

Rassegna

Alterations of cerebral white matter structure in psychosis and their clinical correlations: a systematic review of Diffusion Tensor Imaging studies

Alterazioni strutturali della sostanza bianca cerebrale nella psicosi e le relative correlazioni cliniche: una rassegna sistematica degli studi di diffusion tensor imaging

SERENA PARNANZONE¹, DARIO SERRONE¹, MARIA CRISTINA ROSSETTI¹, SIMONA D'ONOFRIO¹, ALESSANDRA SPLENDIANI², VALERIA MICELLI², ALESSANDRO ROSSI¹, FRANCESCA PACITTI^{1*}

*E-mail: francesca.pacitti@cc.univaq.it

¹Department of Biotechnological and Applied Clinical Sciences (DISCAB), University of L'Aquila, Italy

²Department of Biotechnological and Applied Clinical Sciences (DISCAB), Neuroradiological Unit, University of L'Aquila, Italy

SUMMARY. Schizophrenia is a common, severe and chronically disabling mental illness. Most of MRI studies in schizophrenia suggest the involvement of white matter (WM) pathology in multiple cerebral regions in the neurobiology of this condition. White matter fiber tracts connecting numerous cortical regions have been the focus of a number of studies using a magnetic resonance technique called "Diffusion Tensor Imaging" (DTI). A literature search of published DTI studies was conducted using the major database National Centre for Biotechnology information (NCBI) PubMed (MEDLINE). Our review covers 95 published papers. We summarise the main DTI findings involving the different brain regions in patients affected by or at high-risk for psychosis; we discuss clinical implications of these white matter disruptions and the limitations of current studies, listing the potential confounds and suggesting potential future research directions.

KEY WORDS: DTI, psychosis, schizophrenia, white matter.

RIASSUNTO. La schizofrenia è una malattia mentale comune, grave e cronicamente invalidante. La maggior parte degli studi di risonanza magnetica in pazienti affetti da schizofrenia suggerisce il coinvolgimento della sostanza bianca di diverse regioni cerebrali nella patogenesi e nella neurobiologia di questa malattia. I fasci di sostanza bianca interposti tra le diverse regioni corticali sono stati oggetto di numerosi studi che utilizzano una tecnica di risonanza magnetica chiamata "Diffusion Tensor Imaging" (DTI). Nel presente studio è stata condotta una revisione della letteratura sugli studi di DTI pubblicati utilizzando il database National Centre for Biotechnology (NCBI) PubMed (Medline). Questa rassegna comprende 95 articoli pubblicati. Sono stati riportati i principali risultati degli studi di DTI in pazienti affetti da psicosi o ad alto rischio per lo sviluppo di psicosi; sono state discusse le implicazioni cliniche delle alterazioni della sostanza bianca e i limiti degli studi in corso elencando i potenziali fattori di confondimento e suggerendo possibili direzioni future per la ricerca.

PAROLE CHIAVE: DTI, psicosi, schizofrenia, sostanza bianca.

INTRODUCTON

Schizophrenia is a complex psychiatric syndrome comprising of psychiatric symptoms, including auditory hallucinations and delusions, cognitive deficits and social dysfunction¹.

The majority of studies on structural brain changes in patients at ultra-high risk for or affected by psychosis have been based on magnetic resonance imaging. Brain structural MRI is based on the differential behaviour of protons of water molecules in gray and white matter when exposed to a variable magnetic field. The contrast between structures varying in the response to magnetic field alterations allows delineating local groupings of neurons and fibers and determining their sizes in absolute and relative terms².

Most of MRI studies in schizophrenia suggest the involvement of white matter (WM) pathology in multiple cerebral regions in the neurobiology of this condition. As normal brain functions are served by macrostructural circuits of cortical and subcortical areas, disturbed communication between brain regions may be the core pathology of psychosis. WM consists of the axonal projections to other neurons and functional brain areas and is therefore key to neural communication. Myelination is initiated prenatally and completed for most tracts within the first year birth but continues during childhood, adolescence and adulthood and has a region-specific course where prefrontal regions myelinate the last³. Several lines of evidence point to myelin dysfunction, reduced oligodendrocyte number or integrity, or possibly hyperglutamatergic state⁴.

Neurodevelopmental theories have suggested demyelination during adolescence and adulthood to occur in psychosis.

Abnormalities in WM structure and integrity have been correlated with psychotic symptoms, negative symptoms and cognitive deficits⁵.

WM is difficult to study in detail with conventional MRI because of its high degree of homogeneity, moreover conventional techniques do not allow for the evaluation of its directionality and organization. WM fiber tracts connecting numerous cortical regions have been the focus of a number of studies using a magnetic resonance technique called Diffusion Tensor Imaging (DTI). It has become established in the last two decades as a valuable research tool. DTI assesses a non-invasive and in vivo quantification of the diffusion characteristics of water molecules: within a magnetic field these molecules tend to align into preferential directions according to their ability to diffuse across or along the arrangement of biological structures that surround them. In the brain water may diffuse freely in all directions (isotropic diffusion), or restricted along one particular direction of structured tissue such as WM tracts and fibers (anisotropy diffusion). Fractional anisotropy is a quantitative dimension and can take values between 0 and 1. If the anisotropy is high, then most of the diffusion occurs in the highly ordered directions, indicating a high level of orientation in the structure, therefore, decreased anisotropy may predict compromised white matter integrity⁶. Other measures used to compare different voxels in term of diffusion are mean diffusivity (MD), radial diffusivity (RD) and relative anisotropy (RA)⁷. Additionally different approaches have been applied to study differences in regional brain anisotropy between subjects: some studies have used voxel based approaches (VBA), where data sets have been processed with reference to FA normalized to a standard anatomical and averaged template, before being compared to similarly processed data sets; other studies have used a region of interest (ROI) approach in region of the brain thought to be implicated to psychosis. DTI is becoming increasingly important in the field of schizophrenia research⁸.

