The effect of the DISC1 Ser704Cys polymorphism on striatal dopamine synthesis capacity: an [18F]-DOPA PET study

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Abstract

Whilst the role of the Disrupted-in-Schizophrenia 1 (DISC1) gene in the aetiology of major mental illnesses is debated, the characterization of its function lends it credibility as a candidate. A key aspect of this functional characterization is the...
Introduction

The dopamine hypothesis has been a leading theory underlying the neurobiology of schizophrenia for the last four decades (1,2). The hypothesis was initially based on evidence showing that antipsychotic medications block dopamine receptors (3-5) and that drugs increasing dopamine levels elicit psychotic symptoms in healthy people (6-8) and people with schizophrenia (9,10). Using [18F] fluoro-3,4-dihydroxyphenyl-L-alanine (F-DOPA) positron emission tomography (PET), increased presynaptic dopamine synthesis capacity has been found in schizophrenia (11), people with prodromal psychotic symptoms (12,13) and those with clinical progression to psychosis (14). Whilst a substantial body of evidence supports the role of increased presynaptic dopamine synthesis capacity in the patho-aetiology of psychosis, little is known about how genetic factors affect the implicated dopamine system(8) (15).

The Disrupted-in-Schizophrenia 1 (DISC1) gene was originally discovered at the breakpoint of a balanced t(1;11) (q42; q14.3) translocation in a Scottish family with a high prevalence of psychiatric disorders including schizophrenia (16-18). Further evidence for a link between DISC1 and psychotic and affective disorders emerged from the follow-up of families displaying rare DISC1 mutations (19,20) and large family-based studies in the population isolate of Finland (21-23) although a large meta-analysis of families did not observe linkage at this region (24). Furthermore, evidence from individual population-based cohorts has been inconsistent (25,26) leading to ongoing debate on its involvement in schizophrenia (27,28). Whilst this controversy remains unresolved, there is value in seeking convergent evidence via studies elucidating the functional impact of the gene and its variations (29-32). DISC1 is a scaffold protein involved in a wide range of neuronal functions including neuro-signalling (30,33). Preclinical studies show that DISC1 variant models exhibit increased amphetamine-induced dopamine release in the ventral striatum [see (34-37) reviewed in (38)], indicating that DISC1 variations might affect presynaptic dopamine synthesis capacity.

One of the most studied DISC1 single-nucleotide polymorphisms (SNPs) is rs821616 which is a non-synonymous mutation leading to the translation of a serine (ser) (A allele) or a cysteine (cys) (T allele) at codon 704 in exon 11 (39). Importantly, this polymorphism represents therefore not only a variation at the genetic sequence level but also at the protein sequence level of DISC1. At a molecular level, Hashimoto et al. (47) found that overexpression of the ser variant of codon 704 by viral transduction resulted in a significant increase in phosphorylated Extracellular signal-regulated protein Kinases 1 and 2 (ERK1/2), the more biologically active form (40). ERK1/2 in turn regulates the state of phosphorylation of tyrosine hydroxylase, the rate-limiting enzyme for dopamine biosynthesis, to increase its activity and subsequent dopamine synthesis by up to 2-fold (41-44). Dopamine is synthesized by converting first tyrosine into dihydroxyphenyl-L-alanine (L-DOPA) by tyrosine hydroxylase, and second dihydroxyphenyl-L-alanine (L-DOPA) into dopamine by aromatic acid decarboxylase (AADC) (45). [18F]-DOPA PET signal reflects AADC function and dopamine storage capacity (45), but not directly tyrosine hydroxylase function. However, it should be noted that (i) tyrosine hydroxylase is the rate limiting step for dopamine synthesis capacity (43) and (ii) the topological distribution of the [18F]-DOPA signal correlates highly with tyrosine hydroxylase immunostaining in unilaterally 6-hydroxydopamine (6-OHDA)-lesioned rats, thus indicating that the [18F]-DOPA signal is strongly influenced by endogenous dopamine formed by tyrosine hydroxylase (46).

In summary, preclinical findings suggest that the Ser704Cys variation affects dopamine synthesis by regulating ERK1/2 and its control over tyrosine hydroxylase activity. However, it remains unknown whether the Ser704Cys variation is associated with altered dopamine synthesis in humans. The aim of this study was therefore to test the hypothesis that ser homozygotes would exhibit increased striatal dopamine synthesis capacity relative to cys homozygotes and heterozygotes.

