Downregulated Kynurenine 3-Monoxygenase Gene Expression and Enzyme Activity in Schizophrenia and Genetic Association With Schizophrenia Endophenotypes

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Context: Kynurenic acid, a metabolite of the kynurenine pathway of tryptophan degradation, is an antagonist at N-methyl-D-aspartate and α7 nicotinic acetylcholine receptors and modulates glutamate, dopamine, and acetylcholine signaling. Cortical kynurenic acid concentrations are elevated in the brain and cerebrospinal fluid of schizophrenia patients. The proximal cause may be an impairment of kynurenine 3-monoxygenase (KMO), a rate-limiting enzyme at the branching point of the kynurenine pathway.

Objectives: To examine KMO messenger RNA expression and KMO enzyme activity in postmortem tissue from the frontal eye field (FEF; Brodmann area 6) obtained from schizophrenia individuals compared with healthy control individuals and to explore the relationship between KMO single-nucleotide polymorphisms and schizophrenia oculomotor endophenotypes.

Design: Case-control postmortem and clinical study.

Setting: Maryland Brain Collection, outpatient clinics.

Participants: Postmortem specimens from schizophrenia patients (n = 32) and control donors (n = 32) and a clinical sample of schizophrenia patients (n = 248) and healthy controls (n = 228).

Main Outcome Measures: Comparison of quantitative KMO messenger RNA expression and KMO enzyme activity in postmortem FEF tissue between schizophrenia patients and controls and association of KMO single-nucleotide polymorphisms with messenger RNA expression in postmortem FEF and schizophrenia and oculomotor endophenotypes (ie, smooth pursuits eye movements and oculomotor delayed response).

Results: In postmortem tissue, we found a significant and correlated reduction in KMO gene expression and KMO enzyme activity in the FEF in schizophrenia patients. In the clinical sample, KMO rs2275163 was not associated with a diagnosis of schizophrenia but showed modest effects on predictive pursuit and visuospatial working memory endophenotypes.

Conclusion: Our results provide converging lines of evidence implicating reduced KMO activity in the etiopathophysiology of schizophrenia and related neurocognitive deficits.

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Impairment of the kynurenine pathway (KP) of tryptophan metabolism has been suggested to play a role in the pathophysiology of schizophrenia and related cognitive deficits. The KP generates 3 neuroactive metabolites with purported links to neuropsychiatric diseases. These compounds—kynurenic acid (KYNA), 3-hydroxykynurenine, and quinolinic acid—are downstream products of the regulatory enzymes tryptophan 2,3-dioxygenase (TDO), indoleamine 2,3-dioxygenase, and kynurenine 3-monoxygenase (KMO). The levels of KYNA, an endogenous antagonist of the glycine coagonist (glycine) site of the glutamatergic N-methyl-D-aspartate receptor (NMDAR) and the α7 nicotinic acetylcholine receptor (α7nAChR), are elevated in the prefrontal cortex and cerebrospinal fluid of schizophrenia patients. This unique receptor affinity profile of KYNA is particularly interesting when viewed against accumulated evidence implicating NMDAR hypofunction in the pathophysiology of schizophrenia and α7nAChR hypofunction in schizophrenia-related cognitive deficits. In rats, endogenous KYNA controls extracellular levels of cortical acetylcholine, dopamine, and glutamate and the firing rate and burst activity of midbrain dopaminergic neurons.
Remarkably, experimentally increased brain KYNA levels in rats induce deficits in visuospatial working memory, contextual learning, sensory gating, and prepulse inhibition of the acoustic startle reflex.26-28 These neurocognitive deficits are of particular relevance to schizophrenia because they are highly frequent in schizophrenia individuals and their unaffected first-degree relatives and are considered endophenotypes.30,31 Taken together, these findings suggest that cognitive deficits in schizophrenia could be causally related to elevated cortical KYNA concentrations.3

