Long-Term Effects of Olanzapine, Risperidone, and Quetiapine on Dopamine Receptor Types in Regions of Rat Brain: Implications for Antipsychotic Drug Treatment

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ABSTRACT

Changes in members of the dopamine (DA) D₁-like (D₁, D₅) and D₂-like (D₂, D₃, D₄) receptor families in rat forebrain regions were compared by quantitative in vitro receptor autoradiography after prolonged treatment (28 days) with the atypical antipsychotics olanzapine, risperidone, and quetiapine. Olanzapine and risperidone, but not quetiapine, significantly increased D₂ binding in medial prefrontal cortex (MPC; 67% and 34%), caudate-putamen (CPu; average 42%, 25%), nucleus accumbens (NAc; 37%, 28%), and hippocampus (HIP; 53%, 30%). Olanzapine and risperidone, but not quetiapine, produced even greater up-regulation of D₃ receptors in CPu (61%, 37%), NAc (65%, 32%), and HIP (61%, 37%). D₁-like and D₄ receptors in all regions were unaltered by any treatment, suggesting their minimal role in mediating actions of these antipsychotics. The findings support the hypothesis that antipsychotic effects of olanzapine and risperidone are partly mediated by D₂ receptors in MPC, NAC, or HIP, and perhaps D₃ receptors in CPu, NAC, or HIP, but not in cerebral cortex. Selective up-regulation of D₂ receptors by olanzapine and risperidone in CPu may reflect their ability to induce some extrapyramidal effects. Inability of quetiapine to alter DA receptors suggests that nondopaminergic mechanisms contribute to its antipsychotic effects.

Dopamine (DA) exerts its effects in mammalian brain by interacting with several DA receptor types that include D₁-like (D₁, D₅) and D₂-like (D₂, D₃, D₄) receptor families (Baldessarini and Tarazi, 1996). DA receptors, and particularly the D₂-like family, have been implicated in the pathophysiology of psychotic disorders and, more directly, in the pharmacodynamic basis of beneficial effects of antipsychotic drugs (Baldessarini and Tarazi, 2001). They are also implicated in centrally mediated adverse effects typical of most neuroleptic-antipsychotics, including extrapyramidal neurological reactions (particularly, parkinsonism and tardive dyskinesia) and hyperprolactinemia (Baldessarini and Tarsy, 1995). The pharmacological basis of the unusual clinical properties of this unique agent remains unclear. Clozapine interacts with high or moderate potency at serotonergic (5-HT₂A, 5-HT₂C, and others), acetylcholinergic (muscarinic), adrenergic (α₁, α₂, β₂), histaminic (H₁), and other neurohumor receptors. In contrast, it has only moderate affinity for both D₁ and D₂ DA receptors (Baldessarini and Frankenburg, 1991; Brunello et al., 1995). The pharmacological basis of the unusual clinical properties of this unique agent remains unclear. Clozapine interacts with high or moderate potency at serotonergic (5-HT₂A, 5-HT₂C, and others), acetylcholinergic (muscarinic), adrenergic (α₁, α₂, β₂), histaminic (H₁), and other neurohumor receptors. In contrast, it has only moderate affinity for both D₁ and D₂ DA receptors (Baldessarini and Frankenburg, 1991; Brunello et al., 1995; Baldessarini and Tarazi, 1996).

Clozapine also displays somewhat greater affinity for D₄ than other DA receptors (Van Tol et al., 1991), suggesting that these receptors may represent potential sites of action of clozapine and perhaps other antipsychotic agents. D₄ receptors also may be increased in postmortem brain tissue of schizophrenic patients (Seeman et al., 1993; Murray et al., 1995), although these findings remain inconsistent (Lahti et al., 1996). In addition, repeated administration of clozapine,

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ABBREVIATIONS: DA, dopamine; CPu, caudate-putamen; DFC, dorsolateral-frontal cerebral cortex; EC, entorhinal cortex; HIP, hippocampus; MPC, mesioprefrontal cortex; NAc, nucleus accumbens septi (core and shell subdivisions); EPS, extrapyramidal signs; 7-OH-DPAT, R(+)-[2,3,4-³H]7-hydroxy-N,N-di-n-propyl-2-amino-1,2,3,4-tetrahydronaphthalene; DTG, 1,3-ditolylguanidine; RT, room temperature; SCH-23390, R(+)-[N-methyl-³H]7-chloro-8-hydroxy-3-methyl-1-phenyl-2,3,4,5-tetrahydro-1H-3-benzazepine.
as well as other typical and atypical antipsychotics, increased D₂ receptor abundance in rat caudate-putamen (CPu) and nucleus accumbens septi (NAc) (Schoots et al., 1995; Florijn et al., 1997; Tarazi et al., 1997a, 1998) and enhanced D₄ mRNA expression in monkey striatum (Lidow and Goldman-Rakic, 1997). These agents also up-regulated D₂ receptors in rat and monkey prefrontal cortex (Lidow and Goldman-Rakic, 1994; Florijn et al., 1997; Tarazi et al., 1997c, 1998). The findings support the view that D₂ receptors in CPu and NAc, as well as D₂ receptors in prefrontal cortical area, are common sites of action of both typical and atypical antipsychotics, although the physiological consequences of these molecular changes remain incompletely defined. In contrast, typical neuroleptics, but not clozapine, also increased D₂ receptor binding and expression in rat and monkey CPu (Lidow and Goldman-Rakic, 1997; Tarazi et al., 1997a,c, 1998). This selective increase in D₂ receptor labeling in the extrapyramidal CPu probably reflects higher average occupancy of such receptor sites by typical neuroleptic agents and appears to parallel the risk of acute EPS as well as later-emerging tardive dyskinesia.

