Fiber geometry in the corpus callosum in schizophrenia: Evidence for transcallosal misconnection

Thomas J. Whitford a,b,⁎,1, Peter Savadjiev a,d,1, Marek Kubicki a,c, Lauren J. O'Donnell d,e, Douglas P. Terry a, Sylvain Bouix a,c, Carl-Fredrik Westin d, Jason S. Schneiderman a, Laurel Bobrow a, Andrew C. Rausch a, Margaret Niznikiewicz c, Paul G. Nestor c,f, Christos Pantelis b, Stephen J. Wood b,g, Robert W. McCarley c, Martha E. Shenton a,c

a Psychiatry Neuroimaging Laboratory, Department of Psychiatry, Brigham and Women’s Hospital, Harvard Medical School, Boston, MA, USA
b Psychiatry Neuroimaging Laboratory, Department of Psychiatry, Brigham and Women’s Hospital, Harvard Medical School, Boston, MA, USA
c Melbourne Neuropsychiatry Centre, Department of Psychiatry, University of Melbourne and Melbourne Health, Melbourne, VIC, Australia
d Clinical Neuroscience Division, Laboratory of Neuroscience, Department of Psychiatry, Veterans Affairs (VA) Boston Healthcare System, Harvard Medical School Brockton, MA, USA
e Laboratory of Mathematics in Imaging, Brigham and Women’s Hospital, Harvard Medical School, Boston, MA, USA
f Golby Laboratory, Department of Neurosurgery, Brigham and Women’s Hospital, Harvard Medical School, Boston, MA, USA
g School of Psychology, University of Birmingham, UK

A R T I C L E   I N F O

Article history:
Received 30 November 2010
Received in revised form 5 July 2011
Accepted 9 July 2011
Available online 9 August 2011

Keywords:
Callosal
Diffusion-Tensor Imaging
Neurodevelopment
Morphometry
White-matter
Genu

A B S T R A C T

Background: Structural abnormalities in the callosal fibers connecting the heteromodal association areas of the prefrontal and temporoparietal cortices bilaterally have been suggested to play a role in the etiology of schizophrenia.

Aims: To investigate for geometric abnormalities in these callosal fibers in schizophrenia patients by using a novel Diffusion-Tensor Imaging (DTI) metric of fiber geometry named Shape-Normalized Dispersion (SHD).

Methods: DTIs (3T, 51 gradient directions, 1.7 mm isotropic voxels) were acquired from 26 schizophrenia patients and 23 matched healthy controls. The prefrontal and temporoparietal callosal fibers were extracted by means of whole-brain tractography, and their mean SHD calculated.

Results: The schizophrenia patients exhibited subnormal levels of SHD in the prefrontal callosal fibers when controlling for between-group differences in Fractional Anisotropy. Reduced SHD could reflect either irregularly turbulent or inhomogeneously distributed fiber trajectories in the corpus callosum.

Conclusions: The results suggest that the transcallosal misconnectivity thought to be associated with schizophrenia could reflect abnormalities in fiber geometry. These abnormalities in fiber geometry could potentially be underpinned by neurodevelopmental irregularities.

© 2011 Elsevier B.V. All rights reserved.