Recent genetic studies provide support for a role for abnormal KP metabolism in the etiopathophysiology of schizophrenia. These studies include the demonstration of up-regulated brain TDO2 (OMIM 191070) messenger RNA (mRNA) (encoding the TDO enzyme) in postmortem tissue from schizophrenia patients32,33 and in the brains of newborn mice experimentally infected with influenza virus (a relevant animal model of schizophrenia34,35), possibly signifying an enhanced ability of the tissue to generate KYNA downstream (Figure 1). Moreover, an association between polymorphisms in the KMO gene (OMIM 603538) (which encodes the KMO enzyme) and schizophrenia was demonstrated in a Japanese cohort.36 This finding was not replicated in an independent sample drawn from the same population,36 nor was an association with schizophrenia demonstrated in a recent report on a European sample.37 These findings are of particular interest because the KMO gene maps to chromosome 1q42-q44, a region that has shown linkage in schizophrenia samples.38

Difficulties replicating genetic findings are not uncommon in schizophrenia, likely due to the polygenic and heterogeneous nature of this complex disorder. This phenotypic and genetic heterogeneity has hindered the search for schizophrenia liability genes using approaches from classical genetics, yielding associations with candidate loci and genes that are rarely replicated.39 As an alternative to using schizophrenia as an end point, one popular approach is to focus on genes that are directly or indirectly related to neurochemical pathways associated with pathogenesis, thus reducing neurochemical and genetic heterogeneity.3,40 Another approach aims to decrease phenotypic and genetic heterogeneity by focusing on disease-associated heritable quantitative traits (ie, endophenotypes).41,42 Using the latter approach, we have studied abnormal smooth pursuit eye movements (SPEMs), an established schizophrenia endophenotype,33-35 and found that the predictive smooth pursuit component (hereafter referred to as predictive pursuit) is highly heritable.31,46,47 A phylogenetically recent function fully preserved only in primates, SPEM (or eye tracking) is a highly developed behavioral response subserved by a known neuronal network48 and is an important component of the oculomotor response to smoothly moving objects in visual space. In combination with saccadic eye movements, SPEMs capture and maintain the image of a moving object on the fovea as the eyes track it in space and time. In the course of our studies, we have used predictive pursuit to parse differences in small gene effects between schizophrenia groups and healthy control in individuals that otherwise would have gone unnoticed using traditional global SPEM measures, clinical diagnosis, or behavioral symptoms.49,50

In this study, we integrated these 2 alternative approaches and investigated the KP and the predictive pur-
suit endophenotype. Initially, we compared KMO gene expression and KMO enzyme activity in postmortem brain tissue, focusing on the frontal eye field (FEF; Brodmann area 6). On the basis of neuroimaging data from monkeys and humans, this cortical area is a key region associated with SPEMs, and FEF deficits have been consistently found in schizophrenia patients. Comparisons between postmortem FEF specimens from schizophrenia patients and control samples revealed a significant and correlated downregulation of KMO gene expression and KMO enzyme activity in the tissues from the former compared with the latter. Subsequently, we examined the association of 2 KMO single-nucleotide polymorphisms (SNPs) with gene expression in the FEF tissues and 2 schizophrenia oculomotor endophenotypes in a clinical sample.

METHODS

BRAIN TISSUE FOR GENE EXPRESSION AND BIOCHEMICAL STUDIES

Human postmortem brains (n=64 total), stored at −80°C, were obtained from the Maryland Brain Collection (http://www.mprc.umd.edu/mrc.asp). The brains were slowly warmed to −20°C, and the FEF was removed via dissection with a Stryker bone saw from the location denoted by Rosano and colleagues.

Specimens were obtained from 32 schizophrenia donors (15 had taken first-generation antipsychotic medications, 5 had taken second-generation antipsychotics, 2 had taken combined first-generation antipsychotics and second-generation antipsychotics, 5 had not taken antipsychotics for 6 months or more before death, and 5 were of unknown antipsychotics status at the time of death). Normal control specimens (n=32) were from individuals with no history of psychosis, mood disorders, drug dependence, psychiatric treatment, or hospitalization, as determined by medical examiner documentation and telephone screening of the next of kin. Specimens were selected as case-control pairs and were matched on sex, age, postmortem interval, pH, hemisphere, and freezer storage time (Table 1).