Despite its favorable characteristics, clinical use of clozapine is complicated by its high risk of potentially fatal bone marrow toxicity, as well as excessive sedation and dose-dependent risk of epileptic seizures (Baldessarini and Frankenburg, 1991). There is a keen interest in developing novel drugs with less adverse risk than clozapine but comparable antipsychotic effects. Several newer agents have emerged (Arnt and Skarsfeldt, 1998; Waddington and Casey, 2000; Baldessarini and Tarazi, 2001). Among them are the clozapine analogs olanzapine and quetiapine and the benzisoxazole derivative risperidone. Like clozapine, these compounds have multiple sites of molecular interaction and greater affinity for serotonin 5-HT₂A than DA D₂ receptors (Bymaster et al., 1996; Schotte et al., 1996; Gunasekara and Spencer, 1998). This receptor-interaction pattern may contribute to low EPS risk (Meltzer et al., 1989).

Olanzapine, quetiapine, and risperidone have undergone extensive pharmacological and behavioral characterization in animals (Arnt and Skarsfeldt, 1998; Tarazi et al., 2000; Waddington and Casey, 2000), but their long-term effects on DA receptors in mammalian forebrain are not well defined or quantitatively compared with those of other antipsychotics. Accordingly, we applied quantitative in vitro receptor autoradiography to assess the effects of these new agents on the molecular physiology of DA receptors in different forebrain regions following long-term infusion of olanzapine, quetiapine, or risperidone in rats. Our working hypothesis was that these novel atypical antipsychotics would induce regionally selective changes in tissue levels of specific DA receptors more closely resembling those of clozapine than typical neuroleptics.

### Experimental Procedures

#### Materials and Animal Subjects

Radioligands were from NEN Life Science Products, Inc. (Boston, MA): \( R,S, \text{[(-)-[N-methyl-\(^{3}H\)]nemonapride (86 Ci/mmol), S,(-)-[methoxy-\(^{3}H\)]naclopride (74 Ci/mmol), and R,(+)-[N-methyl-\(^{3}H\)]7-chloro-8-hydroxy-3-methyl-1-phenyl-2,3,4,5-tetrahydro-1H-3-benzazepine (SCH-23390; 61 Ci/mmol); or from Amersham (Arlington Heights, IL): \( R,(-)[2,3,4-\text{H}^{3}]-\text{hydroxy-N,N-dil-n-propyl-2-amino-1,2,3,4-tetrahydro-dronaphthalene (7-OH-DPAT; 116 Ci/mmol). Tritium-sensitive Hyperfilms were from Amersham. D-19 photographic developer and fixative were from Eastman Kodak (Rochester, NY). Donated drugs included olanzapine (Eli Lilly, Indianapolis, IN), risperidone (Janssen, Beerse, Belgium), and quetiapine fumarate (Zeneca, Cheshire, UK). 1,3-Ditolylguanidine (DTG), S(-)-etcloplotil hydrochloride, cis-flupenthixol dihydrochloride, fluphenazine dihydrochloride, ketanserin tartrate, pindolol, and S(-)-sulpiride were purchased from RBI-Sigma (Natick, MA). Cation hydrochlorides, guanosine-5'-triphosphate sodium (GTP), and tris-(hydroxy-methyl)-aminomethane (Tris) hydrochloride were from Sigma (St. Louis, MO).

Animals were male Sprague-Dawley rats (Charles River Laboratories, Wilmington, MA), initially weighing 200 to 225 g, maintained under artificial daylight (on, 7:00 AM–7:00 PM) in a temperature- and humidity-controlled environment with free access to standard rat chow and tap water in a USDA-inspected, veterinarian-supervised, small-animal research facility of the Mailman Research Center of McLean Hospital. Animal procedures were approved by the Institutional Animal Care and Use Committee (IACUC) of McLean Hospital, in compliance with pertinent federal and state regulations.

