The Effect of Antipsychotics on the High-Affinity State of D₂ and D₃ Receptors

A Positron Emission Tomography Study With [¹¹C]-(+)-PHNO

Ariel Graff-Guerrero, MD, PhD; David Mamo, MD, MSc; C. M. Shammi, MD; Romina Mizrahi, MD, PhD; Heidi Marcon, BSc; Penny Barsoum, RN; Pablo Rusjan, PhD; Sylvain Houle, MD, PhD; Alan A. Wilson, PhD; Shitij Kapur, MD, PhD

Context: Most antipsychotics are thought to have an effect on D₁ and D₂ receptors. The development of carbon 11–labeled (+)-4-propyl-9-hydroxynaphthoxazine ([¹¹C]-(+)-PHNO), the first agonist radioligand with higher affinity for D₃ than D₂ receptors, allows one to differentiate the effects of antipsychotics on high-affinity vs low-affinity sites of the D₂ receptor and on D₁ vs D₂ receptor subtypes.

Objectives: To examine the effects of antipsychotics (clozapine, risperidone, or olanzapine) on the high- vs low-affinity states of the D₂ and D₃ receptors by comparing the [¹¹C]-(+)-PHNO and [¹¹C]raclopride binding in the D₃ receptor–rich (globus pallidus and ventral striatum) and D₂ receptor–rich (caudate and putamen) regions.

Design: Two sequential studies with different participants and appropriate controls were performed. The first compared the occupancy produced by 3 antipsychotics as measured with [¹¹C]-(+)-PHNO and [¹¹C]raclopride. The second was a double-blind, placebo-controlled experiment to compare the effect of pramipexole (a D₃ receptor–preferring agonist) vs placebo on the increased [¹¹C]-(+)-PHNO signal observed in the globus pallidus of patients.

Setting: Positron Emission Tomography Centre, Centre for Addiction and Mental Health, Toronto, Ontario, Canada.

Participants: Twenty-three patients with schizophrenia and 23 healthy controls.

Main Outcome Measures: Antipsychotic occupancies as measured with [¹¹C]-(+)-PHNO and [¹¹C]raclopride.

Results: The antipsychotic-treated patients showed high occupancies with both [¹¹C]-(+)-PHNO and [¹¹C]raclopride in the dorsal striatum, with [¹¹C]raclopride occupancies about 20% higher. Most strikingly, patients did not show any occupancy with [¹¹C]-(+)-PHNO in the globus pallidus as compared with normal controls or with their own scans using [¹¹C]raclopride. This unblocked [¹¹C]-(+)-PHNO signal was displaced by a single dose of pramipexole.

Conclusions: Antipsychotics block both the high- and low-affinity states of the D₂ receptors across the brain, but antipsychotic treatment does not block the [¹¹C]-(+)-PHNO signal in the D₃ receptor–rich regions, despite the ongoing D₂ receptor blockade. The radiotracer [¹¹C]-(+)-PHNO and the data open up new avenues for exploring the potential therapeutic significance of the D₃ receptor in schizophrenia.

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Understanding the action of antipsychotic drugs has been at the heart of 5 decades of schizophrenia research.¹² The clinical efficacy and adverse effects of antipsychotics have been consistently related to the level of in vivo occupancy at the D₂ receptors.³⁴ Previous studies proposed that the occupancy required for clinical efficacy is in the range of 60%, while the occurrence of adverse effects has been observed at higher than 80% occupancy.³⁴ All these studies have been performed with positron emission tomography (PET) or single-photon emission tomography radioligands that are antagonists for the dopamine D₂/D₃ receptors: carbon 11–labeled raclopride ([¹¹C]raclopride), [¹¹C]FLB ([O-methyl-¹¹C]-(S)-(−)-5-bromo-N-(1-ethyl-2-pyridylidinyl)methyl)-2,3-dimethoxybenzamide), fluor 18–labeled fallypride, or iodine 123–labeled iodobenzamide.¹⁰¹¹ However, since these radioligands have similar affinity for the D₂ and D₃ receptors, one cannot infer selective effects of antipsychotics on D₂ vs D₃ receptors; thus, the differential effects of antipsychotics on D₂ vs D₃ receptors remain unexplored in patients.
The high-affinity state of the D_2 receptor is believed to be the functionally important one, as it mediates the activation of the second-messenger cascade on the postsynaptic membrane after the endogenous agonist has bound to the receptor. What makes the high-affinity state of the D_2 receptors particularly interesting is a series of experiments that have shown an increase in the number of D_2 receptors in the high-affinity state in several animal models of psychosis and after long-term antipsychotic exposure, suggesting that the high-affinity state of the D_2 receptor is involved in the illness and its treatment. While these 2 states have been convincingly demonstrated for the D_2 receptor, the existence of the G-protein coupled and uncoupled states of the D_3 receptors is controversial because of the inability of the G-protein analogs (eg, Gpp(NH)p) to shift it from the high-to the low-affinity state. Since all previous PET imaging studies have used antagonist radioligands, which do not distinguish between the high- and low-affinity stages of the receptors, it remains unknown how antipsychotics bind to these 2 states in vivo.

