Brain Serotonin 5-HT$_{1A}$ Receptor Binding in Schizophrenia Measured by Positron Emission Tomography and $[^{11}C]$WAY-100635

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**Background:** Results of postmortem studies show an elevation in serotonin-1A (5-hydroxytryptamine-1A [5-HT$_{1A}$]) receptor density in the prefrontal and temporal cortices of patients with schizophrenia. This study examined 5-HT$_{1A}$ receptors in vivo in patients with schizophrenia using positron emission tomography and $[^{11}C]$WAY-100635.

**Methods:** The 5-HT$_{1A}$ binding potential of 14 antipsychotic drug–naive patients with a DSM-IV diagnosis of schizophrenia was compared with that of 14 age-matched healthy controls. Positron emission tomography data were analyzed using 9 cortical regions of interest, which were delineated on a coregistered magnetic resonance image and transferred to the positron emission tomographic image, with the cerebellum as the reference region for a simplified reference tissue model. We also performed a voxel-wise comparison using statistical parametric mapping.

**Results:** The region of interest–based analysis revealed a significant mean ± SD cortical 5-HT$_{1A}$ receptor binding potential increase of 7.1% ± 6.4% in patients with schizophrenia (F = 2.975; P = .02); local differences were +20% in the left medial temporal cortex (F = 9.339; P = .005) and +13% in the right mediotemporal cortex (F = 4.453; P = .045). There were no significant differences in regional tracer delivery or cerebellar $[^{11}C]$WAY-100635 uptake. The voxel-based analysis also confirmed a group difference in the left medial temporal cortex.

**Conclusions:** The biological significance of elevated 5-HT$_{1A}$ receptor density in schizophrenia remains unclear. Given the location of 5-HT$_{1A}$ receptors on pyramidal cells, this elevation may reflect an abnormal glutamatergic network. Our finding needs to be viewed in light of preclinical evidence supporting a role for 5-HT$_{1A}$ receptors in mediating antipsychotic action and extrapyramidal adverse effects of drugs.

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PARTICIPANTS AND METHODS

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Fourteen right-handed patients (6 women and 8 men; mean age, 26 years; age range, 22-37 years) with a DSM-IV diagnosis of schizophrenia were included in the study. Each patient experienced a first psychotic episode, had not received any psychotropic medication except for benzodiazepines within 1 month of the PET scan, and had never been treated with an antipsychotic agent. Patients were recruited from the Schizophrenia and Continuing Care Program of the Centre for Addiction and Mental Health, where they had been evaluated as either inpatients or outpatients. The diagnosis of schizophrenia was ascertained using a Structured Clinical Interview for DSM-IV, which was performed by an experienced psychiatrist (J.T., N.P.L.G.V., Z.J.D., or S.T.-W.).

Fourteen age-matched individuals (8 women and 6 men; mean age, 28 years; age range, 19-36 years) comprised the control group. These 14 controls were recruited from the community by advertisements and were part of a bigger pool of healthy individuals described in an earlier [11C]WAY-100635 PET study. Patients were excluded from the study if they experienced a serious medical or neurologic illness, had a significant head injury, or were pregnant. Furthermore, exclusion criteria for control subjects were any Axis I psychiatric diagnosis as confirmed by the Structured Clinical Interview for DSM-IV, nonpatient edition, or treatment with psychotropic medications within 3 months of the study.

All patients gave written consent after the procedure had been fully explained. The study and recruitment procedures were approved by the research ethics board of the Centre for Addiction and Mental Health and the Department of Psychiatry, University of Toronto.

IMAGE ACQUISITION AND ANALYSES

The selective 5-HT1A receptor antagonist [11C]WAY-100635 was synthesized according to modifications of the McCarron method using a short fluorocarbon resin tube loosely packed with polypropylene wool as a substitute for the narrow polypropylene tubing originally used. This procedure yielded syntheses with high purity (>95%) and average specific activity of 47 GBq/µM (1270 mCi/µM) at the time of injection.

Positron emission tomographic images were obtained during 60 minutes using a GEMS PC2048-13B camera (General Electric Medical Systems, Milwaukee, Wis) in 15 one-minute frames followed by another 9 five-minute frames after bolus injection of a mean±SD of 9.8±0.6 mCi (363±22 MBq) of [11C]WAY-100635. The images were corrected for attenuation with a 68Ge transmission scan and were reconstructed using filtered back projection (Hanning filter, 5 mm full-width at half maximum), and 15 axial slices, each 6.5-mm thick, were obtained.

