Blockade of 5-HT$_{1A}$ Receptors by (+)-Pindolol Potentiates Cortical 5-HT Outflow, but not Antidepressant-Like Activity of Paroxetine: Microdialysis and Behavioral Approaches in 5-HT$_{1A}$ Receptor Knockout Mice

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Selective serotonin reuptake inhibitors like paroxetine (Prx) often require 4–6 weeks to achieve clinical benefits in depressed patients. Pindolol shortens this delay and it has been suggested that this effect is mediated by somatodendritic 5-hydroxytryptamine (5-HT) 1A autoreceptors. However, clinical data on the beneficial effects of pindolol are conflicting. To study the effects of (+)-pindolol–paroxetine administration, we used genetic and pharmacological approaches in 5-HT$_{1A}$ knockout mice (5-HT$_{1A}$/C0/C0). Two assays, in vivo intracerebral microdialysis in awake mice and the forced swimming test (FST), were used to assess the antidepressant-like effects of this drug combination. Basal levels of extracellular serotonin, 5-HT ([5-HT]$_{\text{ext}}$) in the frontal cortex (FCX) and the dorsal raphe nucleus (DRN) did not differ between the two strains of mice, suggesting a lack of tonic control of 5-HT$_{1A}$ autoreceptors on nerve terminal 5-HT release. Prx (1 and 4 mg/kg) dose-dependently increased cortical [5-HT]$_{\text{ext}}$ in both genotypes, but the effects were greater in mutants. The selective 5-HT$_{1A}$ receptor antagonist, WAY-100635 (0.5 mg/kg), or (+)-pindolol (5 and 10 mg/kg) potentiated the effects of Prx (4 mg/kg) on cortical [5-HT]$_{\text{ext}}$ in 5-HT$_{1A}$/+/+ mice, but not in 5-HT$_{1A}$/−/− mice. Similar responses were obtained following local intra-raphe perfusion by reverse microdialysis of either WAY-100635 or (+)-pindolol (100 µM each). In the FST, Prx administration dose-dependently decreased the immobility time in both strains of mice, but the response was much greater in 5HT$_{1A}$/−/− mice. In contrast, (+)-pindolol blocked Prx-induced decreases in the immobility time while WAY-100635 had no effect in both genotypes. These findings using 5-HT$_{1A}$/−/− mice confirm that (+)-pindolol behaves as an antagonist of 5-HT$_{1A}$ autoreceptor in mice, but its blockade of paroxetine-induced antidepressant-like effects in the FST may be due to its binding to other neurotransmitter receptors.

Keywords: microdialysis; 5-HT$_{1A}$ receptor antagonist; (+)-pindolol; selective serotonin reuptake inhibitor; forced swimming test; dorsal raphe nucleus

INTRODUCTION

The clinical benefits of selective serotonin (5-HT) reuptake inhibitors (SSRI), like paroxetine are only evident after 4–6 weeks of treatment (Blier and de Montigny, 1994). One possible explanation for the long delay of action could be a negative feedback control exerted by 5-HT$_{1A}$ autoreceptors on nerve terminal 5-HT release (Artigas et al, 1996). Although this initially blunts the effects of SSRI, 5-HT$_{1A}$ autoreceptors are gradually desensitized during chronic SSRI administration allowing the development of the antidepressant effect (Blier et al, 1987; Invernizzi et al, 1996). This notion led clinicians to propose a pharmacological strategy to accelerate the antidepressant response by blocking the action of presynaptic 5-HT$_{1A}$ receptors during SSRI administration. (+)-Pindolol is a β1−2 adrenergic receptor antagonist with a putative antagonistic action on 5-HT$_{1A}$ receptors (Newman-Tancredi et al, 1998; Castro et al, 2000), with a greater occupation at somatodendritic 5-HT$_{1A}$ receptors than at post synaptic receptors (Martinez et al, 2000, 2001). Several open clinical studies have shown a
faster onset of antidepressant effects of SSRIs when combined with (±)-pindolol in depressed patients (Artigas et al., 1994; Blier and Bergeron, 1995). Nevertheless, the recent meta-analysis of Ballesteros and Callado (2004), pooling nine randomized controlled trials, has come to a different conclusion, as that the efficacy of pindolol + SSRI pooling nine randomized controlled trials, has come to a recent meta-analysis of Ballesteros and Callado (2004), et al., 1994; Blier and Bergeron, 1995). Nevertheless, the different conclusion, as that the efficacy of pindolol + SSRI induced 5-HT release in various brain areas (Hjorth and Auerbach, 1994; Hjorth, 1996; Dawson and Nguyen, 2000).