Recently, our group has developed carbon 11-labeled (+)-4-propyl-9-hydroxynaphthoxazine (\([\text{C}]\)-PHNO), a D_2/D_3 receptor agonist radiotracer for use in humans. This preferential in vitro binding to the D_3 receptor has been confirmed ex vivo in rodents and in vivo in nonhuman primates and humans, allowing for a prominent signal from the striatum, globus pallidus (GP), and substantia nigra. Because \([\text{C}]\)-PHNO is an agonist radiotracer, it binds preferentially to the high-affinity state of the receptor. In addition, \([\text{C}]\)-PHNO shows more than 10-fold higher in vitro affinity for the D_2 receptor than the D_3 receptor. This preferential in vitro binding to the D_2 receptor has been confirmed ex vivo in rodents and in vivo in nonhuman primates and humans, allowing for a prominent signal from the striatum, globus pallidus (GP), and substantia nigra. Consequently, the GP can be used as a preferential D_2 receptor binding region and the dorsal striatum, as a preferential D_2 receptor region. Therefore, the concomitant use of \([\text{C}]\)-PHNO and a non-specific D_2/D_3 receptor antagonist radiotracer like \([\text{C}]\)raclopride provides an opportunity to study the differential effects of antipsychotics on high- vs high- and low-affinity states by comparing \([\text{C}]\)-PHNO vs \([\text{C}]\)raclopride and of D_3 vs D_2 receptors by comparing the caudate and putamen vs the GP in the same subject.

The aim of this study was to compare the effects of 3 commonly used antipsychotic drugs (clozapine, risperidone, and olanzapine) on the D_2 and D_3 receptors as measured with \([\text{C}]\)-PHNO and \([\text{C}]\)raclopride. While the 2 radiotracers gave relatively similar occupancies in the caudate and putamen, they showed widely divergent results in the GP, where no occupancy was found with \([\text{C}]\)-PHNO. To understand this discrepancy further, and to confirm the D_3 receptor of \([\text{C}]\)-PHNO signal in the GP, we challenged a second set of patients with a single dose of pramipexole dihydrochloride, a preferential D_3 receptor agonist, to obtain displacement (reduction) of the increased binding in the GP and corroborate the D_3 receptor nature of this signal.

**STUDY GROUPS**

**Antipsychotic-Treated Patients**

Twenty patients with either schizophrenia, schizoaffective disorder, or schizotypal disorder were recruited with the Mini-International Neuropsychiatric Interview Plus and underwent PET scanning once on separate days, 1 day apart. The age range for inclusion was 18 to 50 years, and the patients were receiving clozapine, olanzapine, or risperidone as antipsychotic monotherapy at a steady clinical dose for more than 4 weeks without use of depot antipsychotic drugs during the previous 6 months. The first scan was performed with \([\text{C}]\)-PHNO and the second, with \([\text{C}]\)raclopride. The PET scans were acquired at the expected serum peak time of the last antipsychotic dose (2, 6, and 3 hours for risperidone, olanzapine, and clozapine, respectively). Blood samples for the quantification of antipsychotic and prolactin plasma levels were obtained before and after each PET scan. The reported plasma levels were the mean of both measures.