Clinical information was obtained through family interviews, including the Structured Clinical Interview for DSM-IV Axis I Disorders (SCID-IV). Senior psychiatrists performed best-estimate diagnoses using the Diagnostic Evaluation After Death in conjunction with review of past medical and psychiatric records. Postmortem clinical diagnoses were established according to the method developed by Roberts and colleagues.

All specimens were obtained with informed consent of the legal next of kin with approval from the office of the chief medical examiner of the state of Maryland.

Table 1. Postmortem Frontal Eye Field Tissue Specimens

<table>
<thead>
<tr>
<th>Study Group</th>
<th>No. of Specimens</th>
<th>Ethnicity of Specimens (EA/AA), No.</th>
<th>Sex (F/M), No.</th>
<th>Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy control individuals</td>
<td>32</td>
<td>20/12</td>
<td>5/27</td>
<td>46.9 (13.3) 14.5 (5.8) 6.63 (0.2) 6.6 (0.8)</td>
</tr>
<tr>
<td>Schizophrenia patients</td>
<td>32</td>
<td>21/11</td>
<td>5/27</td>
<td>44.7 (12.7) 14.0 (6.9) 6.70 (0.2) 7.1 (0.6)</td>
</tr>
</tbody>
</table>

Abbreviations: AA, African American/mixed ethnicity; EA, European American; PMI, postmortem interval; RIN, RNA integrity number (scale, 1-10).

None of the characteristics differed significantly between the schizophrenia and control groups.

Table 2. Demographic and Endophenotypic Measures of Study Participants

<table>
<thead>
<tr>
<th>Demographics</th>
<th>Healthy Control Participants</th>
<th>Schizophrenia Patients</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>43.3 (14.6)</td>
<td>45.2 (12.4)</td>
<td>.14</td>
</tr>
<tr>
<td>Female sex, %</td>
<td>47.8</td>
<td>26.2</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Ethnicity (EA/AA), %</td>
<td>57.9/42.1</td>
<td>50.0/50.0</td>
<td>.19</td>
</tr>
<tr>
<td>Predictive pursuit</td>
<td>0.57 (0.22) (n = 144)</td>
<td>0.48 (0.21) (n = 162)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Viscuospatial memory</td>
<td>1.57 (0.58) (n = 73)</td>
<td>2.64 (1.83) (n = 82)</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>

Abbreviations: AA, African American/mixed ethnicity; EA, European American.

Data are presented as mean (SD) unless otherwise indicated.

n = 228 unless otherwise indicated.

n = 248 unless otherwise indicated.

On the basis of the Oculomotor Delayed Response Task.

ASSOCIATION AND PHENOTYPIC STUDY PARTICIPANTS

Schizophrenia individuals (n=248) were recruited from outpatient research programs at the Maryland Psychiatric Research Center and Baltimore area mental health centers (Table 2). Enrollment was based on consensus diagnosis of schizophrenia derived from all available information, including past medical and psychiatric histories and the SCID-IV (patient version). We attempted to match healthy controls (n=228) with the demographic characteristics of our outpatient population via 2 methods. Using public databases, we conducted random telephone screenings to recruit controls by matching them to the age (SD, 3 years), sex, ethnicity, and zip code of recruited patients. The zip code was determined by the residence at the time of the patient’s first psychotic episode. Alternately, if zip codes were unavailable, we used targeted local community media advertisements based on patients’ county of residence. The design was intended to re-create, in the controls, the environment in which patients resided during the premorbid period that led to the first psychotic break. Thus, comparison subjects were drawn from similar geographic areas as the patient group. Because many neurophysiologic measures may be affected by age, particularly in individuals 60 years or older, endophenotypic studies were restricted to individuals between ages 18 and 58 years. Healthy controls did not meet DSM-IV criteria for Axis I disorders (confirmed by SCID-IV, nonpatient version) and had no family history of psychosis based on the Family History Research Diagnostic Criteria interview that extended through 3 generations. Respondents were excluded if they had general medical or neurologic con-
ditions that could affect measurement of oculomotor movements, reported substance dependence within 6 months before study enrollment or current substance abuse, or had mental retardation.