1. Introduction

Abnormalities in transcallosal connectivity have been suggested to play an etiological role in the development of schizophrenia (Crow et al., 1989; Crow, 1997; Crow, 1998; Highley et al., 1999; DeLisi, 2001). The callosal fibers connecting the language centers of the prefrontal and temporoparietal cortices bilaterally have been specifically implicated (Crow, 2000; DeLisi, 2001), which is consistent with theories that emphasize the role of pathology in the heteromodal association cortex in the etiology of schizophrenia (Pearson et al., 1996; Ross and Pearson, 1996). In support of this hypothesis, several studies have inferred the existence of structural abnormalities in the corpus callosum in schizophrenia patients, in vivo, with Diffusion-Tensor Imaging (DTI) (Kanaan et al., 2005; Kubicki et al., 2007; Bora et al., 2011). However, while the physiological bases of these white matter abnormalities are unclear and likely reflect a combination of factors, including myelin damage, damage to the axon membrane and abnormal axonal packing density (Beaulieu, 2002; Kubicki et al., 2007; Whitford et al., 2011b), abnormalities in fiber geometry may also be a factor (Buchbaum et al., 2006; Savadjiev et al., 2010). In order to test, in vivo with DTI, whether patients with schizophrenia have abnormalities in callosal fiber geometry, it is necessary to use an index that is sensitive to geometric variations in the patterns of diffusion exhibited by a neighborhood of voxels, as opposed to an index that is sensitive only to the diffusion properties exhibited by a given voxel. However, while several studies have used such voxel-based indices as Fractional Anisotropy (FA) and Mean Diffusivity to identify abnormalities in the corpus callosum in patients with schizophrenia (Mitelman et al., 2007; Shergill et al., 2007;...
Low IQ scores, as assessed by performance on the Reading scale of the Wide Range Achievement Test (WRAT-3) (Wilkinson, 1993). The demographic details and exclusion criteria for all participants are summarized in Table 1. After a detailed description of the study, each participant gave written informed consent to participate. This study was approved by the Hospital Human Participants Committee, and the Brigham and Women's Hospital Internal Review Board Committee, and the Internal Review Board Committee of the VA Boston Healthcare System, Brockton, MA. Diagnosis of schizophrenia was made in accordance with DSM-IV criteria on the Structured Clinical Interview for DSM-IV, conducted by a clinically and research-trained psychologist, together with a review of the medical record. At the time of scanning, 23 of the 26 patients were taking neuroleptic medications (see Table 1). Patients’ medication dosages were converted into a common chlorpromazine-equivalent CPZ-equivalent (mg/day). The exclusion criteria were: a history of neurological illness including epilepsy, a lifetime history of substance dependence or a history of substance abuse within the past 5 years, a history of steroid use, a history of electroconvulsive shock therapy, and estimated premorbid IQ below 75. Furthermore, control participants were screened for the presence of an Axis-I disorder using the SCID-Non-Patient edition, and were also excluded if they reported having a first-degree relative with an Axis I disorder.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Healthy Controls (n=23)</th>
<th>Schizophrenia Patients (n=26)</th>
<th>HC vs. SZ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean          SD     Range</td>
<td>Mean         SD    Range</td>
<td>p-value</td>
</tr>
<tr>
<td>Age (years)</td>
<td>42.46 (SD 10.3) (22–55)</td>
<td>44.0 (SD 9.7) (22–55)</td>
<td>p=.59</td>
</tr>
<tr>
<td>Handedness1</td>
<td>0.75 (SD 0.19) (.41–1.00)</td>
<td>0.73 (SD 0.25) (.25–1.00)</td>
<td>p=.76</td>
</tr>
<tr>
<td>Gender</td>
<td>100% male</td>
<td>100% male</td>
<td>–</td>
</tr>
<tr>
<td>Education (years)</td>
<td>14.89 (SD 1.9) (12–19)</td>
<td>13.13 (SD 1.8) (9–18)</td>
<td>p&lt;.001</td>
</tr>
<tr>
<td>Parental SES2</td>
<td>2.39 (SD 1.2) (1–5)</td>
<td>2.54 (SD 1.1) (1–4)</td>
<td>p=.68</td>
</tr>
<tr>
<td>Premorbid IQ3</td>
<td>104 (SD 11) (77–117)</td>
<td>99 (SD 12) (81–118)</td>
<td>p=.18</td>
</tr>
<tr>
<td>PANS-S-Positive</td>
<td>–</td>
<td>20.75 (SD 9.17) (7–41)</td>
<td>–</td>
</tr>
<tr>
<td>PANS-S-Negative</td>
<td>–</td>
<td>20.13 (SD 10.14) (7–43)</td>
<td>–</td>
</tr>
<tr>
<td>Neuroleptic dosage4</td>
<td>–</td>
<td>341 (SD 269) (0–900)</td>
<td>–</td>
</tr>
<tr>
<td>Duration of illness (years)</td>
<td>–</td>
<td>20.08 (SD 10.35) (3–34)</td>
<td>–</td>
</tr>
<tr>
<td>Neuroropic Class</td>
<td>–</td>
<td>Typical n=21; Atypical n=19</td>
<td>Both Typical and Atypical n=2; Unmedicated: n=3</td>
</tr>
</tbody>
</table>