Owing to the conflicting clinical and preclinical results, we decided to address the question of the mechanism of action of pindolol and to study the effects of an optimal combination of (±)-pindolol and paroxetine by using genetically modified, 5-HT1A receptor knockout mice (5-HT1A−/−, for a review, see Toth, 2003) to study the effects of an optimal combination of (±)-pindolol and paroxetine, which seem to be the more efficient (Plenge and Mellerup, 2003). We also studied the selectivity of (±)-pindolol by using reverse microdialysis to perfuse this compound directly in the DRN. To assess the neurochemical actions of (±)-pindolol at presynaptic 5-HT1A receptors, we performed a series of in vivo microdialysis experiments in both the DRN and frontal cortex (FCX). We also tested the effect of (±)-pindolol in combination with paroxetine in a behavioural model, the forced swimming test (FST), a useful model that predicts the antidepressant-like activity of new compounds with a good reliability and predictive validity for the screening of antidepressant drugs (Petit-Demouliere et al., 2005).

MATERIALS AND METHODS

Animals
Male C57Bl/6 wild-type (5-HT1A+/+) and homozygous 5-HT1A receptor knockout mice (5-HT1A−/−) (Parks et al., 1998), 6–8 weeks old, weighing 24–32 g, were used in all experiments. Mice maintained at Weill Medical College of Cornell University were transferred to our laboratory in order to grow a stable colony in the animal facility of the Faculté de Pharmacie, University of Paris XI, France. Experimental animals were housed in the animal care facility in groups of 4–6 and kept under standard conditions. Procedures were conducted in conformity with the institutional guidelines that are in compliance with national and policy (Council directive # 87–848, October 19, 1987, Ministère de l’Agriculture et de la Forêt, Service Vétérinaire de la Santé et de la Protection Animale, permissions # 92–196 to AM Gardier).

Chemicals and Drugs
Racemic 8-hydroxy-2-(di-n-propylamino)tetralin hydrobromide (8-OH-DPAT) and N-[2-[4-(2-methoxyphenyl)-1-piperazinyl]ethyl]-N-2-pyrindinylcyclohexanecarboxamide (WAY-100635) were purchased from Sigma-Aldrich (Saint Quentin Fallavier, France). The SSRI, paroxetine hydrochloride was a gift from GlaxoSmithKline Laboratory (Harlow, UK), (±)-pindolol base from Novartis laboratory (Rueil-Malmaison, France), and citalopram hydrobromide from Lundbeck laboratory (Copenhagen, Denmark). All chemical compounds except (±)-pindolol were dissolved in distilled water. (±)-Pindolol was dissolved in Tween 20% for systemic administration. Paroxetine was administered by intraperitoneally (i.p.) and the 5-HT1A receptor agonists and antagonists were administered subcutaneously (s.c.) or perfused locally. Control animals were injected using the appropriate vehicle and the same administration route. For their local perfusion into the DRN or the FCX, WAY-100635 (100 μM) and citalopram (1 μM) were dissolved in artificial cerebrospinal fluid (aCSF) and perfused at a flow rate of 0.5 and 1.5 μl/min, respectively; (±)-pindolol (100 μM) was first dissolved in perchloric acid (1%) and then diluted in aCSF and perfused at 0.5 μl/min.

Microdialysis Procedure
Concentric dialysis probes were made of cuprophan fibers and constructed as previously described (Malagie et al., 2001; Guiard et al., 2004). All probes present an active length of 2 and 5 mm for the FCX and DRN, respectively (× 0.30 mm outer diameter). Animals were anaesthetized with chloral hydrate (400 mg/kg, i.p.) and were implanted with a probe, cemented in place in the FCX and/or in the DRN, based on coordinates taken from the mouse brain atlas (Franklin and Paxinos, 1997) (coordinates: from bregma (in mm) FCX, A = +1.6, L = +1.3, V = −1.6; DRN, A = −4.5, L = 0, V = −4.0 (A, anterior; L, lateral; and V, ventral)). Animals were allowed to recover from the surgery overnight. The next day, ≈20 h after surgery, the probes were continuously perfused with an artificial cerebrospinal fluid (composition in mM: NaCl 147, KCl 3.5, CaCl2 1.26, MgCl2 1.2, NaH2PO4 1.0, NaHCO3 25.0, pH 7.4 ± 0.2) at a flow rate of 1.5 μl/min in the FCX and 0.5 μl/min in the DRN using a CMA/100 pump (Carnegie Medicin, Stockholm, Sweden). Dialysate samples were collected every 15 min in the FCX and every 30 min in the DRN in tubes and were analyzed for 5-HT by a high-performance liquid chromatography apparatus (XL-ODS, 4.6 × 7.0 mm, particle size 3 μm; Beckman) coupled to an amperometric detector (1049A, Hewlett-Packard, Les Ulis, France) (Malagie et al., 2001). Usually four fractions were collected to obtain basal values (means ± SEM) before drug administration. The limit of sensitivity for 5-HT was ≈0.5 fmol/sample (signal-to-noise ratio = 2). At the end of the experiments, localisation of microdialysis probes was verified histologically (Figure 1).