The study sample of 476 individuals included 256 self-identified European Americans and 220 who self-identified as African American/of mixed ethnicity. Completed endophenotypic measurements were available in subgroups as predictive pursuit subcomponent of SPEM (n = 306) and oculomotor delayed response (ODR; also known as memory-guided saccade, a visuospatial working memory measure (n = 136).52 All participants gave written informed consent in accordance with the University Of Maryland Institutional Review Board guidelines. In schizophrenia patients, the evaluation of the capacity to sign consent was performed to assess their understanding of the study before signing consent.

LABORATORY PROCEDURES

RNA Isolation and Reverse Transcription

We performed RNA isolation and reverse transcription, as previously described.60 Briefly, tissues were homogenized and total RNA extracted using TRIZOL Reagent (Life Technologies Corporation, Carlsbad, California), purified using Qiagen RNeasy mini spin columns (Qiagen, Hilden, Germany), and treated with DNase. The quality of the RNA was confirmed by high-resolution capillary electrophoresis (Agilent Technologies, Santa Clara, California) and assessed by an HTEC 500 detector (Eicom Corporation, San Diego, California), using a mobile phase consisting of 80 µL of the tissue preparation was incubated for 40 minutes at 37°C in a solution containing 1 mM nicotineamide adenine dinucleotide phosphate, 3 mM glucose-6-phosphate, 1 U/mL glucose-6-phosphate dehydrogenase, 100 µM L-kynurenine, 10 mM potassium chloride, and 1 mM edetic acid, in a total volume of 200 µL. Blanks were obtained by including the specific enzyme inhibitor Ro 61-8048 (100 µM; provided by W. Frostl, MD, Novartis AG, Basel, Switzerland) in the incubation solution. After centrifugation (16 000g for 15 minutes), 20 µL of the supernatant was applied to a 3-µm high-performance liquid chromatography column (HR-80; 80 x 4.6 mm; ESA Biosciences Inc, Chelmsford, Massachusetts), using a mobile phase consisting of 1.5% acetonitrile, 0.9% triethylamine, 0.39% phosphoric acid, 0.27 mM edetic acid, and 8.9 mM sodium heptane sulfonic acid and a flow rate of 1.0 mL/min. In the eluate, the reaction product, 3-hydroxykynurenine, was detected electrochemically using an HTEC 500 detector (Eicom Corporation, San Diego, California; oxidation potential, +0.5 V). The retention time of 3-hydroxykynurenine was approximately 11 minutes. The protein content of the samples was measured spectrophotometrically using the method developed by Lowry et al.

Table 3. Effect of KMO Genotype on Endophenotypes in Healthy Control Individuals and Schizophrenia Patients Combined

<table>
<thead>
<tr>
<th>Variable</th>
<th>TT (n = 24)</th>
<th>CT (n = 105)</th>
<th>CC (n = 157)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predictive pursuit gaina</td>
<td>0.51 (0.15)</td>
<td>0.53 (0.15)</td>
<td>0.47 (0.13)</td>
</tr>
<tr>
<td>Visuospatial working memory, absolute error in degreesb,b</td>
<td>1.99 (2.46)</td>
<td>1.77 (0.78)</td>
<td>2.46 (1.65)</td>
</tr>
</tbody>
</table>

a Significant main effects of genotype corrected P < .05.
b Based on the Oculomotor Delayed Response Task.