**Patients With Pramipexole Challenge**

Three patients treated long-term with risperidone and with similar characteristics to the antipsychotic-treated patients were scanned twice with \([\text{C}]\)-PHNO at least 2 days apart. The PET scans were timed 12 hours after the last oral dose of risperidone. Two hours before each PET scan, the subjects received a single oral dose of 0.5 mg of pramipexole dihydrochloride or placebo.

**Healthy Controls**

Twenty-three healthy controls (17 male, 6 female; mean [SD] age, 34.5 [8.38] years) were recruited through local advertisement. Each was scanned with \([\text{C}]\)-PHNO and \([\text{C}]\)raclopride. Psychiatric disorders were excluded using the Mini-International Neuropsychiatric Interview Plus. The age range for inclusion was 18 to 50 years. Subjects with any medical or neurological conditions or with Axis I psychiatric diagnoses were
MAGNETIC RESONANCE IMAGING

Subjects underwent a proton density image (echo time=17 milliseconds; repetition time=6000 milliseconds; field of view=22 cm, 2-dimensional, 256 × 256; slice thickness, 2 mm; number of excitations=2), acquired on a 1.5-T Signa scanner (General Electric Medical Systems, Milwaukee, Wisconsin). These images were used for the analysis of the PET scans.

IMAGE ANALYSIS

The procedure for the analysis of the $[^{11}C]$raclopride and $[^{11}C]$-(-)-PHNO PET images was performed as previously described.25,34,35 The quantitative estimate of binding was estimated using the Simplified Reference Tissue Method (SRTM),36 with the cerebellar cortex as the reference region. This method has been validated to reliably estimate the nondisplaceable binding potential (BP$_{ND}$), which compares the concentration of radioligand in the receptor-rich region with the receptor-free region,37 for both $[^{11}C]$raclopride38 and $[^{11}C]$-(-)-PHNO.30 In addition, to assure the robustness of our findings, we analyzed the data using 3 additional methods: the interval ratio,39 the multilinear reference tissue model (MRTM), and the multilinear reference tissue model 2 (MRTM2).40 We included the interval method as an intuitive approach based on the shape of the time activity curves, and the MRTM and MRTM2 were included because, in contrast to SRTM, they are linearized reference tissue methods that are resistant to noise.40 The times for the interval method were caudate and putamen, 840 to 1800 seconds; ventral striatum, 900 to 3000 seconds; and GP, 2100 to 4200 seconds. These intervals showed the lowest variation in our controls (<5%). The BP$_{ND}$ was estimated using PMOD v.2.7 software (PMOD Technologies Ltd, Zurich, Switzerland). In addition, PMOD provided for SRTM, MRTM, and MRTM2 the coefficients of variation of the standard error of the parameter identifiability (called “standard error” of the compartmental fit).

Parametric voxel-wise BP$_{ND}$ maps from the dynamic images in native space were generated according to the method of Gunn et al.,41 with the cerebellum as the reference region, and as implemented in PMOD v.2.7 software. The
BPND map images were spatially normalized into Montreal Neurological Institute brain space by nearest neighbor interpolation and with a voxel size fixed at 2 x 2 x 2 mm using the SPM2 software. The normalized images were smoothed with a gaussian filter in each coordinate direction, with a kernel of 4 mm.

Receptor occupancy was defined as the percentage of reduction of the BPND from a baseline state to the treated state. To calculate receptor occupancy, a measure of baseline BPND in the drug-free (untreated) state was necessary. Since we could not obtain baseline measures of D2 receptors for the antipsychotic-treated patients within our current design, we used estimates of BPND from age- and sex-matched controls derived from healthy volunteers, using the slope and intercept for each region of interest obtained from the linear regression of BPND and age for each sex (eTable 1, http://www.archgenpsychiatry.com). Also, as an additional analysis, the data from drug-free patients were pooled with the healthy controls data to estimate the percentage of receptor occupancy and did not modify the occupancies as estimated with healthy controls (analysis presented). The occupancies reported in the results correspond to those obtained with SRTM unless otherwise indicated. The occupancies were estimated with the following formula:

\[
\text{% Occupancy} = \frac{\text{BPND}_{\text{Baseline Estimate}} - \text{BPND}_{\text{Patient}}}{\text{BPND}_{\text{Baseline Estimate}}} \times 100\%.
\]