### Drug Treatment and Tissue Preparation

Four groups (\( N = 7 \)) of rats received control vehicle, olanzapine (5.0 mg/kg/day), risperidone (3.0 mg/kg/day), or quetiapine fumarate (10.0 mg/kg/day) by osmotic minipumps (Alzet, Palo Alto, CA) implanted subcutaneously to ensure continuous and steady infusion of drugs and overcome variations in tissue drug levels that would result from daily injections. Doses are based on typical behaviorally active doses in rats (Moore et al., 1992; Ellenbroek et al., 1996). After 4 weeks of treatment, rats were decapitated; brains were removed, quick-frozen in isopentane on dry ice, and stored at ~80°C until autoradiographic analysis. Frozen coronal sections (10 μm) were cut in a cryostat at ~20°C, mounted on gelatin-coated microscopic slides, and stored at ~80°C until use. Tissue sections were obtained from CPu, NAc, hippocampus (HIP); areas of cerebral cortex including dorsolateral-frontal (DFC) and mesioprefrontal (MPF), and entorhinal (EC) regions; islands of Calleja including the major island, and the olfactory tubercle. These selected cortical, limbic, and extrapyramidal brain regions mediate cognitive, emotional, and motor behaviors that are typically disturbed in patients with psychotic disorders and altered by antipsychotic drug treatment (Benes, 2000; Baldessarini and Tarazi, 2001).

#### Receptor Autoradiography

Brain sections from all drug-treated rats were evaluated at the same time in each radioreceptor assay to minimize experimental variability. Sections were first preincubated for 1 h at room temperature (RT) in 50 mM Tris-HCl buffer (pH 7.4) containing (mM): NaCl (150), KCl (5), CaCl₂ (2), and MgCl₂ (1), for the D₁-like, D₂, and D₄ receptors in different forebrain regions following long-term infusion of olanzapine, quetiapine, or risperidone in rats. Our working hypothesis was that these novel atypical antipsychotics would induce regionally selective changes in tissue levels of specific DA receptors more closely resembling those of clozapine than typical neuroleptics.
D3 Receptors. Sections were preincubated for 1 h in Tris buffer modified as stated to minimize labeling of the high-affinity agonist binding state of D3 receptors, then incubated for 1 h in the same buffer containing 3 nM [3H]7-OH-DPAT, with 5 μM DTG to mask sigma sites. Nonspecific binding was determined with 1 μM S(−)-eticlopride. After incubation, slides were washed twice for 3 min in ice-cold fresh buffer and dried (Tarazi et al., 1997c, 1998).

D2 Receptors. Tissue sections were preincubated for 1 h at RT in the D2 assay buffer, and then for 1 h with 1.0 nM [3H]nemonapride, 300 nM S(−)-raclopride to occupy D2/D3 sites, and other masking agents (0.5 μM DTG and 0.1 μM pindolol) used in the D2 assay. Nonspecific binding was determined with 10 μM S(−)-sulpiride. The highly D4-selective ligands L-745,870 and RBI-257 displaced approximately 80% of binding remaining in the presence of raclopride in adult CPu and NAc tissue, indicating that most of the raclopride-insensitive binding sites are D4 receptors (Tarazi et al., 1997b,c, 1998).

Autoradiography and Image Analysis

Radiolabeled slides and calibrated 3H-standards (Amersham) were exposed to Hyperfilm (Eastman Kodak) for 2 to 5 weeks at 4°C. [3H]SCH-23390- and [3H]nemonapride-labeled brain sections were exposed for 2 (CPu and NAc) or 5 weeks (cortex and HIP) and [3H]7-OH-DPAT for 4 weeks. Films were developed in Kodak D-19 developer and fixative. Optical density (O.D.) in brain regions of interest was measured with a computerized densitometric image analyzer (MCID-M4, Imaging Research, St. Catharines, ON, Canada). Brain regions of interest were outlined (Fig. 1), and their O.D. was measured. Left and right sides of two contiguous sections represented total binding, and two other sections represented nonspecific binding; the four determinations were averaged for each subject (N = 7 rats/treatment). O.D. was converted to nanocuries per milligram of tissue with calibrated 3H-standards, and after subtracting nonspecific from total binding, specific binding was expressed as femtomoles per milligram of tissue.

Statistical Analysis

Two-way analysis of variance (ANOVA) was employed to evaluate overall changes across treatments and brain regions for each assay. Given overall significance of effects for drug or brain region, post hoc Dunnett t tests were used to test for significant differences due to each drug treatment in preselected anatomical areas. Unless stated otherwise, data are presented as means ± S.E.M. Comparisons were considered significant at p < 0.05 in two-tailed tests, with degrees of freedom (df) based on N = 7 subjects/treatment group.

Results

Four weeks of continuous infusion of all test agents failed to alter tissue concentrations of D1-like receptors in any brain region (Table 1). In contrast, olanzapine and risperidone significantly increased labeling of D2 receptors in several forebrain areas, including MPC (by 67 and 34%, respectively), NAc (37 and 28%), CPu (by a lateral and medial average of 42 and 25%), and HIP (53 and 30%), but did not alter D2 binding in DFC or EC (Table 2). Similar to D1-like receptors, there were no changes in D3-selective labeling in any brain region analyzed or with any agent (Table 3). Even more than signals representing mainly D2 receptors (uncorrected for overlap with D3 or D4 receptors), D4 labeling was up-regulated in several regions by treatment with olanzapine and risperidone, including NAc (by 65 and 33%, respectively), CPu (average of 61 and 37%), and HIP (61 and 37%), with no significant changes in several regions of cerebral cortex (Table 4). It is particularly noteworthy that quetiapine was anomalous and the only tested antipsychotic that did not alter expression of any DA receptor type in any brain region examined.