KMO Activity

On the day of the assay, tissues were thawed and homogenized (1:5, wt/vol) in ultrapure water. After further dilution (1:5, vol/vol) in 100 mM Tris hydrochloride buffer (pH 8.1) containing 10 mM potassium chloride and 1 mM edetic acid, 80 µL of the tissue preparation was incubated for 40 minutes at 37°C in a solution containing 1 mM nicotineamide adenine dinucleotide phosphate, 3 mM glucose-6-phosphate, 1 U/mL glucose-6-phosphate dehydrogenase, 100 µM L-kynurenine, 10 mM potassium chloride, and 1 mM edetic acid, in a total volume of 200 µL. Blanks were obtained by including the specific enzyme inhibitor Ro 61-8048 (100 µM; provided by W. Frostl, MD, Novartis AG, Basel, Switzerland) in the incubation solution. After centrifugation (16 000g for 15 minutes), 20 µL of the supernatant was applied to a 3-µm high-performance liquid chromatography column (HR-80; 80 x 4.6 mm; ESA Biosciences Inc, Chelmsford, Massachusetts), using a mobile phase consisting of 1.3% acetonitrile, 0.9% triethylamine, 0.39% phosphoric acid, 0.27 mM edetic acid, and 8.9 mM sodium heptane sulfonic acid and a flow rate of 1.0 mL/min. In the eluate, the reaction product, 3-hydroxykynurenine, was detected electrochemically using an HTEC 500 detector (Eicom Corporation, San Diego, California; oxidation potential, +0.5 V). The retention time of 3-hydroxykynurenine was approximately 11 minutes. The protein content of the samples was measured spectrophotometrically using the method developed by Lowry et al.

Genotyping

The SNP genotyping was performed on genomic DNA isolated with the QIAamp DNA Maxi Kit (Qiagen) from postmortem tissue for the gene expression association studies and from leukocytes obtained from the clinical sample for the endophenotype association studies. Context sequences and assay identification numbers of genotyped KMO SNPs are given in Table 3. For each PCR reaction, 2 ng of genomic DNA was used in a 5-µL reaction mixture (1.3 mM magnesium chloride, 200 µM deoxyribonucleotide mix, 0.25 µM of each primer, 5% dimethyl sulfoxide, and 1.5 U Taq polymerase). The PCR program included denaturation of DNA (5 minutes at 94°C), 30 cycles of 30 seconds at 94°C, 30 seconds at 62°C, and 30 seconds at 72°C. This sequence was followed by a final extension of 10 minutes at 72°C. All PCR reactions were performed using the Bio-rad Multiplatform Thermocycler, which has 4 blocks of 384 wells (Bio-Rad Laboratories Inc).
SNP Selection

We selected 2 KMO SNPs for analysis: 1 that results in a nonsynonymous change in KMO gene sequence (KMO rs1053230) and 1 (KMO rs2275163) that was previously reported to be associated with schizophrenia. Both SNPs have minor allele frequencies of 0.15 or more in European American and African American/mixed ethnicity populations (http://hapmap.ncbi.nlm.nih.gov/) (Table 4).

PHENOTYPIC MEASURES

Oculomotor Measures

Oculomotor measures were scored by investigators masked to the identity and group membership of study participants. Self-reported smokers were requested to refrain from smoking for at least 1 hour before testing.

Smooth Pursuit Eye Movement Task

In the smooth pursuit task, a target starts from a center fixation and moves back and forth across the screen. Participants were instructed to follow the moving target (velocity of 18.7° per second; amplitude, greater or less than 12°) across the computer monitor with their eyes. After 4 to 6 half-cycles, the target was unpredictably masked (ie, made invisible) for 500 milliseconds. Of the 25 trials presented, 15 had the masking appear at some point during a half-cycle and the rest at the change in ramp direction. Participants were instructed to follow the moving target even when it became briefly invisible. Pursuit gain was defined as the ratio of pursuit eye velocity to target velocity. Pursuit gain measures from the masked period from these 2 types of trials were averaged to obtain a measure of predictive pursuit gain. The scoring algorithm of the measures has been fully described elsewhere.

Oculomotor Delayed Response Task

In this task, participants fixated on a centrally located set of crosshairs. A target was flashed for 250 milliseconds between 2.5° and 10.0° to the left or right of the central fixation point. Participants continued to fixate until the fixation cross was turned off 10 seconds after the target was briefly shown. With this offset of the center crosshairs, participants were instructed to move their eyes to the location where the target had flashed. Feedback was provided by a small circle that appeared after 1.5 seconds, indicating where the target had flashed at the beginning of the trial. Absolute error in degrees was the primary dependent measure.