The percentage of BPND change after the pramipexole challenge was estimated considering as baseline the PET scan with placebo.

\[
\text{% BPND Change} = \frac{\text{BPND}_{\text{Placebo}} - \text{BPND}_{\text{After Pramipexole}}}{\text{BPND}_{\text{Placebo}}} \times 100\%.
\]

Nonlinear regression analysis was applied to correlate the plasma level of clozapine, olanzapine, or risperidone with the respective occupancy (SRTM). The data were fitted to a rectangular hyperbola (1-site binding model) described by the equation:

\[
\text{Occupancy} = \frac{X \times \text{Antipsychotic (Plasma Level)}}{\text{Antipsychotic (Plasma Level)} + ED_{50}}
\]

where \( ED_{50} \) represents the plasma level of antipsychotics resulting in 50% receptor occupancy and \( X \) corresponds to the ceiling receptor’s occupancy. In the models, \( X \) was fixed to 100 and \( ED_{50} > 0 \).

### Table 2. Comparison of Occupancies Between \[^{11}C\]-(-)-PHNO and \[^{11}C\]-Raclopride in the Group of Patients Treated Long-Term

<table>
<thead>
<tr>
<th></th>
<th>[^{11}C]-(-)-PHNO</th>
<th>[^{11}C]-Raclopride</th>
<th>Comparison*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caudate (mean)</td>
<td>53.33 (5.18)</td>
<td>71.48 (10.28)</td>
<td>( P &lt; .001 )</td>
</tr>
<tr>
<td>Clozapine</td>
<td>55.20 (14.92)</td>
<td>65.68 (10.11)</td>
<td></td>
</tr>
<tr>
<td>Olanzapine</td>
<td>50.18 (19.24)</td>
<td>76.82 (8.29)</td>
<td></td>
</tr>
<tr>
<td>Risperidone</td>
<td>54.84 (11.99)</td>
<td>72.06 (10.45)</td>
<td></td>
</tr>
<tr>
<td>Putamen (mean)</td>
<td>41.69 (15.69)</td>
<td>69.06 (11.99)</td>
<td>( P &lt; .001 )</td>
</tr>
<tr>
<td>Clozapine</td>
<td>41.03 (12.34)</td>
<td>59.44 (11.48)</td>
<td></td>
</tr>
<tr>
<td>Olanzapine</td>
<td>43.56 (22.04)</td>
<td>76.46 (7.84)</td>
<td></td>
</tr>
<tr>
<td>Risperidone</td>
<td>40.27 (12.75)</td>
<td>71.65 (10.04)</td>
<td></td>
</tr>
<tr>
<td>VS (mean)</td>
<td>17.32 (24.88)</td>
<td>72.27 (11.34)</td>
<td>( P &lt; .001 )</td>
</tr>
<tr>
<td>Clozapine</td>
<td>26.47 (25.66)</td>
<td>63.31 (10.55)</td>
<td></td>
</tr>
<tr>
<td>Olanzapine</td>
<td>11.21 (20.88)</td>
<td>78.31 (7.24)</td>
<td></td>
</tr>
<tr>
<td>Risperidone</td>
<td>13.80 (55.92)</td>
<td>75.69 (10.72)</td>
<td></td>
</tr>
<tr>
<td>GP (mean)</td>
<td>70.74 (86.52)</td>
<td>59.03 (14.20)</td>
<td>( P &lt; .001 )</td>
</tr>
<tr>
<td>Clozapine</td>
<td>-100.89 (130.66)</td>
<td>47.64 (15.11)</td>
<td></td>
</tr>
<tr>
<td>Olanzapine</td>
<td>-68.26 (28.45)</td>
<td>64.67 (10.21)</td>
<td></td>
</tr>
<tr>
<td>Risperidone</td>
<td>-38.46 (66.80)</td>
<td>65.76 (9.31)</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: \[^{11}C\]-Raclopride, carbon 11–labeled raclopride; \[^{11}C\]-(-)-PHNO, carbon 11–labeled 4-propyl-9-hydroxynaphthoxazine; GP, globus pallidus; VS, ventral striatum. *\( F_{1,36} = 36.59; P < .001 \).