Rotarska-Jagiela et al., 2008; Gasparotti et al., 2009; Whitford et al., 2010a), very few studies have used neighborhood-based DTI indices to investigate for abnormalities in fiber geometry in these patients. Furthermore, the few neighborhood-based DTI indices that do exist, such as Inter-Voxel Coherence (Pierpaoli and Basser, 1996), are limited in the degree to which they can distinguish between alternative geometric patterns. Inter-Voxel Coherence cannot, for example, distinguish between the two markedly different geometric scenarios presented in Fig. 1A and B, as it calculates the average degree of collinearity between the diffusion tensor of a reference voxel (i.e., the central voxel) and the adjacent voxels, which is the same in both cases given that the peripheral tensors in Fig. 1B are simply shuffled from the peripheral tensors in Fig. 1A.

In light of the shortcomings of the existing indices of fiber geometry, the present study used a new index of fiber geometry dubbed Shape Normalized Dispersion (SHD). As has been discussed previously (Savadjiev et al., 2010), SHD is more sensitive to variations in fiber geometry, and is more specific as to their ontology, than previously used metrics such as Inter-Voxel Coherence. SHD is a scalar measure of local white matter geometry that is based on a mathematical framework that computes local variation in tensor orientation. Grossly speaking, SHD is a measure of the degree to which fibers locally deviate from being parallel. As SHD is based on diffusion tensor field derivatives, it incorporates information from the local voxel neighborhood, and is sensitive to geometric differences between patterns of tensor orientations within a voxel neighborhood, such as between the patterns illustrated in Fig. 1.

In summary, the present study aimed to use the novel diffusion metric of SHD to test whether schizophrenia patients exhibited geometric abnormalities in the callosal fibers connecting the heteromodal association areas of the prefrontal and temporoparietal cortices bilaterally.

2. Materials and methods

2.1. Participants

Twenty-six male patients with chronic schizophrenia were recruited from out-patient, in-patient, day treatment, and foster care programs at the VA Boston Healthcare System, Brockton, MA. Diagnosis of schizophrenia was made in accordance with DSM-IV criteria on the basis of the Structured Clinical Interview for DSM-IV, conducted by a clinically and research-trained psychologist, together with a review of the medical record. At the time of scanning, 23 of the 26 patients were taking neuroleptic medications (see Table 1). Patients’ medication dosages were converted into a common chlorpromazine-equivalent CPZ-equivalent based scale for the purposes of comparison (Woods, 2003). The severity of patients’ clinical symptoms was quantified with the Positive and Negative Symptom Scale (PANSS) (Kay et al., 1987), which was administered by a trained clinical psychologist (PN).

Twenty-three male healthy control participants were recruited from the general community. The control participants were group matched to the patients on age, handedness (Oldfield, 1971), parental socioeconomic status (Hollingshead, 1965), and estimated premorbid IQ, as assessed by performance on the Reading scale of Wide Range Achievement Test (WRAT-3) (Wilkinson, 1993). The demographic details and exclusion criteria for all participants are summarized in Table 1. After a detailed description of the study, each participant gave written informed consent to participate. This study was approved by the VA Boston Healthcare System, the Harvard Medical School Internal Review Board Committee, and the Brigham and Women’s Hospital Human Participants Committee.
2.2. Image acquisition

Diffusion data were acquired on a 3 T GE Echospeed system (General Electric Medical Systems, Milwaukee, WI). Diffusion-weighted images were acquired using an echo planar imaging sequence, with the following parameters: TR 17,000 ms, TE 78 ms, FOV 24 cm, 144×144 matrix, 1.7 mm slice thickness, approximate scan time = 17 min. A double echo option was used to reduce eddy-current related distortions. To reduce the impact of EPI spatial distortion, an 8-channel coil and ASSET (Array Spatial Sensitivity Encoding techniques, GE) with a SENSE-factor (speed-up) of 2 was used. Eighty-five axial slices parallel to the AC–PC line covering the whole brain were acquired in 51 gradient directions with b = 900 s/mm². Eight baseline scans with b = 0 s/mm² were also acquired. Diffusion-Tensor Images (DTIs) were estimated from the Diffusion-Weighted Images on the basis of a Least-Squares Estimation.