Table 4. SNP Genotyping

<table>
<thead>
<tr>
<th>Gene Symbol</th>
<th>Chromosome</th>
<th>ABI Assay No.</th>
<th>SNP</th>
<th>Function</th>
<th>RefSNP Alleles</th>
<th>MA</th>
<th>Context Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>KMO</td>
<td>1q42-q44</td>
<td>C_8856260_10</td>
<td>rs1053230</td>
<td>Nonsyn</td>
<td>A/G</td>
<td>A</td>
<td>CTACATGTCACGCGATTTTCTTCG/C/TGCTGAGAAGACCATGGAAGACTGGAAT</td>
</tr>
<tr>
<td>KMO</td>
<td>1q42-q44</td>
<td>C_16183814_10</td>
<td>rs2275163</td>
<td>Intron</td>
<td>C/T</td>
<td>T</td>
<td>CGAAACCTCATTAGAAGAAAGAAT/GTTGAATATTGCTGTGAGGAG</td>
</tr>
</tbody>
</table>

Abbreviations: ABI, Applied Biosystems Inc; MA, minor allele; Nonsyn, nonsynonymous; RefSNP Alleles, National Center for Biotechnology Information reference SNP alleles; SNP, single-nucleotide polymorphism.

aHaplotype-tagged SNP is based on a minor allele frequency of ≈0.15.
KMO mRNA EXPRESSION

Expression of KMO mRNA in the FEF was significantly reduced (~33%) in schizophrenia compared with control samples ($F_{(1,63)} = 8.59; P = .005$; Figure 2A). The mean (SD) KMO mRNA expression values observed in FEF tissue from 30 healthy controls and 30 SZ patients.

patients who had not been taking medications for 6 months or more before death (0.78 [0.47]; n=5) were not different from those in patients who had been taking medications at the time of death (0.94 [0.36]; n=27).

KMO ENZYME ACTIVITY

KMO activity was also significantly reduced (~30%) in schizophrenia compared with control FEFs ($F_{(1,6)} = 5.64; P = .02$; Figure 2A). The KMO gene expression and enzyme activity in the FEF were significantly correlated (Pearson correlation: combined group $r=0.66, P < .001$; within groups: schizophrenia, $r=0.43, P < .01$; and controls, $r=0.63, P < .001$; Figure 2B). The mean (SD) KMO activity in samples from patients who had not been taking medications for 6 months or more before death (15.70 [8.44] pmol/h per milligram of protein; n=5) was not different from that in patients who had been taking medications (15.62 [8.35] pmol/h per milligram of protein; n=27).

EFFECTS OF KMO SNPS ON KMO mRNA EXPRESSION IN FEF

KMO mRNA levels were slightly higher in schizophrenic samples carrying the rs2275163 minor allele (TT/CT) compared with the major allele homozygotes (ie, CC) (nominal $P = .05$; effect size = 0.61; Figure 3), although this difference did not achieve our threshold for statistical significance. No significant differences were found in expression levels between samples with and without the minor allele at rs1053230 ($P = .50$; effect size = 0.30). No significant genotype effect on KMO activity was found.

ENDOPHENOTYPE AND SNP ASSOCIATION STUDIES IN THE CLINICAL SAMPLE

Results of SNP genotyping were available for 286 of the 306 study participants who completed predictive pur-

Figure 2. KMO messenger RNA (mRNA) expression and kynurenine 3-monoxygenase (KMO) enzyme activity. A, Mean KMO mRNA expression and KMO enzyme activity in frontal eye field (FEF) tissues obtained post mortem from schizophrenia (SZ) patients and healthy control individuals. Both measures are significantly reduced in the FEF of SZ patients: *$P < .05$, †$P < .005$ (analysis of variance). Error bars indicate SD. B, Scatterplot of Pearson correlation ($r=0.66$) between KMO gene expression (RQ values, normalized to GAPDH) and KMO enzyme activity in FEF tissue from 30 healthy controls and 30 SZ patients.