Histological Verification of Microdialysis Probes’ Implantation
The placement of microdialysis probes was verified using adaptation of the technique described previously (Bert et al., 2004). After the microdialysis study, mice were killed by cervical dislocation, brains were removed
and stored at +4°C in Formalin 2%. To determine the exact probe implantation in the FCX or DRN, brains were placed in a Kryomat apparatus and kept at −25°C. Brain regions were identified by using the 'Mouse brains' atlas (Hof et al., 2000) and coronal frozen sections of brain were sliced serially at 50 μm intervals. Slices were prepared from AP +2 to +1 mm and AP −4 to −5 mm for the FCX and DRN, respectively. Each slice was photographed using a digital camera (C-4000 Zoom, Olympus) and the appropriate placement of the probe estimated in comparison to the corresponding slices obtained by the 'Mouse brains' atlas software (Hof et al., 2000). Only mice with probes confined to either the FCX or the DRN were used for subsequent data analysis and a cartography of probes implantation in the DRN was performed (Figure 1).

Figure 1 Histological verification of microdialysis probes' implantation. Coronal sections drawings of a C57BL/6 mouse brain showing the location of the concentric microdialysis probes in the frontal cortex (a) and dorsal raphe nucleus (b) according to Hof et al 'Mouse brains' atlas (2000). (a) The black line indicates the brain zone of dialysis of the membrane. The probes were implanted with the following stereotaxic coordinates (coordinates for bregma in mm) in the FCX: AP +1.6, L ±1.3, V −1.6. (b) The dotted line indicates the location of the dorsal raphe nucleus (DRN). The black continuous line indicates the zone of dialysis of the membrane. The probes were implanted with the following stereotaxic coordinates in the DRN: AP −4.5, L 0, V −4.

The Mouse FST

The FST was applied as described by Porsolt et al (1977): mice were dropped individually into glass cylinders (height: 25 cm, diameter: 10 cm) containing 10 cm water height, maintained at 23–25°C. Animals were tested for a total of 6 min. Two mice were tested simultaneously and the time of immobility was recorded during the last 4 min of the 6-min testing period, after 2 min of habituation. The test was performed by the same well-trained experimenter, who was unaware of the treatment administered.

Data Analysis and Statistics

Statistical analysis was performed using the computer software StatView 5.0. (Abacus Concepts, Inc, Berkely, CA,
Table 1 Basal 5-HT Levels in the Frontal Cortex (FCX) and in the Dorsal Raphe Nucleus (DRN) in 5-HTIA+/+ and 5-HTIA−/− Mice

<table>
<thead>
<tr>
<th>Genotype</th>
<th>FCX (fmol/20 μl)</th>
<th>DRN (fmol/10 μl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-HTIA+/+ mice</td>
<td>4.30 (±0.19; n = 122)</td>
<td>23.70 (±4.00; n = 46)</td>
</tr>
<tr>
<td>5-HTIA−/− mice</td>
<td>4.35 (±0.15; n = 132)</td>
<td>23.95 (±3.12; n = 25)</td>
</tr>
</tbody>
</table>

No statistical differences for the 5-HT basal levels were observed between both genotype in the FCX or the DRN. Mean ± SEM, n = number of determinations.

RESULTS

Basal Extracellular Levels of 5-HT in the FCX and Dorsal Raphe in 5-HTIA+/+ and 5-HTIA−/− Mice

Table 1 shows the mean ± SEM of basal [5-HT]ext levels in the FCX (in fmol/20 μl) and DRN (in fmol/10 μl) of the various groups of mice studied. Basal extracellular 5-HT levels were not different between 5-HTIA+/+ and 5-HTIA−/− mice either in the FCX (F(1,252) = 0.47, p = 0.82) or in the DRN (F(1,69) = 0.01, p = 0.97).

Effects of Systemic Administration of 8-OH-DPAT on Cortical Dialysate 5-HT in 5-HTIA+/+ and 5-HTIA−/− Mice

Two-way ANOVA (treatment × genotype) of 5-HT outflow, measured as AUC calculated during a 60 min post-treatment period revealed a significant main effect of genotype factor (F(1,34) = 5.06, p < 0.05), treatment (F(1,34) = 5.83, p < 0.05), and treatment × genotype interaction (F(1,34) = 12.45, p < 0.01) (Figure 2). Specifically, the 5-HTIA receptor agonist 8-OH-DPAT (0.5 mg/kg, s.c.) decreased cortical [5-HT]ext in 5-HTIA+/+ mice by about 38% (p < 0.01), but caused no change in 5-HTIA−/− mice (Figure 2c) (p = 0.34).

Effects of Local Intra-Raphe Infusion of (+)-Pindolol Alone on Cortical and DRN [5-HT]ext in the Presence of Citalopram (1 μM) in 5-HTIA+/+ and 5-HTIA−/− Mice

Two-way ANOVA (treatment × genotype) of AUC values, however, revealed no significant effect of treatment factor (F(1,18) = 1.76, p = 0.20) and genotype factor (F(1,18) = 0.34, p = 0.57) indicating that administration of (+)-pindolol (100 μM) in the DRN had no effect either on local (ie DRN) or on cortical dialysate 5-HT levels in both 5-HTIA+/+ mice and 5-HTIA−/− mice. **p < 0.01 significantly different from the vehicle-treated group; ***p < 0.001 and significantly different from 5-HTIA+/+ mice (two-way ANOVA followed by a PLSD post hoc test).
5-HT_{1A}+/+ and 5-HT_{1A}−/− mice (see Supplementary information, Figure 8).