Results

Demographics, scan parameters including the injected dose and substance use characteristics are shown in Table 1. A total of 46 ser homozygotes and 56 cys homozygotes and heterozygotes (which encompass 45 heterozygotes and 11 cys homozygotes) were included in the study. The genotype frequencies (shown in Table 1) did not significantly deviate from Hardy-Weinberg equilibrium ($\chi^2 = 1.422$ with $P = 0.233$), with a Minor Allele Frequency (T allele) of 0.335. Age (year) and $K_{\text{Dop}}$ (1 min $^{-1}$) in the striatum were normally distributed across the two groups whereas injected dose (MBq) was not. There was no significant difference in age between groups $t(100) = 1.588$, $P = 0.115$ (independent t test) and no significant difference in injected dose $P = 0.408$ (Mann-Whitney U test). Levene’s test indicated no difference between the variances in the two groups, $F = 0.398$, $P = 0.529$. The univariate analysis of covariance (ANCOVA) showed that the main effect of the DISC1 SNP rs821616 on the dopamine synthesis capacity in the striatum was significant, $F(1, 96) = 6.555$, $P = 0.012$, partial $\eta^2 = 0.064$ (Fig. 1). The effects of...
and heterozygotes significantly increased in ser homozygotes compared with cys homozygotes and heterozygotes (AT or TT genotypes) and no association found (25) mainly in the American (49) and Chinese Han (50–52). Inconsistencies have been found, with some studies indicating increased risk associated with the ser (A) allele (48,51), whilst others the cys (T) allele (50,52) and no association found (25) mainly in the Japanese population (53–55). A recent meta-analysis has also reported association of the ser allele with schizophrenia in Chinese (OR = 1.338) and Japanese populations (OR = 1.524), as well as in the overall mixed race sample (56). The inconsistences in these results might be owing to different ethnic populations. It should be noted that ever expanding studies of schizophrenia with an odds ratio in the range of 1.3–4.18 in various populations including European (48), mixed European/African-American (49) and Chinese Han (50–52). Inconsistencies have been found, with some studies indicating increased risk associated with the ser (A) allele (48,51), whilst others the cys (T) allele (50,52) and no association found (25) mainly in the Japanese population (53–55). A recent meta-analysis has also reported association of the ser allele with schizophrenia in Chinese (OR = 1.338) and Japanese populations (OR = 1.524), as well as in the overall mixed race sample (56). The inconsistences in these results might be owing to different ethnic populations.

Moreover, the effect of the Ser704Cys polymorphism remained significant when we only included subjects from PET scanner 2 [F(1, 28) = 5.273, P = 0.029 (N = 16 cys homozygotes and heterozygotes, N = 17 ser homozygotes)], but not PET scanner 1 only [F(1, 30) = 0.766, P = 0.388 (N = 19 cys homozygotes and heterozygotes, N = 16 ser homozygotes)] and PET scanner 3 only [F(1, 29) = 0.426, P = 0.519 (N = 21 cys homozygotes and heterozygotes, N = 13 ser homozygotes)]. It is important to recognize that we measured the final step in the synthesis of dopamine, the conversion of l-DOPA into dopamine via AADC. However, the parameter measured could be affected by other variables including the uptake of l-DOPA into the brain, although this should be controlled for by the reference region and there is no a priori reason to consider that this should be affected by the DISC1 protein. Importantly, this polymorphism was chosen based on a specific prior hypothesis. Although there was evidence to reject the null hypothesis, the P-value would not survive genome-wide correction and therefore the result requires replication.

Implications for mental disorders

The Ser704Cys polymorphism has been associated with schizophrenia with an odds ratio in the range of 1.3–4.18 in various populations including European (48), mixed European/African-American (49) and Chinese Han (50–52). Inconsistencies have been found, with some studies indicating increased risk associated with the ser (A) allele (48,51), whilst others the cys (T) allele (50,52) and no association found (25) mainly in the Japanese population (53–55). A recent meta-analysis has also reported association of the ser allele with schizophrenia in Chinese (OR = 1.338) and Japanese populations (OR = 1.524), as well as in the overall mixed race sample (56). The inconsistences in these results might be owing to different ethnic populations. It should be noted that ever expanding studies of European ancestry population level genetic variants in schizophrenia continually demonstrate no significant associations at the entire DISC1 locus (57,58), although there is evidence implicating the DISC1 interactor phosphodiesterase 4B as a