2.3. Whole-brain tractography

The tractography protocol used in this study has been described in detail elsewhere (Whitford et al., 2010a). Deterministic (streamline) tractography was performed via a Runge–Kutta second order protocol. Seedpoints were placed at every point for which Westin’s Linear Anisotropy measure (CL; Westin et al., 2002) was greater than 0.3 (the seeding criterion), with a stopping criterion of CL = 0.15, a step size of 0.5 mm and a length criterion of 20 mm.

2.4. Fiber clustering and extraction of the prefrontal and temporoparietal callosal fibers

The whole-brain tractography procedure (see Fig. 2A) generated an estimated twenty thousand fibers per participant. As described in detail elsewhere (O’Donnell and Westin, 2007; Whitford et al., 2010a), these fibers were then clustered into 200 fiber-clusters (FCs) (Fig. 2B), each consisting of a spatially and morphometrically similar subset of the fibers generated from the whole-brain tractography (Fig. 2A). Tractography and fiber clustering were performed using Matlab 7.0 (www.mathworks.com) and 3D-Slicer (www.slicer.org).

Thirty-seven of these 200 FCs were identified as the corpus callosum (Fig. 2C). The prefrontal callosal FCs were defined as the 11 corpus callosum FCs that lay anterior to the premotor cortex (see Fig. 2D), based on the consensus of two independent raters (TW and DT, inter-rater reliability = .907), and confirmation from a third rater (MK). The temporoparietal callosal FCs were defined as the 10 callosal FCs that lay posterior to the somatosensory cortex and which either a) projected superiorly to the parietal cortex but not posteriorly to the visual cortex, or b) projected inferiorly to the temporal cortex (see Fig. 2D). The temporoparietal FCs were also defined on the consensus of TW and DT (inter-rater reliability = .930), and confirmation from MK. Following their definition, the prefrontal and temporoparietal fibers of the corpus callosum were automatically extracted for all participants as per the protocol of O’Donnell and Westin (2007).

2.5. Diffusion indices

Shape Normalized Dispersion (SHD) was calculated at every voxel in every participant’s DTI, as per the protocol of Savadjiev et al. (2010). Each participant’s mean SHD in the prefrontal callosal fibers was calculated by averaging the SHD values of all voxels through which any of the prefrontal FCs passed. Similarly, average SHD in the temporoparietal callosal fibers was calculated by averaging the SHD of all voxels through which any of the temporoparietal FCs passed.

Fractional Anisotropy (FA) was also calculated at every voxel in every participant’s DTI (Basser and Pierpaoli, 1996), and average FA was calculated for the prefrontal and temporoparietal callosal fibers. FA was entered as a covariate in the between-group analysis of SHD. While FA is mathematically independent of SHD (Savadjiev et al., 2010), it was included as a covariate to control for the possibility of any observed group differences in SHD ultimately being driven by group differences in FA. Such a scenario could arise, for example, if FA measures were dependent to some extent on fiber geometry, or if FA and SHD had a common dependence on noise in the data, or other factors in the imaging process.

2.6. Statistical analysis

Statistical analyses were performed using SPSS v11 (www.spss.com). Analysis-of-Variance (ANOVA) was used to investigate for between-group differences in SHD and FA in the prefrontal and temporoparietal fibers of the corpus callosum. Spearman’s correlations were used to investigate the relationship between patients’ SHD in the prefrontal and temporoparietal fibers and their chlorpromazine-equivalent medication dosage. Partial correlations, controlling for chlorpromazine-equivalent medication dosage, were used to investigate the relationship between patients’ SHD in the prefrontal and temporoparietal fibers and their scores on the seven positive and seven negative subscales of the PANSS.