Discussion

Long-Term Effects of Newer Antipsychotics on the D1 Receptor Family

Continuous subcutaneous infusion of olanzapine, quetiapine, or risperidone did not alter binding of [3H]SCH-23390 in

Fig. 1. Sites of autoradiographic analyses of rat brain regions sampled in 10-μm coronal sections from A (A 3.2–4.2), B (A 1.7–2.2), C (A 0.7–1.2), and D (A 0.2–0.7 mm anterior to bregma, according to Paxinos and Watson (1982); CP, caudate-putamen (L, lateral; M, medial); ICJ, islands of Calleja; ICJ-M, major island of Calleja; Olf Tub, olfactory tubercle.
TABLE 1
D$_1$-like receptor binding after 4 weeks of continuous infusion of antipsychotic drugs

Data are mean ± S.E.M. values (N = 7 rats/group) for binding (fmol/mg of tissue and (percentage of control), determined by quantitative autoradiography following continuous subcutaneous infusion of vehicle or antipsychotic drugs for 4 weeks, all as described under Experimental Procedures. No statistically significant drug effect was found.

<table>
<thead>
<tr>
<th>Brain Region</th>
<th>Controls</th>
<th>Olanzapine</th>
<th>Risperidone</th>
<th>Quetiapine</th>
<th>Clozapinea</th>
<th>Fluphenazinea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cerebral cortex</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Medial-prefrontal</td>
<td>14.0 ± 0.5 (100)</td>
<td>13.3 ± 0.6 (95)</td>
<td>11.9 ± 1.5 (85)</td>
<td>15.5 ± 1.0 (107)</td>
<td>(93)</td>
<td>(102)</td>
</tr>
<tr>
<td>Dorsolateral</td>
<td>7.5 ± 0.9 (100)</td>
<td>6.2 ± 0.8 (82)</td>
<td>9.0 ± 0.8 (120)</td>
<td>8.2 ± 0.8 (109)</td>
<td>(100)</td>
<td>(96)</td>
</tr>
<tr>
<td>Nucleus accumbens</td>
<td>85.7 ± 4.1 (100)</td>
<td>86.0 ± 4.3 (100)</td>
<td>88.4 ± 7.3 (103)</td>
<td>81.1 ± 6.0 (95)</td>
<td>(92)</td>
<td>(96)</td>
</tr>
<tr>
<td>Caudate-putamen</td>
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<tr>
<td>Medial</td>
<td>87.6 ± 7.1 (100)</td>
<td>90.0 ± 10.3 (103)</td>
<td>78.0 ± 4.6 (99)</td>
<td>74.8 ± 7.2 (85)</td>
<td>(99)</td>
<td>(101)</td>
</tr>
<tr>
<td>Lateral</td>
<td>90.9 ± 7.9 (100)</td>
<td>98.8 ± 11.6 (109)</td>
<td>78.4 ± 4.3 (103)</td>
<td>83.3 ± 6.3 (92)</td>
<td>(91)</td>
<td>(104)</td>
</tr>
<tr>
<td>Hippocampus</td>
<td>7.5 ± 10.0 (100)</td>
<td>8.6 ± 0.5 (115)</td>
<td>8.3 ± 0.7 (111)</td>
<td>8.9 ± 0.6 (119)</td>
<td></td>
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</tr>
<tr>
<td>Entorhinal cortex</td>
<td>10.8 ± 0.7 (100)</td>
<td>11.3 ± 1.1 (105)</td>
<td>12.5 ± 0.6 (116)</td>
<td>12.6 ± 0.4 (117)</td>
<td></td>
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</tr>
</tbody>
</table>

a Data (percentage of control) for clozapine (40 mg/kg/day) and fluphenazine (1 mg/kg/day) were determined previously (Tarazi et al., 1998) and are shown for comparison.

TABLE 2
D$_2$ receptor binding after 4 weeks of continuous infusion of antipsychotic drugs

Data are mean ± S.E.M. values for binding (fmol/mg of tissue and (percentage of control), determined by quantitative autoradiography following continuous subcutaneous infusion of vehicle or antipsychotic drugs for 4 weeks, with significant differences from controls indicated in bold (*p < 0.05, N = 7 rats/group), all as described under Experimental Procedures.