For the quantification of 5-HT1A receptor binding in human brain, 2 approaches were used: one based on predefined regions of interest (ROIs) and the other a voxel-wise analysis.

Each participant underwent magnetic resonance imaging (MRI) (GE Signa 1.5-T scanner; spin-echo sequence T1- and proton density–weighted images; and x, y, and z voxel dimensions 0.78, 0.78, and 3.00 mm, respectively). The MRIs were coregistered to each PET image by using RView8/mpr software. For ROI analysis, brain regions were delineated on the coregistered MRI using previously defined landmarks. Anatomic ROIs were drawn bilaterally in the dorsolateral prefrontal (DLPFC), anterior cingulate (ACC), medial temporal (MTC), lateral temporal (LTC), and parietal cortices and in the cerebellum by an operator masked to the condition. The gray matter of the cerebellum was delineated on consecutive slices where the middle cerebellar peduncle was clearly visible. The DLPFC was delineated on axial MRI slices in which the caudate, putamen, and globus pallidus were all clearly visualized. The ACC was delineated on the same slices and identified as a gray matter structure on both sides of the interhemispheric fissure extending posterior to the anterior commissure.

RESULTS

The mean±SD age of patients and controls was 26±5 years and 28±3 years, respectively. There was no significant difference in age between groups (t26 =1.071; P = .29).

The ROI-based analysis revealed a mean±SD 5-HT1A receptor BP increase of 7.1%±6.4% in patients with schizo-

EARLIER EFFORTS TO QUANTITATIVELY ANALYZE 5-HT1A RECEPTORS USING THE AGONIST LIGAND 8-OH-DPAT WERE HAMPERED BY THE FACT THAT IT LABELS 5-HT1A RECEPTORS ONLY IN THEIR HIGH-AFFINITY STATE. THIS PROBLEM HAS RECENTLY BEEN OVERCOME BY THE DISCOVERY OF WAY-100635, A SELECTIVE HIGH-AFFINITY (Kd<1nM) 5-HT1A ANTAGONIST, WHICH LABELS BOTH LOW- AND HIGH-AFFINITY RECEPTORS. WAY-100635 HAS BEEN LABELED AT THE [CARBONYL-11C] POSITION AND CAN BE USED FOR THE QUANTITATIVE ANALYSIS OF BINDING TO 5-HT1A RECEPTORS IN HUMANS. USING [CARBONYL-11C]N-[2-[4-(2-METHOXYPHENYL)-1-Piperazinyl]ethyl]-N-(2-pyridinyl) cyclohexane carboxamide ([11C]WAY-100635) AND POSITRON EMISSION TOMOGRAPHY (PET), CORTICAL 5-HT1A BINDING CAN BE QUANTITATIVELY ANALYZED USING THE CEREBELLUM AS AN INPUT FUNCTION OF A SIMPLIFIED REFERENCE TISSUE MODEL (SRTM). USING THIS METHOD, AN AGE-DEPENDENT DECREASE IN CORTICAL 5-HT1A RECEPTOR BINDING POTENTIAL IN HEALTHY VOLUNTEERS WAS RECENTLY DEMONSTRATED, CONSISTENT WITH FINDINGS FROM POSTMORTEM STUDIES WHICH SHOWED A DECLINE IN 5-HT1A RECEPTOR NUMBERS WITH AGE.

WE PRESENT A PET STUDY IN 14 NEUROLEPTIC DRUG-NAIVE PATIENTS WITH A DSM-IV DIAGNOSIS OF SCHIZOPHRENIA WHO EXPERIENCED A FIRST PSYCHOTIC EPISODE. ON THE BASIS OF HUMAN POSTMORTEM STUDIES, WE HYPOTHESIZED THAT IN VIVO 5-HT1A RECEPTOR BP AS MEASURED WITH [CARBONYL-11C]WAY-100635 AND PET IS HIGHER IN THE FRONTAL AND TEMPORAL CORTEXES OF PATIENTS WITH SCHIZOPHRENIA COMPARED WITH AN AGE-MATCHED CONTROL GROUP.
genu of the corpus callosum. The MTC was delineated as a mediotentorial gray matter region corresponding to the hippocampus, amygdaloid nucleus, and parahippocampal gyrus. The LTC included temporal gray matter located laterally starting with the same slice, where the MTC was delineated, and extending superior to slices in which the caudate, putamen, and globus pallidus were clearly visualized. The parietal cortex was delineated on 3 slices corresponding to the inferior parietal lobe extending anterior to the postcentral sulcus.