Effect of Systemic Administration of Paroxetine on Cortical Dialysate 5-HT in 5-HT_{1A}+/+ and 5-HT_{1A}−/− Mice

Two-way ANOVA (treatment × genotype) on AUC values revealed significant main effect of genotype (F(1,39) = 14.42; p < 0.001), treatment (F(2,39) = 11.26; p < 0.001), and treatment × genotype interaction (F(2,39) = 5.63; p < 0.01) (Figure 3). While both a low (1 mg/kg) and a high (4 mg/kg) paroxetine dose increased dialysate 5-HT levels in 5-HT_{1A}−/− mice (p < 0.05 and p < 0.001 respectively), only the higher paroxetine dose (4 mg/kg) increased [5-HT]_{ext} in 5-HT_{1A}+/+ mice (Figure 3c) (p < 0.05).

Antidepressant-Like Effects of Paroxetine on the Immobility Time in the Mouse FST in 5-HT_{1A}+/+ and −/− Mice

Next, FST was carried out during the peak of paroxetine effect (30 min after the drug, see gray area in Figure 3) and immobility time was measured in the last 4 min of the 6 min test in both genotypes. Two-way ANOVA (treatment × genotype) on the immobility time revealed significant main effect of genotype (F(1,122) = 57.17; p < 0.001), treatment (F(4,122) = 13.69; p < 0.001), and an interaction between these two factors (F(4,122) = 6.69; p < 0.001). As Figure 4 shows, paroxetine (1–4 mg/kg) had a more robust effect on the behavior of 5-HT_{1A}−/− mice (p < 0.05, p < 0.001, p < 0.01 for 1, 2, and 4 mg/kg, respectively).

These data indicate that 5-HT_{1A}−/− mice have a dramatically increased sensitivity to the antidepressant-like effects of paroxetine.

Dose–Response Study of the Systemic Administration of (+)-Pindolol on Paroxetine (4 mg/kg)-Induced Increases in Cortical Dialysate 5-HT in 5-HT_{1A}+/+ and 5-HT_{1A}−/− Mice

Two-way ANOVA (treatment × genotype) on AUC values revealed significant main effect of treatment (F(5,122) = 5.54; p < 0.001) and genotype (F(1,122) = 4.04; p < 0.05) (Figure 5). Specifically, (+)-pindolol at 5 and 10 mg/kg s.c. (but not at 1 mg/kg), administered 1 h after paroxetine, potentiates the elevation in [5-HT]_{ext} when compared to the paroxetine/vehicle group in 5-HT_{1A}+/+ mice (p < 0.01 for 5 and 10 mg/kg of pindolol). Similarly, the 5-HT_{1A} receptor antagonist WAY-100635 potentiates the effects of paroxetine (p < 0.001). In contrast, neither (+)-pindolol nor WAY-100635 potentiates the effect of paroxetine in 5-HT_{1A}−/− mice (p = 0.65 and p = 0.76, respectively). In both genotypes, neither (+)-pindolol nor WAY-100635 have an effect on extracellular 5-HT levels when administered alone (data not shown). These data indicate that the presence of 5-HT_{1A} receptor is essential for the potentiation of paroxetine’s effect by either pindolol or WAY-100635 (for the time course study, see Figure 9 in Supplementary information).
Figure 4 Antidepressant-like effects of paroxetine on the immobility time in the mouse forced swimming test (FST) in 5-HT1A+/+ and 5-HT1A−/− mice. Results are expressed as means ± SEM of the immobility time (in seconds): 5-HT1A+/+ (C) and 5-HT1A−/− mice (■) received either the vehicle or paroxetine (0.25, 1.2, 4 mg/kg, i.p.). Statistical analysis were carried out using a two-way ANOVA followed by Fisher PLSD: *p<0.05; **p<0.01) significantly different from the appropriate control group; ***p<0.001; and significantly different from 5-HT1A+/+ mice. Statistical analysis was carried out using a two-way ANOVA followed by Fisher PLSD post hoc t-test.

Figure 5 Dose–response study of the systemic administration of (+)-pindolol or WAY-100635 combined with paroxetine (4 mg/kg) on cortical [5-HT]ext in 5-HT1A+/+ and 5-HT1A−/− mice. Data are area under the curve (AUC; mean ± SEM) values calculated for the amount of 5-HT outflow measured during the 0–120 min post-treatment period with paroxetine or paroxetine coadministered with either pindolol (1, 5 or 10 mg/kg, s.c.) or WAY-100635 and expressed as percentages of basal values (n=8–15 mice per group) in 5-HT1A+/+ (a) and 5-HT1A−/− (α) mice. **p<0.01; ***p<0.001 significantly different from the paroxetine-treated group; 6p<0.05 significantly different from the 5-HT1A+/+ mice (two-way ANOVA followed by a PLSD post hoc t-test).