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<tr>
<td>Cerebral cortex</td>
<td></td>
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</tr>
<tr>
<td>Medial-prefrontal</td>
<td>18.4 ± 0.6 (100)</td>
<td>30.8 ± 1.0 (167)*</td>
<td>24.7 ± 1.3 (134)*</td>
<td>20.1 ± 0.5 (109)</td>
<td>(160)*</td>
<td>(146)*</td>
</tr>
<tr>
<td>Dorsolateral</td>
<td>13.0 ± 0.7 (100)</td>
<td>14.9 ± 0.5 (107)</td>
<td>12.6 ± 0.4 (91)</td>
<td>14.7 ± 0.5 (106)</td>
<td>(111)</td>
<td>(92)</td>
</tr>
<tr>
<td>Nucleus accumbens</td>
<td>153.3 ± 7.2 (100)</td>
<td>210.4 ± 14.4 (137)*</td>
<td>198.6 ± 9.8 (128)*</td>
<td>164.4 ± 6.3 (107)</td>
<td>(103)</td>
<td>(167)*</td>
</tr>
<tr>
<td>Caudate-putamen</td>
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<tr>
<td>Medial</td>
<td>169.9 ± 8.5 (100)</td>
<td>244.9 ± 21.7 (144)*</td>
<td>215.9 ± 12.6 (127)*</td>
<td>168.1 ± 11.1 (99)</td>
<td>(104)</td>
<td>(126)*</td>
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<tr>
<td>Lateral</td>
<td>224.5 ± 12.1 (100)</td>
<td>311.4 ± 16.3 (139)*</td>
<td>276.2 ± 18.0 (123)*</td>
<td>231.4 ± 17.4 (103)</td>
<td>(109)</td>
<td>(117)*</td>
</tr>
<tr>
<td>Hippocampus</td>
<td>35.3 ± 1.0 (100)</td>
<td>54.4 ± 3.5 (153)*</td>
<td>46.0 ± 2.1 (130)*</td>
<td>37.5 ± 2.6 (106)</td>
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</tr>
<tr>
<td>Entorhinal cortex</td>
<td>15.1 ± 1.0 (100)</td>
<td>16.4 ± 1.1 (108)</td>
<td>15.4 ± 1.2 (102)</td>
<td>16.9 ± 0.4 (112)</td>
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</table>

* Data (percentage of control) for clozapine (40 mg/kg/day) and fluphenazine (1 mg/kg/day) were determined previously (Tarazi et al., 1997c) and are shown for comparison.

TABLE 3
D$_2$ receptor binding after 4 weeks of continuous infusion of antipsychotic drugs

Data are mean ± S.E.M. values (N = 7 rats/group) for binding (fmol/mg of tissue and (percentage of control), determined by quantitative autoradiography following continuous subcutaneous infusion of vehicle or antipsychotic drugs for 4 weeks, all as described under Experimental Procedures. No statistically significant drug effect was found.

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<th>Quetiapine</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Islands of Calleja</td>
<td>36.9 ± 1.9 (100)</td>
<td>32.8 ± 1.9 (89)</td>
<td>34.5 ± 1.7 (93)</td>
<td>36.5 ± 1.8 (99)</td>
<td>(97)</td>
<td>(100)</td>
</tr>
<tr>
<td>Olfactory tubercle</td>
<td>18.6 ± 0.7 (100)</td>
<td>17.9 ± 1.7 (96)</td>
<td>20.0 ± 1.3 (108)</td>
<td>18.8 ± 1.0 (101)</td>
<td>(102)</td>
<td>(102)</td>
</tr>
<tr>
<td>Nucleus accumbens</td>
<td>17.9 ± 0.7 (100)</td>
<td>18.7 ± 1.3 (104)</td>
<td>17.4 ± 0.6 (97)</td>
<td>19.7 ± 0.8 (110)</td>
<td>(93)</td>
<td>(108)</td>
</tr>
<tr>
<td>Shell</td>
<td>7.9 ± 0.5 (100)</td>
<td>8.5 ± 0.4 (108)</td>
<td>9.0 ± 0.6 (114)</td>
<td>8.8 ± 0.3 (112)</td>
<td>(97)</td>
<td></td>
</tr>
<tr>
<td>Core</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Caudate-putamen</td>
<td>3.4 ± 0.3 (100)</td>
<td>3.3 ± 0.2 (97)</td>
<td>3.3 ± 0.1 (97)</td>
<td>3.4 ± 0.2 (100)</td>
<td>(100)</td>
<td>(118)</td>
</tr>
<tr>
<td>Medial</td>
<td>3.7 ± 0.3 (100)</td>
<td>3.2 ± 0.2 (86)</td>
<td>3.3 ± 0.1 (89)</td>
<td>3.6 ± 0.1 (97)</td>
<td>(100)</td>
<td>(118)</td>
</tr>
</tbody>
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* Data (percentage of control) for clozapine (40 mg/kg/day) and fluphenazine (1 mg/kg/day) were determined previously (Tarazi et al., 1997c) and are shown for comparison.