Figure 3. Mean effects of kynurenine 3-monoxygenase (KMO) rs2275163 genotype groups on KMO gene expression (ie, relative quantitation values normalized to GAPDH) in postmortem frontal eye field (FEF) samples. KMO gene expression is compared between carriers of the minor allele (TT and CT) (black bars) and carriers that are homozygous for the major allele (CC) (gray bars) in control and schizophrenia FEF tissue specimens: *$P < .05$, †$P < .005$, nominal (analysis of variance). Error bars indicate SD. TT and CT: control specimens; n=18, schizophrenia specimens: n=17; CC: control specimens: n=14, schizophrenia specimens: n=15.
suit testing and for all 156 study participants who completed ODR testing to measure visuospatial working memory (Table 2 and Figure 4). The KMO rs2275163 genotype was significantly associated with predictive pursuit in the combined group of patients and controls ($F_{2,270}=4.32$; corrected $P<.05$). Post hoc comparisons showed lower predictive pursuit in individuals with the CC genotype (mean [SD], 0.47 [0.13]; $n=157$) compared with those with the CT genotype (0.53 [0.15]; $n=105$; $P<.001$; effect size=0.46) and no difference regarding those with TT genotypes (0.51 [0.15]; $n=24$; effect size=0.31; Figure 4A). The SNP rs2275163 also was associated with ODR performance ($F_{2,10}=3.78$; corrected $P<.05$), with post hoc comparisons revealing more visuospatial errors in participants with the CC genotype (2.46° [1.65°]; $n=84$) than in those with the CT genotype (1.77° [0.78°]; $n=60$; $P<.009$; effect size=0.47; Figure 4B) but not different from those with TT genotypes (1.99° [2.46°]; $n=12$; effect size=0.28).

No association was found between rs2275163 and the diagnosis of schizophrenia ($P=.62$). Subanalyses based on poor and good predictive pursuit in patients revealed that schizophrenia patients who had poor predictive pursuit ($n=53$) were less likely to be minor allele carriers than were healthy controls ($n=126$) (25.0% vs 50.0%; $P=.03$). In contrast, the proportion of schizophrenia patients who had good predictive pursuit and were minor allele carriers was virtually identical to the proportion of controls with those qualities (49% vs 50%). Age did not differ significantly ($P=.70$) between healthy controls (43.0 [14.0] years) and schizophrenia individuals who had poor eye tracking (44.3 [11.3] years).

**NEUROLEPTIC EXPOSURE**

Neuroleptic medication dosing in schizophrenia patients was converted to chlorpromazine equivalent doses, as previously described.73-75 The mean chlorpromazine equivalents for schizophrenia with good eye-tracking performance (760.3 [448.2] mg; $n=114$) were not significantly different ($P=.14$) from schizophrenia with poor eye-tracking performance (819.6 [410.2] mg; $n=53$).

The present study provides the first demonstration, to our knowledge, of reduced KMO gene expression in postmortem cortical samples from schizophrenia patients. Moreover, the correlated reduction of KMO gene expression and KMO activity in FEF samples from schizophrenia patients shown here complements the recent report by some of us70 of significantly decreased KMO activity in the prefrontal cortex of patients and preliminary observation77 of a similar reduction in enzyme activity in the basal ganglia. For several reasons, the differences between patients and controls reported here are unlikely to be artifacts of antemortem antipsychotic medication exposure. First, similar KMO gene expression and KMO enzyme activity were observed in the FEF of schizophrenia patients who had not been taking medications for 6 or more months before death. Second, long-term (ie, 28-day) treatment of rats with risperidone does not affect cortical KMO gene expression (I. Wonodi, K.V. Satha-saikumar, and R. Schwarcz, unpublished data, available on request from the authors) or KMO enzyme activity.78 Moreover, in postmortem brain studies of schizophrenia patients, total RNA quality rather than exposure to antipsychotic drugs was identified as the most critical factor affecting gene expression.79 and the RNA quality of the tissues used was high (RIN $\geq 6.0$; Table 1).82 Finally, although an effect of excessive nicotine exposure due to the high prevalence of smoking in schizophrenia patients80-82 cannot be discounted categorically, it is notable that no effect on KMO gene expression was found in a study83 in which differential expression of more than 200 genes was observed in schizophrenia smokers compared with schizophrenia nonsmokers.