Decay-corrected time-activity curves (TACs) were obtained for each ROI using the 60 minutes of the data acquisition period because 60-minute TACs in the SRTM yielded test-retest agreement comparable to 90-minute TACs.3,11 Because we were scanning acutely psychotic patients, we tried to keep the scanning time as brief as possible.

Regional BP values were calculated as an estimate of 5-HT1A receptor number in each ROI using the kinetic modeling tool of PMOD Medical Imaging Software (version 2.20).34 To obtain BP values, the cerebellum was used as the reference region for an SRTM.20

For the voxel-wise analysis, parametric 5-HT1A receptor BP images were generated using the SRTM with PMOD. Parametric images were then spatially normalized within the standard Montreal Neurologic Institute brain space using Statistical Parametric Mapping version 99 (SPM99)35 and a ligand-specific template.36

**STATISTICAL ANALYSIS**

Statistical analyses of the ROI data were performed using SPSS for Windows 10.0.0 (SPSS Inc, Chicago, Ill). Parametric statistical analyses were applied after it had been assured that skewness, kurtosis, outliers, and homogeneity of variance of our data met the criteria for a normal distribution.37 In a first step, all regions were pooled together to estimate the mean cortical 5-HT1A receptor BP of each group. To test the hypothesis that 5-HT1A receptor BP is elevated in the frontal and temporal cortices of patients with schizophrenia, regional BP values of patients and controls were compared using multivariate analysis of covariance, with all regional BP values as dependent variables, group (patients vs controls) as a fixed factor, and age as a covariate. Multiplying the area of each ROI by the number of slices and their respective thickness of 6.5 mm provided an approximation for the actual volume of interest (VOI). Additional separate multivariate analyses of variance were performed to compare the VOI and R1 values between groups. R1 is the ratio of tracer delivery to the tissue of interest (K) relative to the reference tissue (K′), and it can be described by the following equation: R1 = k/K′. To compare the uptake in the cerebellum between patients and controls, an analysis of variance was performed, with the area under the curve of the cerebellar TAC as the dependent variable. For the ROI analysis, an α level of P < .05 was considered significant, and all tests were 2-tailed. For the post hoc tests, a Bonferroni correction for multiple comparisons was performed using 9 different cortical regions.

Potential correlations between age and the measured activity in the cerebellar ROI, between age and ROI size or regional BP values, and between each ROI BP value and its respective area were examined using 2-tailed Pearson product moment correlation coefficients. In addition, Pearson product moment correlation coefficients were calculated to reveal possible correlations between 5-HT1A receptor BP in patients and duration of untreated psychosis or severity of illness as measured using the Positive and Negative Syndrome Scale for schizophrenia.38

For the voxel-by-voxel analysis, statistical parametric maps were generated using SPM99. To test whether the measured 5-HT1A receptor BP differed between patients and controls in any given voxel, 2-tailed t tests were applied. Results were displayed as statistical parametric maps using an uncorrected height threshold of P < .01 (t test, > 2.48). We applied 2 contrasts (patient 5-HT1A BP higher than that of controls and vice versa) to a search volume of 93,209 voxels, each with a size of 2 × 2 × 2 mm.

phenia across all 9 cortical ROIs (Figure 1 and Figure 2). A multivariate analysis of covariance revealed a significant group effect (patients vs controls) on the BP values measured in 9 cortical ROIs (F9,17 = 2.975; P = .02), but neither a significant effect of age (F9,17 = 0.814; P = .61) nor a significant age × group interaction (F9,36 = 1.716; P = .08) was found. Post hoc tests of between-subject effects revealed that 5-HT1A receptor BP values of patients were significantly higher in the left LTC (F3,18 = 9.33; P = .005) and the right MTC (F1,4.433; P = .045) (Table). There were no significant differences in BP values in any other ROI. Only the result in the left LTC survived a Bonferroni correction for multiple comparisons (corrected P = .045).