Effects of Local Intra-Raphe Infusion of (+)-Pindolol or WAY-100635 Following Systemic Paroxetine Administration on Dialysate 5-HT in the FCX and DRN in 5-HT1A+/+ and 5-HT1A−/− Mice

FCX. Next, effect of pindolol was studied following local administration to DRN. Two-way ANOVA analysis on AUC values revealed significant main effects of treatment factor (F(5,61) = 8.06, p < 0.001), but not genotype factor (F(1,61) = 0.85; p = 0.36) (Figure 6a–b).

In 5-HT1A+/+ mice, a 1 h intra-raphe perfusion of (+)-pindolol given 1 h after a systemic administration of paroxetine (Figure 6a) potentiated the effects of the SSR1 on cortical [5-HT]ext when compared to the paroxetine/aCSF group (AUC values: 146 ± 9 vs 258 ± 41% (p < 0.01) for paroxetine/aCSF vs paroxetine/aCSF + (+)-pindolol, respectively).

Similarly, intra-raphe perfusion of WAY-100635 (100 μM) (Figure 6a) potentiated the effects of paroxetine (AUC values: 146 ± 9 vs 227 ± 36% (p < 0.05) for paroxetine/aCSF vs paroxetine/aCSF + WAY-100635, respectively).

In 5-HT1A−/− mice, neither intra-raphe perfusion of (+)-pindolol nor WAY-100635 potentiated the effects of paroxetine (Figure 6b). AUC values were 275 ± 48% for paroxetine/aCSF and 222 ± 46% (p = 0.31), 253 ± 14% (p = 0.67), for paroxetine/aCSF + (+)-pindolol and paroxetine/aCSF + WAY-100635, respectively (for the time course study, see Figure 10 in Supplementary information).

DRN. Two-way ANOVA analysis on AUC values revealed significant main effects of treatment factor (F(5,70) = 11.68; p < 0.001) and genotype factor (F(1,70) = 6.86; p < 0.05) (Figure 6c–d).

As we observed in the FCX, the effects of paroxetine (4 mg/kg) were higher in 5-HT1A−/− mice than in 5-HT1A+/+ mice.

In 5-HT1A+/+ mice, intra-raphe perfusion of (+)-pindolol given 1 h after a systemic administration of paroxetine (Figure 6c) potentiated the effects of the SSR1 on dialysate 5-HT in the DRN, when compared to the paroxetine/aCSF group (AUC values were 284 ± 38% for the paroxetine/aCSF + (+)-pindolol group (p < 0.05)).

Local intra-raphe perfusion of WAY-100635 (100 μM) (Figure 6d and f) also potentiated the effects of paroxetine (AUC values were 273 ± 60% for paroxetine/aCSF + WAY-100635 group (p < 0.05)).

In 5-HT1A−/− mice, neither intra-raphe perfusion of (+)-pindolol nor WAY-100635 potentiated the effects of paroxetine (Figure 6d). AUC values were 352 ± 78% for paroxetine/aCSF, 312 ± 39 and 365 ± 117%, for paroxetine/aCSF + (+)-pindolol and paroxetine/aCSF + WAY-100635, respectively (p = 0.70 and p = 0.17 for paroxetine/aCSF + (+)-pindolol and paroxetine/aCSF + WAY-100635, respectively) (for the time course study, see Figure 10 in Supplementary information).

Antidepressant-Like Effects of the Co-Administration of Paroxetine and (+)-Pindolol or WAY-100635 in 5-HT1A+/+ and 5-HT1A−/− Mice in the FST

Two-way ANOVA analysis on immobility time values revealed significant main effect of treatment (F(5,99) = 9.76; p < 0.001) and genotype factors (F(1,99) = 4.51; p < 0.05) (Figure 7). Neither (+)-pindolol (p = 0.52 and p = 0.75 in 5-HT1A+/+ and 5-HT1A−/− mice, respectively) nor WAY-100635 (p = 0.55 and p = 0.44 in 5-HT1A+/+ and 5-HT1A−/− mice, respectively) alone had an effect on the immobility time when compared to the appropriate vehicle-treated group (see Figure 11 in Supplementary information). Pindolol, but not WAY100635 (p = 0.21 and p = 0.35
when compared to the appropriate paroxetine/vehicle group in 5-HT1A+/+ and 5-HT1A−/− mice, respectively), blocked the antidepressant-like effects of paroxetine in both genotypes (p<0.05 and p<0.01 when compared to the appropriate paroxetine/vehicle group in 5-HT1A+/+ and 5-HT1A−/− mice, respectively).

**DISCUSSION**

In the present study, after the validation of our genetic mice model (5-HT1A−/−) using the intracerebral in vivo microdialysis and the mouse FST, we investigated, using these two different approaches (neurochemical and behavioral ones), the mechanism of action of (+)-pindolol alone or in combination with paroxetine.