### RESULTS

The patients treated long-term with olanzapine, clozapine, or risperidone had mean (SD) occupancies with \[^{11}C\]-Raclopride of 71% (10%) and 69% (12%) in the caudate and putamen, respectively. The mean (SD) occupancies with \[^{11}C\]-(-)-PHNO were lower: 53% (5%) and 41% (15%) in the caudate and putamen \((t_{19} = -5.15; P < .001\) and \(t_{19} = -7.16; P < .001\), respectively. The most striking results were in the D3 receptor–rich region (GP) wherein \[^{11}C\]-Raclopride showed mean (SD) occupancies of 59% (14%). In contrast, the BPND as measured by \[^{11}C\]-(-)-PHNO was higher rather than lower in antipsychotic-treated patients compared with healthy controls, with binding values in the GP (mean [SD]) 70% (86%) higher than the estimated baseline (unmedicated) measure using healthy controls \((t_{19} = -6.96; P < .001\). The mean (SD) occupancy with \[^{11}C\]-Raclopride was 72% (11%) in the ventral striatum, while with \[^{11}C\]-(-)-PHNO, this was 17% (34%) \((t_{19} = -6.04; P < .001\), which is between that observed in the dorsal striatum (caudate and putamen) and the GP (Table 2) (Figures 1, 2, and 3). To confirm the reliability of this finding across different analytic methods, the \[^{11}C\]-(-)-PHNO occupancies were obtained using BPND derived by the interval ratio, MRTM, and MRTM2 methods. The results with all the methods showed higher BPND in patients taking antipsychotics than controls in the GP (eTable 2).
The clinical variables and the serum plasma level of the antipsychotics and metabolites were not different between the [11C]-(+)-PHNO and [11C]raclopride PET scan days. There were no significant correlations between the estimated occupancies and clinical measures (Positive and Negative Syndrome Scale, Simpson-Angus Scale, Barnes Akathisia Scale, Clinical Global Impression scale) (P > .05). The nonlinear regression analysis results between antipsychotic plasma levels and respective occupancy (SRTM) are presented in eTable 3. We did not obtain a significant relationship between plasma levels and the degree of BPND elevation or occupancy in the GP and ventral striatum with [11C]-(+)-PHNO.

DISPLACEMENT OF ELEVATED BINDING BY THE PRAMIPEXOLE CHALLENGE

The patients included in the pramipexole challenge were receiving long-term treatment with risperidone (mean [SD] dose, 5.2 [1.3] mg/d) and, as expected, showed a mean (SD) 40% (33%) occupancy in the caudate and 41% (20%) in the putamen and a 64% (18%) elevation of BPND in the GP, as described in the previous group of subjects. Two hours after the administration of an oral dose of 0.5 mg of pramipexole dihydrochloride, the patients showed almost no change in the caudate (mean [SD], 0.8% [11%]), putamen (mean [SD], −0.8% [7.6%]), and ventral striatum (mean [SD], 7.5% [2%]) BPND but showed a mean (SD) 45% (8%) reliable decrease in the signal derived from the GP (BPND from mean [SD], 5.3% [1.0%] to 2.8% [0.1%]) (Figure 4).

COMMENT

To our knowledge, this is the first study to compare the antipsychotic occupancies as measured by an agonist and an antagonist radiotracer and provides the first evidence of the effects of antipsychotics on the low- and the high-affinity states of the dopamine receptors, as well as providing insights into the differential effect of the drugs on D3 and D2 receptors. Our results indicate that while antipsychotics do block both the low-affinity and the high-affinity states of the D2 receptors as estimated by [11C]-(+)-PHNO and [11C]raclopride, antipsychotics do not block the D3 receptors as estimated by [11C]-(+)-PHNO in the D3 receptor–rich regions (GP and ventral striatum). The data with pramipexole, a D3 receptor–preferring agonist, show that the signal with [11C]-(+)-PHNO in the D3 receptor–rich regions is displaceable and supports a D3 receptor basis for this signal.