any region of rat forebrain considered (Table 1). This radioligand labels both highly abundant D$_1$ receptors and rarer D$_5$ sites (Baldessarini and Tarazi, 1996). Lack of adaptive changes in D$_1$-like binding with the three newer antipsychotic agents tested agrees with similar previous findings following treatment with dissimilar agents including haloperidol, fluphenazine, raclopride, and clozapine (Florijn et al., 1997a, 1997b; Tarazi et al., 1997a, 1997b, 1997c). Interest in D$_1$-like receptors as potential targets for novel antipsychotic drugs was encouraged by findings in positron emission tomography studies that clozapine in clinically relevant doses occupied D$_1$-like sites more than typical neuroleptics did, suggesting that D$_1$-like receptors may contribute to the unique clinical properties of clozapine (Farde et al., 1989). However, clinical trials have yielded no support for the hypothesis that D$_1$ antagonists may exert antipsychotic activity (Debeaufreaper et al., 1995). Lack of adaptive changes in D$_1$-like receptor levels after prolonged administration of olanzapine, risperidone, or quetiapine (Table 1) as well as clozapine and typical neuroleptics (Florijn et al., 1997b; Tarazi et al., 1997a, 1997b, 1997c) adds to the impression that these receptors are not likely to play a major role in mediating effects of antipsychotic agents. Nevertheless, open-minded caution is required concerning the pharmacological potential of D$_1$ antagonists since current understanding of the physiology of these most abundant of the cerebral DA receptors remains remarkably limited (Baldessarini and Tarazi, 1996).

**Long-Term Effects of Olanzapine, Risperidone, and Quetiapine on the D$_2$ Receptor Family**

**D$_2$ Receptors.** D$_2$ receptor potency of tested agents ranks risperidone ($K_i = 6.0$ nM) > olanzapine ($K_i = 31$ nM) > quetiapine ($K_i = 380$ nM) (Schotte et al., 1996). Infusion of olanzapine and risperidone, but not quetiapine, increased binding of [$^3$H]nemonapride in MPC (Table 2). Such increases mainly reflect up-regulation of D$_2$ receptors since...
Effects of Novel Antipsychotics on Dopamine Receptors

TABLE 4

D_{4} receptor binding after 4 weeks of continuous infusion of antipsychotic drugs
Data are mean ± S.E.M. values for binding (fmol/mg of tissue) and (percentage of control), determined by quantitative autoradiography following continuous subcutaneous infusion of vehicle or antipsychotic drugs for 4 weeks, with significant differences from controls indicated in bold (*p < 0.05, N = 7 rats/group), all as described under Experimental Procedures.

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<th>Risperidone</th>
<th>Quetiapine</th>
<th>Clozapine*</th>
<th>Fluphenazine*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cerebral cortex</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medial-prefrontal</td>
<td>11.0 ± 0.6 (100)</td>
<td>11.3 ± 0.8 (113)</td>
<td>11.1 ± 0.7 (111)</td>
<td>10.8 ± 0.3 (108)</td>
<td>(117)</td>
<td>(106)</td>
</tr>
<tr>
<td>Dorsolateral</td>
<td>6.3 ± 0.3 (100)</td>
<td>6.8 ± 0.4 (108)</td>
<td>6.4 ± 0.5 (102)</td>
<td>6.0 ± 0.6 (95)</td>
<td>(97)</td>
<td>(75)</td>
</tr>
<tr>
<td>Nucleus accumbens</td>
<td>29.3 ± 1.1 (100)</td>
<td>48.2 ± 2.8 (165)*</td>
<td>38.9 ± 3.3 (133)*</td>
<td>28.6 ± 3.3 (98)</td>
<td>(171)*</td>
<td>(224)*</td>
</tr>
<tr>
<td>Caudate-putamen</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medial</td>
<td>31.4 ± 2.4 (100)</td>
<td>50.2 ± 3.6 (160)*</td>
<td>42.7 ± 1.8 (136)*</td>
<td>29.1 ± 2.9 (93)</td>
<td>(143)*</td>
<td>(160)*</td>
</tr>
<tr>
<td>Lateral</td>
<td>37.5 ± 1.6 (100)</td>
<td>61.4 ± 1.3 (162)*</td>
<td>51.6 ± 2.6 (137)*</td>
<td>41.9 ± 4.6 (111)</td>
<td>(143)*</td>
<td>(163)*</td>
</tr>
<tr>
<td>Hippocampus</td>
<td>18.0 ± 0.5 (100)</td>
<td>29.0 ± 1.6 (161)*</td>
<td>24.7 ± 0.9 (137)*</td>
<td>19.1 ± 1.5 (106)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Entorhinal cortex</td>
<td>6.9 ± 0.6 (100)</td>
<td>7.4 ± 0.5 (107)</td>
<td>7.3 ± 0.5 (106)</td>
<td>8.2 ± 0.3 (119)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Data (percentage of control) for clozapine (40 mg/kg/day) and fluphenazine (1 mg/kg/day) were determined previously (Tarazi et al., 1997c) and are shown for comparison.

cortical D_{3} receptors did not increase significantly (Table 4), and D_{3} receptors are minimally expressed in rat frontal cortex (Sokoloff et al., 1990; Baldessarini and Tarazi, 1996). Similar D_{2} receptor up-regulation and increased D_{2} mRNA expression have been found in cerebral cortex of rats and nonhuman primates after repeated treatment with typical and atypical antipsychotics (Damask et al., 1996; Florijn et al., 1995; Lidow and Goldman-Rakic, 1997; Tarazi et al., 1997c, 1998). D_{2} receptor up-regulation in MPC by olanzapine and risperidone further supports the importance of D_{2} receptors in this region as a common target for both typical and atypical antipsychotics.