In functional terms, our data suggest that KP flux toward 3-hydroxykynurenine and quinolinic acid might be compromised in several brain regions and possibly throughout the brain of schizophrenia individuals. This implies that the substrate of KMO (ie, kynurenine) might eventually accumulate in hyperphysiologic concentrations, resulting in a shift toward enhanced KYNA formation (Figure 1). Notably, elevations in brain kynuren-
ine and secondary increases in KYNA formation may be accentuated further by increased synthesis of the metabolite in the brain and/or increased kynurenine influx from the circulation secondary to peripheral KP activation.3,32-34,85 Of particular relevance to schizophrenia, redirected cortical KP metabolism toward increased KYNA production is positioned to play a critical role in NMDAR and α7nAChR hypofunction, which are presumed to be causally related to cognitive deficits in the disease (Figure 1).14-21 We are currently in the process of examining KYNA and several other KP metabolites and enzymes as part of a comprehensive follow-up study.

Our SNP association analyses revealed that the KMO CC genotype was associated with neurocognitive endophenotypic deficits (ie, in predictive pursuit and visuospatial working memory) in the clinical sample and revealed a trend toward reduced KMO mRNA expression in FEF tissue from schizophrenia patients in the postmortem sample. Although no significant difference was observed in CC genotype frequencies between healthy controls and the total sample of schizophrenia patients, patients with good predictive pursuit had similar proportions of the CC genotype as controls. Differences only emerged when CC genotype frequencies were compared between healthy controls and schizophrenia patients who displayed poor eye tracking. These results merit further exploration. For example, in a genetic background that includes KMO risk variants, additional environmental and/or genetic “hits” could lead to increased cortical KYNA levels and KYNA-related cognitive impairments. We also note that in a previous study86 that examined a Japanese sample, the CC genotype was nominally less frequent in schizophrenia.

The mechanism by which KMO rs2275163, which maps to intron 9 of the KMO gene, might affect KMO gene expression is unclear. Because it is neither a nonsynonymous coding nor a promoter SNP,85 our findings might indicate susceptibility mutation(s) in linkage disequilibrium with KMO rs2275163 or multiple functional rare variants in synthetic association with the KMO CC genotype.86,87 Extensive molecular characterization, including gene resequencing, is currently underway and may identify the putative causative variant(s) captured by the SNP association in this study. Alternatively, KMO rs2275163 might influence KMO function by posttranscriptional and posttranslational modifications possibly involving micro-RNAs (miRNAs). The latter provides a particularly plausible mechanism because 50% of miRNA genes are located in intronic regions of protein-coding genes and control gene expression posttranscriptionally by regulating mRNA translation or stability via interactions with the 3’ UTRs of the mRNAs. So far, however, no miRNAs from the KMO genomic region have been deposited in the miRBase database for chromosome 1 (www.mirbase.org).86

In summary, the present study provides the first evidence of a significantly correlated reduction in KMO gene expression and KMO enzyme activity in postmortem tissue from schizophrenia patients obtained from a cortical region associated with SPEMs and KMO variation affecting predictive pursuit eye movements in a clinical schizophrenia sample. Although the results from our clinical population could provide a plausible explanation for the failure of Aoyama and colleagues36 to replicate a KMO SNP association with schizophrenia, our results also could be explained by ascertainment strategies and/or cryptic population stratification across samples. More generally, our data support the concept that schizophrenia-related endophenotypes could be used to dissect the effects of susceptibility genes of small effect.30,36-39 It follows that extreme-trait designed studies87 focusing on subgroups identified by endophenotypic markers might help resolve inconsistencies across genetic data sets. Therefore, future studies probing the complex interactions between molecular genetic and specific neurochemical perturbations using endophenotypes may advance our understanding of the etiopathophysiology of schizophrenia. This, in turn, could facilitate the development of novel, targeted treatments for cognitive deficits in schizophrenia and possibly in other neuropsychiatric diseases.

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