The major new finding in our study is that the [11C]-(+)-PHNO binding in the GP and ventral striatum is not blocked by long-term antipsychotic exposure in patients with schizophrenia. Our group recently reported that the [11C]-(+)-PHNO binding is not different between drug-free patients with schizophrenia and age- and sex-matched healthy controls in any brain region.33

What makes the D3 receptors particularly interesting is their preferential distribution in the limbic regions and their rigid configuration in high-affinity states for dopamine.17,16 This configuration may imply that in vivo this receptor is occupied by endogenous dopamine for longer periods, suggesting a special role for D3 receptors in mediating tonic (background) dopamine transmission.44 As a result of this functional distribution and sensitivity to background dopamine levels, small changes in their number may have important functional implications, especially for neuropsychiatry disorders.

Several converging lines of evidence suggest that our results likely reflect the D3 receptor binding signal of the radioligand [11C]-(+)-PHNO as confirmed by the following: (1) The main distribution of the increased BPND was within the D3 receptor–rich area (mainly GP) where [11C]-(+)-PHNO has shown preferential distribution and selectivity in vitro and in vivo.18,23-26 (2) Studies in D3 receptor knockout mice confirm that tritium-labeled (3H) (+)-PHNO binding in this region is D3 receptor related.28 (3) Studies in nonhuman primates have shown that the [11C]-(+)-PHNO signal in GP binding is preferentially displaced with the preferential D3 receptor agonist BP987.26 and antagonist SB277011.28 (4) In normal human volunteers, we have recently shown that the [11C]-(+)-PHNO signal in GP binding is preferentially displaced after a single dose of a D3 receptor antagonist ABT925.27 and partially displaced with the D3/D2 receptor antagonist haloperidol.21 (5) Finally, most importantly, the [11C]-(+)-PHNO binding in patients exposed to risperidone long-term was displaced by a challenge with the preferential D3 receptor agonist pramipexole. Thus, it seems reasonable to suggest that patients treated long-term with antipsychotics show an unblocked signal in the GP that could be best understood as D3 receptor binding.

The results indicate a higher BPND in the GP with [11C]-(+)-PHNO that could reflect either an increase in the available number of D3 receptors in the region (Bmax), an increase in the apparent affinity (Kp), or a reference tissue–based quantitation artifact (something we discuss further later). A treatment-induced increase in D3 receptor
Figure 2. Nondisplaceable binding potential (BP_{ND}) of carbon 11–labeled (+)-4-propyl-9-hydroxynaphthoxazine ([\textsuperscript{11}C]-(+)-PHNO) (A) and [\textsuperscript{11}C]raclopride (B) estimated by the simplified reference tissue model of every region of interest. The BP_{ND} corresponds to controls, controls corrected (estimated sex- and age-corrected by linear regression), and patients treated with clozapine, olanzapine, and risperidone. Horizontal lines indicate the mean BP_{ND} from each region of interest.
binding may be explained by changes induced by antipsychotics on a variety of intracellular mechanisms leading to an increase in $B_{\text{max}}^{45-47}$. However, the preclinical data on this matter are equivocal. Some studies have reported an increase in $D_3$ receptor messenger RNA,$^{48-50}$ but other studies have found no change in $D_3$ receptor messenger RNA or $D_3$ receptor labeling.$^{51-55}$ Additionally, a postmortem study$^{54}$ in patients with schizophrenia treated long-term did not find any difference in the total number and affinity (dissociation constant) of $D_3$ receptors. At present, both an increase in the $B_{\text{max}}$ or $K_d^{11032}$ remain possible and only further experimentation will choose between them.

The occupancies in the $D_2$ receptor–rich areas (caudate and putamen) were always lower with $[^{11}\text{C}]$(+)-PHNO (Table 2). A simple explanation for the difference in occupancy could be that antipsychotics show less affinity for the high- vs the low-affinity states of the $D_2$ receptors, and since $[^{11}\text{C}]$(+)-PHNO is assumed to label only the former, the 2 radioligands may result in different occupancies. This assumption has been indirectly sustained by the higher sensitivity of $[^{11}\text{C}]$(+)-PHNO for amphetamine displacement than $[^{11}\text{C}]$raclopride in anesthetized cats.$^{56}$ However, this higher sensitivity was not replicated in an ex vivo dissection study in awake rodents,$^{57}$ though it is suggested by the study in awake and healthy humans.$^{35}$ The cause of this discrepancy between studies is still elusive, though the cat and human studies suggest that $[^{11}\text{C}]$(+)-PHNO binds preferentially to the high-affinity states of the dopamine receptor.