Repeated treatment with olanzapine and risperidone also enhanced binding to D_{2} receptors in HIP but not in DFC nor EC (Table 2). Such enhancement of D_{2} expression in HIP probably reflects an increase in the transcriptional activity of the D_{2} receptor gene since repeated treatment with clozapine increased D_{2} mRNA expression in HIP but not EC (Ritter et al., 1997). D_{2} receptors in HIP, where DA innervation is limited, evidently are regulated differently from those in EC, where DA innervation is much denser (Goldsmith and Joyce, 1994). D_{2} receptors in HIP, but not EC, may act as additional common targets of olanzapine, risperidone, and perhaps other antipsychotics. Blockade and up-regulation of hippocampal D_{2} receptors by antipsychotics may contribute to improvement of delusions and hallucinations of psychotic patients by ameliorating DA hyperactivity postulated to occur in their HIP (Kriechhaus et al., 1992).

Repeated treatment with olanzapine and risperidone, but not quetiapine, also increased D_{3} receptor labeling in CPu (Table 2). Similar responses have been found after long-term treatment with typical neuroleptics but not clozapine (Florijn et al., 1997; Tarazi et al., 1997a,c, 1998). Up-regulation of D_{2} receptors in CPu may disturb neurotransmission in circuits involved in regulating movement and posture (Albin et al., 1989) and generally correlates with EPS risk. Similar responses to newer antipsychotics (olanzapine, risperidone) with relatively low EPS risk were, therefore, unexpected.

Additional indications that these drugs can occupy D_{3} receptors in human basal ganglia come from positron emission tomography studies showing that relatively high, but clinically encountered, doses of olanzapine and risperidone lead to occupation of striatal D_{3} receptors similar to that produced by typical neuroleptics and much more than that produced by clozapine (Farde et al., 1989; Kapur et al., 1999) or quetiapine (Gefvert et al., 1998). Quetiapine has the most benign clinical EPS risk of the three novel agents tested, ranking well below risperidone and probably also olanzapine (Gunasekara and Spencer, 1998; Leuchtt et al., 1999; Baldessarini and Tarazi, 2001; Tarsy et al., 2001). The lack of clinical EPS with quetiapine is paralleled by its low D_{2} affinity (Schotte et al., 1996) and weak antagonism of behavioral effects of DA microinjected directly into rat CPu (Campbell et al., 1991). Risperidone shares many characteristics of typical neuroleptics, including severe hyperprolactinemia and dose-dependent EPS risk (Fleischhacker and Marder, 2000; Baldessarini and Tarazi, 2001; Tarsy et al., 2001). In addition to its ability to occupy striatal D_{2} receptors, olanzapine has relatively potent antimuscarinic properties compared with risperidone or quetiapine (Bymaster et al., 1996; Schotte et al., 1996) that probably limits its risk of EPS effects.

Other studies using low daily doses of olanzapine (0.35–2 mg/kg) or risperidone (0.25–0.5 mg/kg) did not find D_{3} receptor up-regulation in rat or monkey striatum (Kuoppamaki et al., 1995; Lidow and Goldman-Rakic, 1997; Kusumi et al., 2000). In addition, long-term treatment with low doses of olanzapine (0.5–2 mg/kg) resulted in lesser oral chewing movements (a proposed animal model of tardive dyskinesia) than did haloperidol (Gao et al., 1998). Nevertheless, the present findings with higher doses of constantly infused olanzapine and risperidone did include significant apparent up-regulation of D_{3} receptors. Moreover, the present and previous results are consistent with clinical evidence that risks of acute EPS and of tardive dyskinesia with risperidone and olanzapine are substantially greater than with either quetiapine or clozapine (Tarsy et al., 2001).

D_{4} Receptors. These low-abundance proteins have a restricted distribution, with notable levels of expression in mammalian basal forebrain, most prominently in the islands of Calleja, followed by olfactory tubercle and NAc shell, with very low levels in CPu (Sokoloff et al., 1990; Levant, 1997; Table 3). Binding of [3H]7-OH-DPAT under D_{4}-selective conditions was unchanged after prolonged exposure to all test agents in all regions examined. Even risperidone, which has relatively high D_{2} affinity (Schotte et al., 1996), failed to alter expression of D_{4} receptors, even in the islands of Calleja and NAc (Table 3), as was found with various other antipsychotics (Levesque et al., 1995; Florijn et al., 1997; Tarazi et al., 1997a,c, 1998).