Table 1. Sample characteristics and scan parameters

<table>
<thead>
<tr>
<th>DISC1 SNP rs821616</th>
<th>Total genotype counts</th>
<th>Cysteine homozygotes and heterozygotes</th>
<th>Serine homozygotes</th>
<th>P value</th>
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<tr>
<td>Total</td>
<td>102</td>
<td>45 (AT) and 11 (TT)</td>
<td>46 (AA)</td>
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<tr>
<td>Females</td>
<td>46</td>
<td>21</td>
<td>16</td>
<td>0.549*</td>
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<td>35</td>
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<td>16</td>
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<td>33</td>
<td>16</td>
<td>17</td>
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<tr>
<td>PET scanner 3</td>
<td>34</td>
<td>21</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>30.2 (9.3)</td>
<td>31.5 (9.9)</td>
<td>28.6 (8.4)</td>
<td>0.113**</td>
</tr>
<tr>
<td>Tobacco smoking status (non-smoker)</td>
<td>75</td>
<td>43</td>
<td>32</td>
<td>0.411*</td>
</tr>
<tr>
<td>Tobacco smoking status (smoker)</td>
<td>27</td>
<td>13</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Radioactivity injected (MBq)</td>
<td>157.7 (16.2)</td>
<td>156.6 (16.2)</td>
<td>159.2 (16.4)</td>
<td>0.529*</td>
</tr>
<tr>
<td>White European</td>
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<td>35</td>
<td>0.503*</td>
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<td>2</td>
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<tr>
<td>Mixed ethnicity</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

All data ± SD.

*Pearson Chi-Square.

Independent t test.

Mann–Whitney U test.

Figure 1. Mean (SEM) striatal dopamine synthesis capacity (Ki value, min⁻¹) in DISC1 rs821616 cys homozygotes and heterozygotes (TT and TA, N = 56) and DISC1 rs821616 ser homozygotes (AA, N = 46). Dopamine synthesis capacity was significantly increased in ser homozygotes compared with cys homozygotes and heterozygotes [F(1, 96) = 6.555, P = 0.012].

Discussion

In line with our hypothesis, we found that participants ser homozygotes (AA genotype) for the Ser704Cys functional DISC1 polymorphism exhibited a significantly greater Ki value in the striatum, indicating greater dopamine synthesis capacity compared with cys homozygotes and heterozygotes (AT or TT genotype). This result is in accordance with preclinical evidence showing that the ser 704 DISC1 variant increases the activity of ERK1/2, which in turn enhances the phosphorylation of tyrosine hydroxylase, the rate limiting step in dopamine synthesis (41,47).

Limitations

The main limitation of this study was that we used data from three different PET scanners, which could add error variance. However, scanner was included as a covariate to adjust for this.
genome-wide significant single gene locus in a recent large schizophrenia genome-wide association study (GWAS) (58). Whilst GWAS have made crucial advances in the understanding of the genetic of schizophrenia, the biological mechanisms directly underlying the disorder remain yet poorly elucidated (59–61). In this context, the DISC1 protein has been suggested as a biological candidate of interest for investigating molecular mechanisms of mental illnesses at the protein levels (33,62). Beyond studies of dichotomous diagnoses, the ser allele has also been associated with increased risk for poor concentration among Korean patients with schizophrenia (63), increased severity of positive symptoms and hallucinations in European patients with First-Episode Psychosis (64) and increased lifetime severity of delusions in European patients with schizophrenia (65). A potential mechanism for the increased risk could be by dysregulating the control of dopamine to lead to increased dopamine synthesis. Findings in prodromal populations show that increased dopamine synthesis is associated with increased risk for psychosis (12,13). The difference in dopamine synthesis capacity we observe here between ser homozygotes and carriers of the alternative allele is much smaller than the differences seen in at risk subjects (14,66). It is therefore likely that the Ser704Cys variant interacts with other genetic changes to mediate risk, potentially by affecting dopamine synthesis.

The fact that the common ser allele has been described as the risk allele is compatible with schizophrenia GWAS, in which ~50% of the implicated index SNPs are the more common alleles (67). At the population level, the genetic susceptibility to schizophrenia is caused by a few rare variants of high penetrance (mainly copy number variants and translocations) and many common variants of small penetrance (SNPs and variable number of tandem repeats) (68). As each SNP very minimally impacts schizophrenia risk and is compatible with modern models of natural selection (67), it is expected that other genetic factors are needed, in the same individual, to increase the liability to a point of schizophrenia onset. For example, the Ser704Cys site affects interaction with nuclear distribution element-like 1 (NDEL1) and its homolog Nuclear Distribution Element 1 (NDE1, also known as NudE) (69,70), and there is evidence for an interaction between NDE1 rs1391768 and the Ser704 allele and the NDE1 rs3784859 and the Cys704 allele on the risk for schizophrenia in European participants (71). Ser704Cys is also the binding site for proteins such as kendrin (also known as pericentrin (PCNT)) and Pericentriolar material 1 (72), which have been both described as risk factor genes for schizophrenia (73). Furthermore, environmental factors such as exposure to psychosocial stress may also interact with the Ser704Cys polymorphism to affect dopamine function and mediate risk for schizophrenia (15). Interestingly, using a transgenic expression of truncated human Disc1 protein with dominant-negative effect, Niwa et al. have shown that an interaction between DISC1 and stress exposure, as a 3-week social isolation paradigm, increased dopamine release after amphetamine challenge (34) and induced alterations in DNA methylation of the tyrosine hydroxylase gene (74).