The explanation of less affinity for the high- vs the low-affinity states seems to be unlikely, as studies in vitro have generally shown that the current antipsychotics have similar affinities for the high- and the low-affinity states. In addition, an ex vivo study in rodents using $[^{11}\text{C}]$(+)-PHNO and $[^{3}\text{H}]$raclopride confirmed the in vitro results, indicating that affinities (ED$_{50}$) for haloperidol and clozapine are the same with both radiotracers.$^{57}$

On the other hand, the more likely explanation is that the lower $[^{11}\text{C}]$(+)-PHNO mean occupancies are related to the signal from $[^{11}\text{C}]$(+)-PHNO having a higher $D_3$ vs $D_2$ receptor contribution as compared with the signal from $[^{11}\text{C}]$raclopride. It has been shown that the rela-

Figure 3. Average time activity curves of patients (n=20) and controls (n=23) for every region of interest. Error bars correspond to standard deviations. SUV indicates standard uptake value.
tive D3 vs D2 receptor density as observed in humans in vitro and in nonhuman primates is caudate less than putamen less than ventral striatum less than GP.28,59-61 This is well supported by recent data from Rabifer et al,28 who demonstrated that the D2 receptor contribution of [11C]-(+)-PHNO in the dorsal striatum in nonhuman primates is between 8% and 21% using the selective D2 receptor antagonist SB277011. In addition, the [11C]-(+)-PHNO signal in the dorsal striatum can be blocked up to 13% to 47% by BP897 and ABT92526,27 in nonhuman primates and humans, suggesting D2 receptor availability in this region. The final possibility is that while the use of reference tissue–based quantitations have been validated for both [11C]-raclopride38 and [11C]-(+)-PHNO,30 they do not reflect absolute parameters—something we discuss further later. Nonetheless, on comparing these 3 possibilities, we favor the differential D3 vs D2 receptor as the preferred explanation as it explains not only the finding in the dorsal striatum, but the differentials in the other regions and is consistent with our main explanation for the GP.

Our study has several limitations but none that we think detract from the main conclusion herein. Since we did not have data on the drug-free state of our antipsychotic-treated patients, we had to derive occupancy levels by reference to a control population. While less than ideal, this is the most common approach in the literature,62 and since we have recently shown that there are no differences between healthy controls and drug-free patients with schizophrenia,64 it is unlikely to have biased our results. Another limitation is that the smoking status of the participants was not recorded. This limitation may be important in light of the effects of cigarette consumption, craving, and its mood or hedonic effect on the dopamine system63-65 and that patients with schizophrenia are more likely to be smokers than the general population.66 However, the overall effect of smoking or nicotine exposure on the BPND is small or null (about 10%). While Brody et al66 reported a mean (SD) reduction of 8.5% (1.5%) in BPND with [11C]-raclopride, Barrett et al67 and Montgomery et al68 did not find any change in BPND with [11C]-raclopride. To our knowledge, this effect has never been explored with an agonist radiotracer.