Lack of response of D_{4} receptors to repeated antipsychotic treatment may reflect their unique molecular mechanisms, including absence of well defined interactions with G-proteins and signal transduction cascades (Sokoloff et al., 1990;...
Levant, 1997). Alternatively, the high avidity of D₃ receptors for DA and their selective protection from alkylolation by very low concentrations of DA (Zhang et al., 1999) suggests that occupation by endogenous DA may limit their interaction with potential antagonists to preclude up-regulation. It also follows that D₃ receptors are less likely to be critical for the actions of known or novel antipsychotics. Instead, D₄ receptors may be involved in stimulant reward and dependence (Pilla et al., 1999).

**D₄ Receptors.** As in previous studies (Tarazi et al., 1997b,c, 1998), D₄ receptors accounted for relatively high proportions (46–54%) of total D₂-like receptors in MPC, DFC, HIP, and EC, but much less (17–19%) in CPu and NAc (Tables 2 and 4). Prolonged administration of olanzapine and risperidone, but not quetiapine, significantly increased D₄ receptors in CPu and NAc (Table 4), presumably reflecting adaptive responses to D₃ blockade since both olanzapine and risperidone have much higher D₄ affinity than quetiapine (Schotte et al., 1996). D₄ receptors were found to increase in rat CPu and NAc after long-term administration of several typical and atypical antipsychotics (Florijn et al., 1997; Tarazi et al., 1997a,c, 1998), as well as olanzapine and risperidone (Table 4), suggesting the impression that striatal limbic D₄ receptors represent a common target of dissimilar antipsychotics. Lack of D₄ up-regulation by quetiapine may, again, reflect its low affinity for all D₂-like receptors (Schotte et al., 1996; Baldessarini and Tarazi, 2001). D₄ up-regulation is also consistent with the proposal that reported increases in D₂-like labeling in postmortem striatum tissue of patients diagnosed with schizophrenia (Seeman et al., 1993; Murray et al., 1995) may reflect responses to antemortem antipsychotic treatment rather than a neuropathology of schizophrenia (Baldessarini and Tarazi, 2001).

Long-term treatment with olanzapine and risperidone increased D₄ receptor labeling in HIP and not EC (Table 4), similar to responses of D₂ receptors (Table 2). This is the first evidence that D₄ receptors in HIP can be affected by novel antipsychotics. Moreover, these receptors may act in synchrony with D₂ receptors in HIP to mediate beneficial clinical actions of antipsychotics. Increased D₂ binding probably reflects post-transcriptional modifications or reduced D₄ receptor turnover since D₄ mRNA expression was decreased after repeated treatment of rats with haloperidol or clozapine (Ritter and Meadow-Woodruff, 1997). Lack of response of D₄ receptors in EC to antipsychotic treatment (Table 4) parallels the nonresponse of D₂ receptors in that relatively well DA-innervated region (Table 2).

In spite of their profound up-regulating effects on D₄ receptor proteins in CPu and NAc, in frontal cerebral cortex, olanzapine and risperidone had only minor effects, and quetiapine had none (Table 4). Other antipsychotics also have had little effect on rat cortical D₂ receptors (Tarazi et al., 1997a,c). Regional differences in the regulation of D₄ mRNA transcription or protein synthesis may account for regional differences in adaptive increases of D₄ receptors and in responses to typical vs atypical antipsychotics. Consistent with this interpretation is a lack of increase in D₄ mRNA or receptor protein in rat cerebral cortex after repeated treatment with clozapine but significant increases in both with haloperidol (Schoots et al., 1995).

**Conclusions**

Similar to other typical and atypical antipsychotics, long-term treatment of rats with olanzapine and risperidone significantly up-regulated D₂ receptors in MPC, as well as D₄ receptors in NAc and CPu. These new findings add support to the hypothesis that these receptors and brain regions may be involved in the beneficial clinical effects of antipsychotics. In addition, both olanzapine and risperidone increased levels of D₂ as well as D₄ receptors in HIP (but not other cortical areas, including DFC and EC), suggesting a third possible site contributing to beneficial effects of atypical antipsychotics.

At behaviorally effective doses, olanzapine and risperidone also increased abundance of D₂ receptors in CPu, similar to the effects of long-term treatment with typical, **but not atypical**, antipsychotics. This finding parallels the moderate, dose-dependent risk of clinical EPS with these agents, consistent with their status as **quantitatively atypical agents** (Baldessarini and Tarazi, 2001; Tarsy et al., 2001). Lack of effects of olanzapine and risperidone on D₁-like or D₃ receptors in any brain region examined adds support to the view that these receptors are probably not notably involved in the actions of various kinds of antipsychotics. Failure of quetiapine to alter abundance of any DA receptor type in any brain region examined is consistent with its low affinity for all DA receptors and suggests that nondopaminergic, and perhaps serotonergic or histaminergic, mechanisms may contribute to the clinical actions of this novel agent.

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