Evidence also suggests that the Ser704Cys polymorphism is a risk factor for affective disorders. The cys allele has been associated with major depression in Japanese population (47), and shown to form a protective haplotype for bipolar spectrum disorder with two others DISC1 SNPs (rs1411771 and rs980989) in Finnish population (75), whereas a higher ser allele rate has been found in South Indian population with bipolar disorder (76). Interestingly, increased dopamine synthesis capacity is seen in both mania (77) and bipolar psychosis (78), whilst major depression with affective flattening is characterized by a decreased synthesis capacity (79,80).

The Ser704Cys SNP has also been shown to have a functional impact at the brain level (39). Compared with healthy cys homozygotes and heterozygotes, ser homozygotes display increased (for the same level of performance, thus putatively inefficient) prefrontal cortex activation in the left middle and left superior frontal gyri and in the homologous right superior frontal gyrus, the left inferior frontal and cingulate cortex, the thalamus and the caudate nucleus in a verbal fluency task (81), as well as an effect on thalamic prefrontal connectivity (82). Ser704Cys SNP has also been shown to affect activation during declarative memory task with inconsistent findings. Callicott et al. (48) found decreased activation bilaterally in the hippocampal formation during a declarative memory task and increased activation bilaterally in the hippocampal formation in an N-back task in ser704 homozygotes controls compared with cys homozygotes and heterozygotes, whereas Di Giorgio et al. (83) found increased hippocampal formation/dorsolateral prefrontal cortex coupling during memory encoding in a declarative memory task in ser homozygotes compared with healthy cys homozygotes and heterozygotes.

In summary, our results provide unprecedented preliminary evidence that DISC1 Ser704Cys has an impact on the dopamine synthesis capacity, in a large sample of 102 healthy volunteers. Further studies should aim at (i) replicating this result in different cohorts; (ii) investigating potential epistatic interactions with DISC1 and other risk genes. Genetic studies based on molecular evidence could help identify the molecular mechanism that underlies the patho- etiology of dopamine-related disorders such as psychotic disorders, and help identify novel potential treatment targets (15).

**Conclusion**

We found that the ser allele of DISC1 Ser704Cys (rs821616) was associated with significantly higher striatal dopamine synthesis capacity, consistently with its previous association with heightened activation of ERK1/2 that stimulates tyrosine hydroxylase activity for dopamine synthesis. This implicates the DISC1 polymorphism in altering a psychosis relevant mechanism in the brain, i.e. the facilitation of greater dopamine synthesis capacity. Although, this effect of rs821616 may be of too small effect to be identified in population-based studies of end state diagnoses at their current large size, it continues to implicate the functional role of DISC1. Firstly by highlighting the role of this polymorphism at this gene in creating variation within the normal functioning of the brain, but also by indicating this function as a potential mechanism through which other rare or familial mutations for major mental illnesses could disrupt functioning and increase risk to these devastating disorders.

**Materials and Methods**

**Overview**

All participants gave informed written consent to take part after full description of the study. All studies were approved by the institutional review board and the local research ethics committee.
Participants
Participants were recruited via advertisement in local media based in London. One hundred and twenty-three participants underwent a $[^{18}F]-$DOPA PET scan. For all participants the inclusion criteria were (i) age above 18 years; (ii) capacity to give written informed consent. The exclusion criteria were (i) any current medical conditions or history of medical condition (past minor self-limiting conditions were permitted); (ii) history of a psychiatric disorder as determined by the Structured Clinical Interview for DSM-IV Axis 1 Disorders, Clinician Version (SCID-CV) (84); (iii) history of substance abuse/dependence as determined by the Structured Clinical Interview for DSM-IV Axis 1 Disorders, Clinician Version (SCID-CV) (84); (iv) history of head injury with a loss of consciousness; (v) a family history of any psychotic disorder in first- or second-degree relatives; (vi) contraindications to PET scanning (significant prior exposure to radiation, pregnancy or breast feeding). All participants provided urine samples prior to the scan to screen for drug use and pregnancy test in women. Six participants were excluded owing to positive urine THC screening, 12 participants were excluded to contamination of samples and 3 participants were excluded owing to current psychotropic medication use. This resulted in the final inclusion of 102 participants (46 females/56 males, age: 30.2 ± 9.3 years, mean ± Standard Deviation). Both scanning and imaging analysis were done blind to the genotype status.