![Fig. 2. A summary of the protocol for DTI pre-processing. Whole-brain tractography was performed on each participant’s DTI (Panel A), and the resultant fibers combined. Fibers with similar shapes and spatial positions were clustered together into 200 clusters (Panel B). The 37 clusters constituting the corpus callosum were extracted (Panel C), and, of these, 11 clusters constituting the prefrontal callosal fibers (in yellow) and the 10 clusters constituting the temporoparietal callosal fibers (in red) were identified and automatically extracted from each participant’s whole-brain tractography image. The prefrontal and temporoparietal fibers of three representative participants are illustrated in Panel D.](image-url)
Given the number of correlations this entailed, $\alpha$ was set to 0.01 for these analyses to control for multiple comparisons.

In a supplementary exploratory analysis, Tract-Based Spatial Statistics (TBSS; Smith et al., 2006) was used to investigate for voxelwise differences in SHD between the SZ and control groups across all major white matter fasciculi. Firstly, all subjects' FA and SHD images were aligned into a common space using the nonlinear registration tool FNIRT (FMRIB Centre, University of Oxford; www.fmrib.ox.ac.uk/analysis/techrep). The aligned FA images were averaged to create a mean FA image, which was then thinned to create a mean FA skeleton. The skeleton represented the centers of all white matter tracts that were common to all subjects. Each subject's aligned SHD data was then projected onto the skeleton, and the resulting data was used to perform voxelwise statistics between subjects. The statistics were performed using the ‘randomize’ tool for permutation testing (Nichols and Holmes, 2002), which is part of the FSL software library (FMRIB Centre, University of Oxford; http://www.fmrib.ox.ac.uk/fsl/).

3. Results

The SZ patients exhibited reduced levels of SHD in the prefrontal fibers of the corpus callosum, relative to HC (mean ± SD) (SZ: 0.04490 ± 0.00132; HC: 0.044191 ± 0.00123; t(47) = 2.752, $p = 0.008$ — see Fig. 3A). This between-group difference in prefrontal SHD remained significant when controlling for between-group differences in FA ($F_{1,46} = 4.294$, $p = 0.044$, partial $\eta^2 = 0.085$), and when the three unmedicated patients were removed from the analysis ($F_{1,46} = 4.939$, $p = 0.032$, partial $\eta^2 = 0.103$).

There was no significant difference between the SZ patients and HC participants in the SHD of the temporoparietal fibers (SZ: 0.04417 ± 0.00204; HC: 0.04427 ± 0.00209, $t(47) = 0.163, p = 0.871$ — see Fig. 3B). This comparison remained non-significant when controlling for between-group differences in FA ($F_{1,46} = 0.014, p = 0.907$, partial $\eta^2 < 0.001$), and when the three unmedicated patients were removed from the analysis ($F_{1,46} = 0.029, p = 0.865$, partial $\eta^2 = 0.001$).

There was a significant between-group difference in the FA of the prefrontal callosal fibers (SZ: 0.46799 ± 0.02531; HC: 0.48241 ± 0.01881, $t(47) = 2.237, p = 0.030$). However, this difference did not remain significant when controlling for between-group differences in SHD ($F_{1,46} = 1.872, p = 0.178$, partial $\eta^2 = 0.093$), or when the three unmedicated patients were removed from the analysis ($F_{1,46} = 1.200, p = 0.279$, partial $\eta^2 = 0.027$). There was no between-group difference in the FA of the temporoparietal fibers (SZ: 0.4992 ± 0.02508; HC: 0.5091 ± 0.02489, $t(47) = 1.388, p = 0.172$). This contrast remained non-significant when controlling for between-group differences in SHD ($F_{1,46} = 1.872, p = 0.178$, partial $\eta^2 = 0.039$), and when the three unmedicated patients were removed from the analysis ($F_{1,46} = 1.714, p = 0.197$, partial $\eta^2 = 0.038$).

There were no significant correlations between patients’ chlorpromazine-equivalent medication dosage and their SHD in either the prefrontal (rho(24) = .238, $p = 0.263$) or temporoparietal (rho(24) = .129, $p = 0.549$) fibers. Similarly, there were no significant correlations between chlorpromazine-equivalent dosage and patients’ FA in the prefrontal (rho(24) = -.103, $p = 0.632$) or temporoparietal (rho(24) = -.248, $p = 0.243$) fibers. There were no significant correlations between either patients’ SHD or FA in either the prefrontal or temporoparietal callosal fibers and their scores on any of the seven positive and seven negative subscales of the PANSS ($p > 0.01$ for all correlations).