### Neurochemical Validation of the Genetic Model, 5-HT1A−/− Mice

Baseline dialysate 5-HT levels in the FCX and DRN. Basal fronto-cortical [5-HT]ext in 5-HT1A−/− mice were similar to those found in 5-HT1A+/+ mice. These results confirm that dialysate 5-HT levels at serotonergic nerve terminals are not enhanced in the mutant mice, as most studies have revealed (see Knobelman’s study (2001b) but on a background strain different from ours). These results differ from those of Parsons et al (2001) who also used mice on C57BL/6 genetic background, but generated elsewhere (Heisler et al., 1998): they found that basal dialysate 5-HT levels were higher in mutants than in controls, both in the FCX and hippocampus. Age of these mice may account for this discrepancy since Parsons et al (2001) used 8- to 10-month-old male mice. Our results provide additional evidence that
somatodendritic 5-HT$_{1A}$ autoreceptors located in the DRN do not exert a tonic inhibitory control on 5-HT release at serotonergic nerve terminals. Also, in agreement with a recent study performed in a C57BL/6 genetic background, in the DRN, we also found no differences between basal [5-HT]$_{ext}$ in 5-HT$_{1A}^+/+$ and 5-HT$_{1A}^{-/-}$ mice (Bortolozzi et al, 2004). Furthermore, the role of 5-HT$_{1A}$ receptors on the noradrenergic system is also important: the blockade of 5-HT$_{1A}$ autoreceptors is known to decrease the noradrenergine release (Haddjeri et al, 1997, 2004).

**Effects of a 5-HT$_{1A}$ receptor agonist, 8-OH-DPAT.** Since the 5-HT$_{1A}$ receptor agonist, 8-OH-DPAT decreased cortical [5-HT]$_{ext}$ in 5-HT$_{1A}^+/+$ mice, presumably by acting on presynaptic 5-HT$_{1A}$ autoreceptors located in the DRN and because it had no effect in 5-HT$_{1A}^{-/-}$ mice, we validated our experimental knockout model. Similar results have been obtained in the striatum and ventral hippocampus either in 5-HT$_{1A}^{-/-}$ mice or in rats (Adell et al, 1993; Knobelman et al, 2001a).

**Dose-Dependent Neurochemical Effects and Antidepressant-Like Activity of Paroxetine in 5-HT$_{1A}^{-/-}$ Mice**

Differences between 5-HT$_{1A}^+/+$ and 5-HT$_{1A}^{-/-}$ mice were observed in the effects of a single paroxetine administration (1–4 mg/kg) on [5-HT]$_{ext}$. This SSRI slightly increased cortical [5-HT]$_{ext}$ in wild-type mice, as most studies have reported in this brain region (Malagie et al, 2001; Parsons et al, 2001; David et al, 2003a), as well as in the striatum and hippocampus (Knobelman et al, 2001a). For each paroxetine dose tested, its effects were almost three-fold higher in 5-HT$_{1A}^{-/-}$ mice than in controls: these potentiated effects were unlikely due to differences between wild-type controls and 5-HT$_{1A}^{-/-}$ mice in the serotonin transporter density in various brain regions (Ase et al, 2001). This larger neurochemical effect of SSRI measured in mutant vs wild-type mice, in forebrain regions was likely due to the lack of presynaptic 5-HT$_{1A}$ autoreceptors and has been described elsewhere (Parsons et al, 2001; Knobelman et al, 2001b). However, the absence of postsynaptic 5-HT$_{1A}$ receptors in constitutive knockout mice generated by homologous recombination cannot be ruled out as contributing to this effect. Indeed, this latter receptor is involved in a long postsynaptic inhibitory feedback loop to raphe nuclei and the brain stem, thus regulating activities of cell bodies of serotonergic neurons (Casasnovas et al, 1999). In other way, this loop has been described using microdialysis in the medial pre-FCX and our work has been performed in a more posterior part of the brain.

Our behavioral data obtained in the mouse FST confirm other reports showing the dose-dependent efficacy of SSRIs in reducing the immobility time in 5-HT$_{1A}^+/+$ mice (David et al, 2003b). As in other studies using Porstol’s Test or the Tail Suspension Test (Steru et al, 1985), we found a difference in baseline activity in this model between wild-type 5-HT$_{1A}^+/+$ and mutant 5-HT$_{1A}^{-/-}$ mice (Heisler et al, 1998; Parks et al, 1998; Ramboz et al, 1998; Mayorga et al, 2001). Overall, these results suggest that the genetic inactivation of 5-HT$_{1A}$ receptors abolished the inhibitory feedback control exerted by somatodendritic 5-HT$_{1A}$ autoreceptors, thus enhancing the response of mutant mice to stressful conditions: indirect activation of presynaptic 5-HT$_{1A}$ receptors by endogenous 5-HT may limit the antidepressant-like effects of the SSRI in the FST in wild-type mice. However, pharmacological studies performed in wild-type mice (O’Neill and Conway, 2001) and rats (Wieland and Lucki, 1990) described an antidepressant-like activity of full and partial 5-HT$_{1A}$ receptor agonists, such as 8-OH-DPAT and buspirone, respectively. It has been suggested that postsynaptic 5-HT$_{1A}$ receptors could mediate the behavioral effect of these agonists (Detke et al, 1995).