$[^{18}F]$-FDOPA PET
PET scanner 1 was an ECAT HR+ 962 PET scanner (CTI/Siemens, Knoxville, TN, USA). The dynamic images were acquired in 3D mode with an axial field of view of 15.5 cm and reconstructed using filterback projection. PET scanners 2 and 3 were two Siemens Biograph HiRez XVI PET-CT scanner (Siemens Healthcare, Erlangen, Germany) at Imanova, Centre for Imaging Sciences. PET scanner 1 and PET scanner 2–3 were identical with the only exception of the axial field of view: 16.2 versus 21.6 cm, respectively. The dynamic images were also reconstructed using a 3D filtered back-projection algorithm (discrete inverse Fourier transform, DIFT) with a 128 matrix, a zoom of 2.6 and a 5 mm isotropic Gaussian smoothing. Participants were scanned at various times of the day. Some of the imaging data has been included in prior reports but not for genetic analysis (85–88). For attenuation and model-based scatter correction, a 10 min transmission scan was performed using a 150-MBq cesium-137 rotating point source for the ECAT HR+ 962 PET scanner and a computed tomography scan (effective dose = 0.36 mSv) for the Siemens Biograph HiRez XVI PET-CT scanners were acquired prior to each PET scan. Experimental protocol was consistent for all the participants (85). Participants were asked to fast and abstain from smoking from midnight on the day of the scan as tobacco use has been associated with increased striatal dopamine synthesis capacity (89) although this has not been replicated (88). Oral doses of carbidopa (150 mg) and entacapone (400 mg) were administrated 1 h before scan has not been replicated (85). Oral doses of carbidopa (150 mg) and entacapone (400 mg) were administrated 1 h before scan has not been replicated (85). For each PET/CT scan, the brain region of interest (ROI) was created on a coronal slice at the anterior commissure. The ROI was created using a curved line defined by the approximate level of the intercommissural point and anterior-posterior commissure. The ROI was normalized with respect to the transverse plane of the brain and the transverse plane of the head was aligned parallel to the transverse plane of the brain. A reference region using a graphical approach (95) and in the cerebellum using the probabilistic Martinez map (95). The cerebellum was used as a reference region as it is largely devoid of dopaminergic neurons or projections (85). A non-linear transformation procedure on SPM8 (http://www.fil.ion.ucl.ac.uk/spm) was used to normalize the ROI map together with the $[^{18}F]$-DOPA template to each individual PET summation image, in order to place the ROI automatically on individual $[^{18}F]$-DOPA PET dynamic images. Influx constant K\textsuperscript{str} value (min\textsuperscript{-1}) for the striatum was calculated relative to uptake in the reference region using a graphical approach (97), a method which has been shown to have good reliability (95).

Genetic analysis
DNA was extracted from blood or cheek swabs using standard methods (98). Genotyping of the rs821616 A>T SNP, was performed by KBioscience (Herts, UK, http://www.kbioscience.co.uk) using a competitive allele-specific polymerase chain reaction system. Quality control procedures included negative control (water) wells and duplicate wells.

Statistical analysis
The normality of the distribution for all variables was examined using the Shapiro–Wilk test, inspection of Q–Q plots and skewness and kurtosis values within range of ±2. Homogeneity of variance was assessed with Levene’s Test for Equality of Variances. An alpha threshold was set at 0.05 (two-tailed) for significance for all statistical comparisons. Statistical Package for the Social Sciences version 24 was used for all statistical analysis (IBM, Armonk, NY, USA). All data are shown as mean ± SD. An univariate ANCOVA was performed on 102 healthy controls, with the DISCI SNP Ser704Cys variation (ser homozygotes versus cys homozygotes and heterozygotes) as the independent variable, K\textsuperscript{str} in the striatum as the dependent variable and age, gender, ethnicity (Table 1) and the three PET scanners separately as covariates as these variables have been previously found to influence dopamine synthesis capacity (99,100). Effect sizes are reported as partial $r^2$. Independent t test
and Mann–Whitney U test were used to compare age and injected dose.

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