In the exploratory TBSS analysis, there were no voxels that differed between the schizophrenia and control groups in terms of their SHD, after correction for familywise error.

4. Discussion

The aim of the present study was to use a novel measure of fiber geometry, SHD (Savadjiev et al., 2010), to investigate whether the callosal fibers connecting the heteromodal association areas of the prefrontal and temporoparietal cortices were morphometrically abnormal in patients with schizophrenia. This is the first study (to our knowledge) that has used a morphometry-specific DTI measure to investigate the structural basis of the transcortical misconnectivity that has been implicated in the etiology of schizophrenia. The results revealed that while the schizophrenia group exhibited abnormal fiber geometry in the prefrontal callosal fibers, they did not exhibit abnormalities in the temporoparietal callosal fibers, relative to matched healthy controls.

While a number of studies have identified abnormalities in the size, shape, asymmetry and diffusivity of the corpus callosum in patients with schizophrenia (Woodruff et al., 1995; DeLisi et al., 1997; Gharalibeh et al., 2000; Brambilla et al., 2005; Walterfang et al., 2008) – although negative findings have also been reported (Rossell et al., 2001; Price et al., 2005) – there has been, to the best of our knowledge, only one previous study that has used a neighborhood-based DTI metric of fiber geometry to investigate for abnormalities in the corpus callosum in patients with schizophrenia. Specifically, Federspiel et al. (2006) used a voxel-based analysis to compare Inter-Voxel Coherence between 12 FES patients and 12 healthy controls and found evidence of coherence reductions in several fasciculi including the corpus callosum. Notwithstanding the aforementioned limitations of Inter-Voxel Coherence, the results of Federspiel et al. (2006) are consistent with the results of the current study insofar as they suggest that schizophrenia may be associated with geometric abnormalities in WM fasciculi. The question remains open, however, as to what geometric scenarios could give rise to the SHD reductions observed in the present study. In contrast to the ‘normal’ callosal fiber structure illustrated in Fig. 4A, there are at least two geometric scenarios that would lead to reductions in SHD and which could thus potentially underpin the SHD reductions exhibited by the schizophrenia patients in the present study. The first possibility is that the fibers did not follow a smooth...
trajectory in their projection to the cortex, but instead followed a variable, ‘wiggly’ trajectory, as illustrated in Fig. 4B. The second possibility is that the fibers had a smooth trajectory but were inhomogeneously distributed, or ‘clumped’ within the fasciculus, as illustrated in Fig. 4C. Both of these scenarios would lead to a reduction in SHD, and thus either (or both) could potentially underlie the SHD reductions exhibited by the schizophrenia patients in the present study.

If the subnormal levels of SHD exhibited by the schizophrenia patients reflected an abnormality in the morphometry of the prefrontal callosal fibers, the question arises as to what were the biological underpinnings of these morphometric abnormalities. One prima facie, albeit speculative, possibility is that the irregular fiber structure was underpinned by abnormalities in the normative processes of neurodevelopment. This possibility is consistent with models of schizophrenia that emphasize neurodevelopmental abnormalities in the etiology of the disease (Akbarian et al., 1996; Kovalenko et al., 2003). Also consistent with this idea is the fact that a primary role of the DISC1 gene, which has consistently been implicated in the etiology of schizophrenia (Roberts, 2007), is in regulating neuronal migration in utero, including in the corpus callosum (Clapcote and Roder, 2006). It must, however, be emphasized that the proposed hypothesis is speculative, and that it is not possible to determine definitively the physiological underpinnings of the observed SHD abnormalities on the basis of these results. Furthermore, it should also be noted that while corpus callosum abnormalities have frequently been reported in patients with schizophrenia, structural abnormalities have also been observed in several other fasciculi – including the uncinate fasciculus (Kubicki et al., 2002), superior longitudinal fasciculus (Karlgodt et al., 2008) and arcuate fasciculus (Whitford et al., 2011a) – and that these abnormalities are consistent with the predictions of other white matter models of the disorder (e.g., Bartozzis, 2002; Whitford et al. in press).