**Neurochemical Effects and Antidepressant-Like Activity of (+)-Pindolol Associated with Paroxetine in 5-HT$_{1A}^{-/-}$ Mice**

Our microdialysis results suggest that, in vivo, in awake mice, (+)-pindolol acts as an antagonist at 5-HT$_{1A}$ receptors. Indeed, (+)-pindolol displayed similar effects as those obtained with the antagonist of reference WAY-100635, that is, potentiating the effects of paroxetine on extracellular cortical 5-HT levels. Preclinical studies have reported conflicting results regarding the ability of (+)-pindolol to antagonize SSRI-induced inhibition of cell firing of 5-HT neurons or 5-HT release at nerve terminals. Numerous electrophysiological studies performed either in vivo in anesthetized animals or in vitro on brain slices suggested that (+)-pindolol behaves as a 5-HT$_{1A}$ receptor antagonist by blocking the SSRI-induced inhibition of 5-HT cell firing (Romero et al, 1996; Corradetti et al, 1998; Rasmussen et al, 2004), while others showed that it has either no effects or an agonistic effect on 5-HT$_{1A}$ receptors (Fornal et al, 1999; Sprouse et al, 2000). Results of intraocular in vivo microdialysis studies brought up less discrepancies: almost all studies demonstrated that pindolol can potentiate the effects of SSRI on dialysate 5-HT levels in brain regions enriched in serotonergic nerve terminals (Deshfield et al, 1996; Hjorth, 1996; Romero et al, 1996; Gobert and Millan, 1999; Dawson and Nguyen, 2000; Cremers et al, 2001; Miguez et al, 2002). The lack of (+)-pindolol effects in 5-HT$_{1A}^{-/-}$ mice suggests that changes in cortical dialysate 5-HT are unlikely due to its antagonistic action on other neurotransmitter receptor subtypes: it binds to 5-HT$_{1B}$ receptors with a third and 1000-fold lower affinity than to 5-HT$_{1A}$ receptors in rats and human, respectively (Castro et al, 2000; Artigas et al, 2001). However, it seems that, in brain regions innervated by the median raphe (hippocampus) rather than by the dorsal raphe (FCX) higher effects of 5-HT$_{1B}$ receptor antagonist on 5-HT release occurred (Malagie et al, 2001; Hughes and Dawson, 2004). Furthermore, other studies have shown that selective $\beta_1$ or $\beta_2$-adrenergic antagonists do not modulate dialysate 5-HT levels in the FCX or ventral hippocampus in rats (Hjorth et al, 1996; Gobert and Millan, 1999).

As we cannot exclude that (+)-pindolol binds to other neurotransmitter receptors and/or in other brain regions following its systemic administration, we studied whether its main site of action was confined to somatodendritic 5-HT$_{1A}$ autoreceptors located in the DRN. Thus, we performed local intra-raphe perfusion of (+)-pindolol (or WAY-100635) by reverse microdialysis: we found responses...
in the FCX and DRN similar to those measured following systemic administration of these compounds. It is likely that 5-HT\textsubscript{1A} autoreceptors were completely blocked following either systemic or intra-raphe (±)-pindolol administration. This assertion is based (1) on a pharmacokinetic studies performed in guinea-pigs (Hasegawa et al, 1989; Cremers et al, 2001), and (2) on the hypothesis that (±)-pindolol displays an affinity for 5-HT\textsubscript{1A} receptors in mice comparable to that measured in rats or guinea-pigs (Ki in a 6–34 nM range).

We used, here for the first time, a dual microdialysis approach by implanting two probes in the brain of awake, freely moving mice. Thus, the neurochemical responses depicted a neurochemical circuitry between the DRN and FCX. Our results show that intra-raphe perfusion of either (±)-pindolol or WAY-100635 had no effects on cortical and DRN dialysate 5-HT levels, when given alone, but potentiated paroxetine’s effects on extracellular 5-HT levels in the two brain regions studied. In rats, similar results were found in the ventral hippocampus following the local perfusion of (±)-pindolol in the median raphe nucleus (Miguez et al, 2002).

In the FST, the effect of the inactivation of the 5-HT\textsubscript{1A} receptor in combination with paroxetine differed depending on the experimental strategy used. By using a genetic strategy, we found that paroxetine-induced decreases in the immobility time was dramatically potentiated in 5-HT\textsubscript{1A}\textsuperscript{−/−} mice compared to wild-type controls. Conversely, by using a pharmacological strategy, we found that (±)-pindolol, but not WAY-100635, blocked paroxetine-induced effects in both genotypes in the FST. Conflicting results were reported in numerous studies using this behavioral test or the Tail Suspension Test that found either no potentiation or a blockade of SSRI effects by 5-HT\textsubscript{1A} receptor antagonists pindolol in rats or wild-type mice (Moser and Sanger, 1999; Tatarczynska et al, 2002).

