but only a moderate increase in extracellular 5-HT levels. Morphine, on the other hand, had a comparable (if somewhat delayed and nonsignificant) effect on 5-HT, but it did not produce an increase in extracellular NE levels. Thus, consistent with the in vitro data, the microdialysis data demonstrate that the norepinephrinergic activity of tapentadol is much more pronounced than its serotonergic activity.

Tapentadol is metabolized predominantly by O-glucuronidation (Terlinden et al., 2006). The O-glucuronide did not show any affinity for the MOR, the NE transporter, or any of the other targets studied and was devoid of any activity in the mouse tail-flick test after i.v. or i.c.v. administration (data not shown). This clearly differentiates tapentadol from other opioids, such as codeine or tilidine, and also from tramadol, which all require metabolic activation or morphine, which is converted to the highly potent morphine-6-glucuronide. Because the analgesic activity of tapentadol resides in the parent molecule, polymorphic CYP2D6 enzymes are not required for conversion to an active metabolite, thereby reducing the likelihood of large individual variations in the analgesic response to tapentadol.

It is well known that MOR agonists and NE reuptake inhibitors have analgesic effects, although the pain conditions in which these two drug classes are most efficacious may be different. It appears that, overall, MOR agonists are predominantly effective against acute, moderate-to-severe pain, whereas NE reuptake inhibitors are particularly effective against chronic pain (Casy and Parfitt, 1986; Carter and Sullivan, 2002). This implies that a compound that combines both mechanisms of action holds the promise of being effec-
active against a large spectrum of pain conditions, ranging from acute to chronic pain. In the present studies, tapentadol showed antinociceptive, antihyperalgesic, and/or antiallodynic effects in various models of acute and chronic (neuropathic) pain, including the L5 spinal nerve ligation model (Kim and Chung, 1992) and streptozotocin-induced polyneuropathy (Courteix et al., 1993); in models of inflammatory pain, such as the yeast model (Randall and Selitto, 1957); and in models of acute nociception, such as hot plate (Eddy and Leimbach, 1953) and tail-flick (D'Amour and Smith, 1941), thus confirming a broad spectrum of analgesic activity that was expected for a compound with MOR agonistic and NE reuptake-inhibiting properties. Although morphine was also found to be active across the various pain models, it should be noted that there was a striking mismatch between the potency difference of morphine and tapentadol with regard to MOR binding on the one hand and analgesic effects on the other hand. The potency difference for MOR binding was approximately 50-fold, whereas the overall potency difference for analgesia was only approximately 2 to 3-fold in most pain models after systemic administration. Based on the MOR agonistic activity alone, tapentadol would have been expected to have a much lower analgesic potency, suggesting that another mechanism of action and/or the kinetics of the compound are likely to contribute to this effect. The in vitro and microdialysis data indicate that the additional mechanism contributing to the analgesic effect of tapentadol is inhibition of NE reuptake. This suggestion was corroborated in in vivo pharmacological antagonism studies. In the SNL model of neuropathic pain, it was shown that the analgesic effect of tapentadol was much more sensitive to the antagonistic effect of a given dose of yohimbine than that of an equianalgesic dose of morphine. Furthermore, under identical experimental conditions, the analgesic effect of morphine was much more sensitive to the antagonistic effect of naloxone than that of tapentadol. Because tapentadol combines MOR agonism and NE reuptake inhibition in a single molecule, isobolographic analysis of the interaction of the two mechanisms of action is not possible. However, preclinical as well as clinical evidence indicates that opioid analgesia can be augmented by monoamine reuptake inhibitors (Ossipov et al., 1982; Levine et al., 1986; Ventafridda et al., 1990). Tolerance to the analgesic effect of opioids can be readily observed in animal pain models (for review, see Trujillo, 2000) and can also occur in the clinical setting, necessitating dose increases during prolonged treatment (Ballantyne and Mao, 2003). Tolerance development to the analgesic effect of tapentadol in the CCI model in rats during repeated administration was much delayed compared with morphine. We also investigated tolerance development in the rat tail-flick model. Preliminary data indicate that, using equianalgesic doses of tapentadol and morphine, the shape of the curve showing the loss of antinociceptive effect of tapentadol was clearly different from that obtained for morphine. Morphine showed an immediate onset of tolerance development and complete tolerance within 21 days of treatment. Tapentadol showed a delayed onset of tolerance development. After on-
set, there was a progressive decline of effect until day 18, followed by a plateau phase of moderate antioinociception (30% MPE) and complete tolerance on day 51. It is noteworthy that the delayed tolerance development was seen only for the analgesic effect of tapentadol; tolerance development for the respiratory depressant effect was not delayed compared with morphine (see Tzschentke et al., 2006). We also have preliminary data showing that the NE reuptake inhibitor desipramine has an analgesic effect in the CCI model that does not show tolerance after more than 3 weeks of daily applications. This suggests that the prolonged analgesic activity of tapentadol may be related to its norepinephrinergic activity.

Notably, tapentadol has also been shown to have a clearly reduced emetic potential compared with morphine and produce less physical dependence than morphine at equianalgesic doses (Tzschentke et al., 2006). Both observations may be related to the reduced MOR binding affinity of tapentadol relative to morphine and, at least in the case of physical dependence, to the NE reuptake inhibitory properties of the compound.

In conclusion, tapentadol was characterized as a new analgesic drug with a dual mode of action. It combines moderate MOR agonistic activity with NE reuptake inhibition in a single, nonnarcotic molecule. No metabolic activation of tapentadol is necessary for analgesia, and it has no active metabolites. Because of its dual mechanism of action, tapentadol has efficacy in a broad spectrum of acute and chronic pain models and possibly an improved tolerability profile. Tapentadol is currently in phase III of clinical development.

Acknowledgments


References


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