The lack of arterial samples to perform a full kinetic analysis may also be a limitation of our study. A full kinetic analysis would allow direct estimation of the BP in the regions of interest without the potential bias induced by specific binding in the reference region and/or by changes in the kinetics of the signal of interest. However, it is of some reassurance to know that in the current study the cerebellar uptake values in patients and controls were not different (Figure 3) (F1,41=0.29; P=.59). The SRTM approach to estimate BPND with the cerebellum as a reference has a good correlation with the BP as estimated with a full kinetic analysis and it was validated in unmedicated controls for both radiotracers.60,68 This approach has been used repeatedly with reliable results with [11C]-raclopride in patients with schizophrenia taking antipsychotics.3-7,8,64 However, to our knowledge, the current study is the first with [11C]-(+)-PHNO in patients taking antipsychotics and some limitations should be considered. To examine the dependence of these findings on any one method, we additionally estimated the BPND with the interval ratio, MRTM, and MRTM2 methods. Across methods, the BPND in the GP of patients treated long-term was always higher than controls (though the extent of the increase varied, 17%, 42%, and 41%, respectively) (eTable 2), even with the MRTM and MRTM2 methods, which showed lower coefficients of variance (eTable 4). However, the visual inspection of the time activity curves from the GP (Figure 3) suggests that while the initial part of the curve is reduced compared with controls (probably secondary to D2 receptor block), the latest part (likely D3 receptor related) is similar to controls. These effects result in a flat curve during the 90 minutes of scanning time, which provides the kinetic model with limited information about the off rate (k4) to properly estimate k3/k4.

An increase of the scanning time, to obtain enough off-rate data, would overcome this limitation in kinetic modeling. However, the short half-life of [11C] would provide noisy data after 90 minutes and the agonist property of [11C]-(+)-PHNO may make a bolus infusion difficult to implement. Thus, while we can be reasonably certain that the current antipsychotics do not induce a decrease of the [11C]-(+)-PHNO binding in the D3 receptor–rich areas in schizophrenia, whether there is a true upregulation (ie, an increase in D3 receptor number) should be regarded as a possibility that may require more data to confirm. We used pramipexole to displace the signal in the D3 receptor–rich areas of the patients treated long-term. Pramipexole is an agonist with an approximately 10-fold preference for D2 receptors over D3 receptors.59,67,68 We were aware of the limited D3 receptor selectivity of pramipexole, but it was the only medication with a high D3 receptor selectivity that was available for us to use in patients. In addition, in vitro studies suggested that the doses...
administered to our patients were still in the D3 receptor selectivity range and this was confirmed post hoc in our study by the selective displacement showed in the GP and not in the dorsal striatum. As better and more selective D3 receptor agents become available, it may become possible to definitively confirm what we propose herein.

Finally, the patients were cross-sectionally chosen to meet the inclusion criteria of this study based on the drug that they were receiving, and their treatment was not prospectively controlled. This was not necessary for the current study and, hence, was not done. While confirming the results with 3 different antipsychotics and 4 modeling methods makes us confident of our finding, the clinical implications of this unblocked [11C]-PHNO signal remain to be elucidated.

To our knowledge, our study provides the first in vivo evidence for the effect of antipsychotics on the D3 receptor and suggests that long-term antipsychotic treatment does not decrease [11C]-PHNO binding in the D3 receptor–rich regions, though it clearly blocks the signal in the D2 receptor–rich regions. This has several important implications. It introduces the application of the D3/D2 receptor agonist radiogand [11C]-PHNO for the study of schizophrenia and antipsychotics; shows that current antipsychotics impact the D2 receptors as measured by an agonist (high-affinity state) and an antagonist (high- + low-affinity state) radiotracer; suggests that current antipsychotics act on D2 receptors in a manner distinct from D3 receptors; and opens up the potential for future investigations of the role of antipsychotics in the D3 receptor system.

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Author Affiliations: Positron Emission Tomography Centre, Centre for Addiction and Mental Health (Drs Graff-Guerrero, Mamo, Shammi, Mizrahi, Rusjan, Houle, Wilson, and Kapur and Ms Marcon and Barsoum) and Department of Psychiatry, University of Toronto (Drs Graff-Guerrero, Mamo, Shammi, Mizrahi, Houle, Wilson, and Kapur). Toronto, Ontario, Canada; Institute of Neurobiology, Universidad Nacional Autonoma de Mexico, Mexico City (Dr Graff-Guerrero); and Division of Psychological Medicine and Psychiatry, Institute of Psychiatry, King’s College London, London, England (Dr Kapur).

Correspondence: Shitij Kapur, MD, PhD, PO Box 053, Institute of Psychiatry, De Crespigny Park, London SE5 8AF, England (shitij.kapur@iop.kcl.ac.uk).

Author Contributions: Drs Graff-Guerrero, Shammi, Houle, and Kapur had full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis.

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