And finally, it is also important to note that the morphometric abnormalities in the prefrontal callosal fibers are not only consistent with theories of transcallosal misconnection, but are also consistent with other neurodevelopmental theories of schizophrenia, such as ‘hypofrontality’ models of the disorder (Weinberger et al., 1994). The results of the current study thus need to be considered in the context of the broader schizophrenia literature, and future studies are needed to ascertain the specificity and etiology of the SHD abnormalities that were observed in schizophrenia patients.

There were at least two limitations to the present study. The first limitation relates to the fact that all of the participants in the study were male. While this was advantageous in the sense that it increased the homogeneity of the sample, it obviously limits the extent to which the results can be generalized to females. The second limitation relates to the fact that all of the schizophrenia patients were chronically ill and thus had typically been exposed to a variety of neuroleptic medications over many years. While no significant or near-significant correlations were observed between patients’ SHD and their chlorpromazine-equivalent medication dosage, the fact that neuroleptics have been shown to affect the structure of white matter fasciculi in and of themselves, such as by eliminating myelin-forming oligodendroglia (Konopaske et al., 2008), raises the possibility that they may also have an effect on fiber geometry. It should also be noted that the schizophrenia patients had typically been ill for many years, and consequently may have experienced longitudinal changes in brain structure over the course of their illness, irrespective of any pharmacological or psychological treatments they may have received.

In summary, the present study used a novel metric of fiber geometry, SHD, to identify morphometric abnormalities in the prefrontal fibers of the corpus callosum in patients with chronic schizophrenia. These morphometric abnormalities could potentially be underpinned by abnormalities in the normative processes of neurodevelopment. The results of the study provide support for the idea that schizophrenia is associated with aberrant inter-hemispheric communication between the frontal lobes.

![Fig. 4. Schematic examples of normal (Panel A) and abnormal (Panels B and C) fiber structures. Panel A represents a smoothly fanning fiber structure such as might be expected in the corpus callosum in a healthy individual. Panels B and C represent abnormal fiber structures which would exhibit lower levels of SHD relative to Panel A and thus could potentially underpin the subnormal levels of SHD exhibited by the schizophrenia patients in the prefrontal callosal fibers in the present study. Panel B represents a fiber structure consisting of fibers that do not follow a smooth trajectory in their projection to the cortex, but instead follow a ‘wiggly’ trajectory. Panel C represents a ‘clumped’ fiber structure in which the fibers are inhomogeneously distributed within the fiber bundle.](image)

**Role of funding source**
This work was supported by the National Health and Medical Research Council of Australia (520627 to TW; 350223 and 628711 to SW; 628386, 350241 and 566529 to CP), the National Institutes of Health (R01 MH068464-0 and U54 EB005149 to MK; R25 CA089017-06A2 to LOD; R01 MH 082918 to SB; T32 MH 016259 to JS; R01 MH 074794 and P41 RR 013218 to CPW; K05 MH 070047 and R01 MH 50747 and U54 EB005149 to MES; MH 040799 to RWM; the Boston Center for Intervention Development and Applied Research – CIDAR, P50 MH 080272 to RWM and MES), the Department of Veterans Affairs (VA Merit Awards, and VA Schizophrenia Research Center Grants to MES and RWM), Harvard Medical School (Milton Award to MK), the Center for Integration of Medicine and Innovative Technology Soldier in Medicine Award (grant to SB), and the NARSAD Brain and Behavior Research Fund (NARSAD 17537 to TW).

**Contributors**
TW and PS designed the study, were involved in data acquisition, processing and analysis, and wrote the first draft of the manuscript. MK, LOD, SB, CPFW, RM and MS were involved in data acquisition, processing and interpretation. DT, JS, LB, AR, MN, PN, CP and SW were involved in data analysis and interpretation. All authors contributed to and have approved the final manuscript.

**Conflict of interest**
All authors declare that they have no conflicts of interest.
Acknowledgements

The authors would like to thank the participants of the study.

References