A multivariate analysis of variance revealed no significant group differences in regional tracer delivery (R1) between patients and controls (F9,18 = 1.427; P = .25). Mean VOI values were 23 mL for the cerebellum, 21 mL for the left PFC, 22 mL for the right PFC, 15 mL for the ACC, 12 mL for the left temporal cortex, 12 mL for the right temporal cortex, 4 mL for the left MTC, 4 mL for the right MTC, 26 mL for the left parietal cortex, and 27 mL for the right parietal cortex. There was no significant difference in VOIs between patients and controls (F10,17 = 0.882; P = .57). Furthermore, there was no significant difference in the area under the curve of the cerebellar TAC between groups (F1 = 0.194; P = .66) (Figure 3).

Pearson correlation coefficients (r) did not reveal any significant correlation between age and the area under the curve of the cerebellum or BP in any cortical ROI, between age and VOI, or between regional BP values and their respective VOIs. Furthermore, there was no significant correlation between MTC 5-HT1A receptor BP and duration of untreated psychosis in patients (left MTC: r = 0.06; P = .84; right MTC: r = −0.18; P = .57). Binding potential values were not significantly correlated to severity of illness as measured using the Posi-
tive and Negative Syndrome Scale for schizophrenia sum, positive, negative, and general scores, with \( r = 0.05 \) to 0.37 and the corresponding \( P = .41 \) to .92.

The voxel-wise analysis produced no robust evidence for a pronounced elevation in \([^{11}C]WAY-100635\) uptake in the prefrontal or temporal cortex in schizophrenia. Statistical parametric mapping showed only one activity cluster denoting higher \([^{11}C]WAY-100635\) uptake in patients with schizophrenia, consisting of 86 voxels extending laterally from the Montreal Neurologic Institute brain space coordinates \(-16, -6, \) and \(-40 \) mm (x, y, and z, respectively), with \( z = 2.99 \) and \( P_{10} = .001 \). Plotting this activity cluster on an averaged composite MRI of all patients, which had been normalized to the Montreal Neurologic Institute brain space, revealed a region in the left MTC similar to the one in which we found the most pronounced difference between patients and controls with the ROI-based approach (Figure 4).

The main finding of this in vivo PET study was an increase in cortical 5-HT\(_{1A}\) receptor BP in schizophrenia. The most pronounced difference between patients and controls was a 20% increase in \([^{11}C]WAY-100635\) binding in the left MTC of patients with schizophrenia found by ROI-based PET analysis, which was confirmed by an additional voxel-wise analysis using SPM99.

This in vivo PET study of 5-HT\(_{1A}\) receptors in schizophrenia did not detect a significant elevation in \([^{11}C]WAY-100635\) binding in the prefrontal cortex of patients, which is in contrast to results of postmortem studies\(^6\)\(^{-13}\) showing a 20% to 79% elevation in 5-HT\(_{1A}\) receptor number in that region.

Postmortem studies have several limitations. All patients in the postmortem studies had received several years of antipsychotic drug treatment, and all patients except 5 in the study by Hashimoto et al\(^6\) were receiving antipsychotic agents at the time of death. In contrast, all patients in our study were antipsychotic drug naive. Hence, the more pronounced increase in postmortem 5-HT\(_{1A}\) receptors could be an effect of long-term drug treatment.

In contrast to the postmortem studies with an average illness duration of approximately 20 years, our sample consisted of first-episode patients with a mean±SD duration of untreated psychosis of 21±18 months (range, 7 months to 5 years). Owing to this relatively restricted range, we were not able to systematically investigate the effects of disease progression.

For tracer kinetic modeling, we used the cerebellum as the reference region for an SRTM because the cerebellum is relatively devoid of 5-HT\(_{1A}\) receptors.\(^{13}\) Furthermore, the SRTM proved to be more reliable than kinetic modeling using arterial data\(^{21}\) and provided excellent test-retest reproducibility with \([^{11}C]WAY-
A test-retest study in 6 control subjects provided strong evidence that we would be able to correctly identify a group difference of 20% to 79% with acceptable sensitivity. Twenty- and 90-minute TACs gave comparable results. With 60-minute TACs, the magnitude of the mean error between 2 \([\text{carbonyl-11C}]\)WAY-100635 PET scans of the same individual ranged from 2% to 7% in cortical ROIs.