Receptor Subtypes Involved in the Antidepressant-Like Activity of Pindolol

Non-5-HT\textsubscript{1A} receptor, 5-HT\textsubscript{1B} receptors, or β\textsubscript{1,2}-adrenoceptors? In the present study, the effects of pindolol in the behavioral test were different when combined with paroxetine, from those of WAY-100635 in both genotypes. It is likely that pindolol bound to non-5-HT\textsubscript{1A} receptors to induce these effects in the FST because (1) WAY-100635 had no effect in wild-type mice and (2) pindolol did block the effects of paroxetine in 5-HT\textsubscript{1A}\textsuperscript{−/−} mice. Such non-5-HT\textsubscript{1A} receptor subtypes could be either 5-HT\textsubscript{1B} receptors, or β\textsubscript{1,2}-adrenoceptors. Indeed, pindolol has an affinity for 5-HT\textsubscript{1B} receptors in rats (Titeler et al, 1987; Hoyer, 1988; Tsuchihashi et al, 1990; Langlois et al, 1993), or humans (Gobert and Millan, 1999). Furthermore, the guinea-pig has often served as an animal model to assess 5-HT\textsubscript{1B/1D} receptor function. Thus, (−)-pindolol displayed a significant binding affinity to 5-HT\textsubscript{1B} and 5-HT\textsubscript{1D} receptors (Zgombick et al, 1997; Moret and Briley, 1997). (−)-Pindolol potentiated the effect of milnacipran, a dual noradrenaline (NA) and serotonin reuptake inhibitor, on the extracellular levels of NA and 5-HT in the hypothalamus of guinea-pig (Moret and Briley, 1997). Tatarczynska et al (2004) found that 5-HT\textsubscript{1B} receptor agonists combined with an SSRI can reduce the immobility time in the mice FST. Results from our laboratory have demonstrated that the 5-HT\textsubscript{1B} receptor antagonist GR127935 (as pindolol here) blocks the anti-immobility effects of paroxetine in this paradigm in wild-type mice, but not in 5-HT\textsubscript{1B}\textsuperscript{−/−} mice, suggesting that activation of 5-HT\textsubscript{1B} receptors mediate, at least in part, the antidepressant-like activity of this SSRI (Gardier et al, 2001). Another possibility could be an antagonistic action of pindolol on β\textsubscript{1,2}-adrenoceptors. However, Detke et al (1995) found no blockade of the anti-immobility effects of 8-OHDPAT by either betaxolol or ICI 118551, antagonists at β\textsubscript{1} and β\textsubscript{2} adrenoceptor subtypes, respectively.

The results of the present study in wild-type mice are also in line with others, who found no potentiation of the effects of paroxetine by WAY-100635 (Cryan et al, 1998), but a blockade of this effect by pindolol in another model (Cryan et al, 1999). Only one pharmacological study found a potentiation of the antidepressant-like effects of an SSRI (fluoxetine) with (±)-pindolol in mice, but the high dosage of pindolol administered (32 mg/kg) is questionable (Redrobe et al, 1996). The dosage of both the antidepressant and the 5-HT\textsubscript{1A} receptor antagonist may be critical for the potentiation of the antidepressant-like effect of SSRIs in the FST.

Pre- vs postsynaptic 5-HT\textsubscript{1A} receptors? In wild-type mice, two different approaches (neurochemical and behavioral ones) studying the effects of coadministration of pindolol with paroxetine gave opposite responses: a potentiation or blockade in microdialysis experiments and the FST, respectively. It suggests that two different receptors having a distinct cellular distribution have been mobilized in these responses. Since intracerebral microdialysis is known to be a presynaptic test, changes in cortical extracellular 5-HT levels likely involved the effects of (±)-pindolol on presynaptic 5-HT\textsubscript{1A} autoreceptors. From this assertion, we can conclude that responses in the FST likely involved postsynaptic receptors in wild-type mice.

In conclusion, the results of microdialysis experiments suggest that activation of presynaptic 5-HT\textsubscript{1A} autoreceptors limits the effects of SSRIs on cortical dialysate 5-HT because the paroxetine response in the FCX was potentiated by pindolol in 5-HT\textsubscript{1A}\textsuperscript{+/+}, but not in 5-HT\textsubscript{1A}\textsuperscript{−/−} mice. The results of behavioral experiments suggest that (1) activation of 5-HT\textsubscript{1A} receptors limits the antidepressant-like activity of paroxetine and (2) the effects of pindolol in the FST are not mediated by activation of 5-HT\textsubscript{1A} receptors because pindolol gave similar responses in both genotypes (it blocked the antidepressant-like activity of paroxetine). Thus, a non-5-HT\textsubscript{1A} postsynaptic receptor, which remains to be identify, seems to be involved in the antidepressant-like activity of the combined treatment paroxetine + (±)-pindolol in this paradigm in mice.

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