Most postmortem studies selected limited and often arbitrary brain regions to study. Only 2 groups studied samples from all cortical regions. All other investigated only the prefrontal cortex or the prefrontal and temporal cortices. Although all of the postmortem studies report “prefrontal” increases, the data came from Brodmann areas (BAs) 9th, 10th, 11 and 12th, 24, 9a, and 44th; or 46th. To avoid an unjustified restriction to frontal brain areas, we analyzed 5-HT1A receptor BP in cortical ROIs drawn in the DLPFC, ACC, MTC, LTC, and parietal cortex. However, we are aware of several limitations inherent to the ROI approach. The intrinsic spatial resolution of our PET camera is 4.5 to 5.5 mm in the transaxial plane. Therefore, we chose to delineate rather large areas comprising several BAs. In the case of the DLPFC, this ROI roughly corresponds to portions of BAs 9, 10, and 46, whereas in case of the ACC, we tried to confine this ROI to BA 32 and frontal parts of BA 24.

The process of coregistering introduces another source of error, which also contributes to the anatomic inaccuracy of the ROI approach. Moreover, if any given pathologic condition afflicts only parts of an ROI, a possible BP increase or decrease will be diluted, and, therefore, the chance to miss a group difference is high. On these grounds we chose to corroborate the results of the ROI-based approach by applying an additional voxel-wise SPM99 analysis. Because of the restricted field of view of our PET camera (15 slices of 6.5 mm each, which translates into 9.75 cm with regard to the z-axis), even the voxel-wise approach cannot be considered to cover the entire brain. Nevertheless, SPM99 revealed an elevated 5-HT1A receptor BP in the left MTC of patients, confirming the strongest result of the ROI-based approach.
We matched our control group for age but not for sex because it had been shown post mortem and in vivo using PET and $[^{11}C]$WAY-100635 that 5-HT$_{1A}$ density declines with age, whereas in both studies sex did not significantly affect 5-HT$_{1A}$ receptor BP.

Based on the results of postmortem studies, we expected at least a 25% BP elevation in the frontal cortices of patients in vivo. Using values from controls (mean ± SD frontal BP, 3.2 ± 0.4), we estimated that our study had a power of 0.98 (1–β) to detect a 25% elevation in frontal 5-HT$_{1A}$ receptor BP in patients at α<.05. However, this study did not reveal such an elevation in frontal brain regions. On the other hand, to decide whether the 4% to 5% nonsignificant difference reported in the DLPFC is truly within chance or due to a type II error, we would have to increase our sample size 10-fold, which is not feasible because of practical limitations.

There is preclinical evidence to support a role for 5-HT$_{1A}$ agonism in the antipsychotic action and extrapyramidal adverse effects of drugs. The 5-HT$_{1A}$ agonist 8-OH-DPAT enhanced the antipsychotic-like effect of the D$_2$/D$_3$ antagonists raclopride and haloperidol and antagonized the catalepsy induced by the D$_2$ agonist SCH23390 in rats. Several atypical antipsychotic drugs are partial agonists at the 5-HT$_{1A}$ receptor, including clozapine, ziprasidone, quetiapine, and tio- spirone hydrochloride. Clinical studies of adding 5-HT$_{1A}$ partial agonists may help to clarify the possible importance of 5-HT$_{1A}$ agonism in the treatment of schizophrenia.

The biological significance of elevated 5-HT$_{1A}$ receptor numbers in schizophrenia as indicated by several studies is noteworthy. Several atypical antipsychotic drugs are partial agonists at the 5-HT$_{1A}$ receptor, including clozapine, ziprasidone, quetiapine, and tio-spirone hydrochloride. Clinical studies of adding 5-HT$_{1A}$ partial agonists may help to clarify the possible importance of 5-HT$_{1A}$ agonism in the treatment of schizophrenia.

The finding that MTC has a 13% elevation in the right frontal cortex is an anatomic region known to be affected in schizophrenia. The biological significance of elevated 5-HT$_{1A}$ receptor numbers in schizophrenia as indicated by several studies is noteworthy. Several atypical antipsychotic drugs are partial agonists at the 5-HT$_{1A}$ receptor, including clozapine, ziprasidone, quetiapine, and tio-spirone hydrochloride. Clinical studies of adding 5-HT$_{1A}$ partial agonists may help to clarify the possible importance of 5-HT$_{1A}$ agonism in the treatment of schizophrenia.

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