The aim of this study was to review the knowledge about the abnormalities of WM in patients at ultra-high risk for psychosis (UHR), patients with a first-episode psychosis (FEP) and chronic schizophrenia patients (SZ) compared with controls (HC), making clearer the role of WM integrity alterations in the etiopathogenesis, anatomical bases and clinical or neuro-cognitive correlates of the disorders.

METHODS

A literature search of published DTI studies was conducted using the major database National Centre for Biotechnology information (NCBI) PubMed (Medline).

The key words used were: "schizophrenia" and "DTI" or "diffusion tensor imaging", "psychosis" and "DTI" or "diffusion tensor imaging". Studies were included if they satisfied the following criteria: the patient population had a diagnosis of psychosis or was considered at ultra-high risk for psychosis, diffusion tensor imaging was an imaging technique used, the article was published in English. Additionally, they were chosen if they were found to be relevant to the focus of this systematic review.

Our review covers 95 papers published between September 2005 and March 2015: 32 papers were excluded.

RESULTS

In 25 studies the patient population included people considered at ultra-high risk for psychosis. To be considered at high-risk for psychosis patients had to satisfy almost one of these criteria: 1) they had schizotypal personality features; 2) they had sub-threshold psychotic symptoms; 3) they had a first-degree relative with schizophrenia-like disorder; 4) they had brief psychotic moments with spontaneous remission in less than 1 week (Table 1).

We have decided to mention some of the studies excluded because they can provide additional information.

In a study was examined the ability of DTI to differentiate between UHR, FEP and HC subjects: the results suggest that DTI allowed discrimination of UHR from HC subjects³⁴.

Patients with only cannabis use disorder (CUD) have also been studied with DTI method: they had lower FA than HC in left inferior FOF²⁷, and altered FA values in left ILF and left inferior FOF compared to HC; greater consumption of cannabis predicted a greater decrease in left ILF FA in CUD³⁵.

In the study by Mittal et al.³⁶ youth at high-risk for psychosis presented neurological disfunction and abnormal neurodevelopment misured by the presence of neurological soft signs (NSS) and a decrease of FA in right/left superior CP at 12 months, controls showed a normative increase while there were no group differences at baseline. NSS predicted a longitudinal decrease in cerebellar-thalamic FA and elevations in negative but not positive symptoms 12 months later.

According to Derosse et al.³⁷ cumulative risk for psychosis (including low IQ, low parental socioeconomic status, history of adolescent cannabis use and childhood trauma, high levels of subclinical psychotic-like experiences) was associated with lower FA in left SLF.

In the study by Skranes et al.³⁸ very low birth weight children had reduced FA values in CI, CE, CC, ILF, SLF; children with low IQ had reduced FA in CE, SLF, ILF; fine motor impairment was related to low FA in CI, CE and SLF; mild social deficits correlated with reduced FA in CE and SLF.

Prenatal and neonatal DTI were obtained in the offspring of mothers with schizophrenia or schizoaffective disorder and matched comparison mothers: there were no group differences in white matter diffusion tensor properties³⁹.

In 41 studies the patient population included people experiencing a first episode of psychosis. (Table 2)

According to Peters et al.⁷⁵ FEP with cannabis use before age 17 showed increased directional coherence in the bilateral UF, anterior CI and FL while these abnormalities were absent in FEP without cannabis use before age 17: this is in contrast with most DTI studies which have produced evidence of WM hypoconnectivity.

In 46 studies the patient population included people with chronic schizophrenia (Table 3).

Tang et al.¹¹⁰ obtained DTI and magnetic resonance spectroscopy from 40 subjects with schizophrenia: N-Acetylaspartate and DTI anisotropy indices were reduced in medial temporal regions.

Patients with temporal lobe epilepsy and interictal psychosis were studied with DTI by Flügel et al.¹¹¹; they showed lower FA values in both frontal and temporal regions and

Alterations of cerebral white matter structure in psychosis and their clinical correlations

Table 1. Main findings of DTI studies in people considered at high-risk for psychosis.

Authors	Sample	Mean age (years)	Abnormalities	Correlations	Comments
Katagiri et al. ⁹	41	23.1	FA reduced in CC		increase in FA in the same region in the group with improvement in sub-threshold positive symptoms
Bloemen et al. ¹⁰	37	19.5	Lower FA in bilateral medial FL in patients later developing psychosis compared with HC and lower FA values lateral to the right putamen and left superior TL compared to UHR patients who did not develop psychosis	Positive PANSS scores correlated negatively with FA in right superior TL; UHR patients later developing psychosis have positive PANSS scores negatively correlated with FA in left middle TL	
Muñoz Maniega et al. ¹¹	22	30	Reduced FA in anterior limb of CI		
Camchong et al. ¹²	22	48.5	Reduced FA values in medial FL white matter		
Nakamura et al. ¹³	15	37.7	FA reduced in UF	FA reduced in right UF with clinical symptoms; FA reduced in left UF with cognitive function	
Karlsgodt et al. ¹⁴	36	17.0	FA reduced in SLF	Lower FA in H and ILF predicted functional deterioration	Absence of age-associated increase in FA in H and ILF
Peters et al. ¹⁵	17	21.7		FA in UF, AF, CC, PC, AC did not differ between patients that developed or not a psychotic disorder	
Peters et al. ¹⁶	10	21.6	No differences in FA from FEP and HC		
Peters et al. ¹⁷	10	21.6	Reduced FA in right superior FL and left middle FL		
Bertisch et al. ¹⁸	39			FA in left subgenual AC, left CG, left LG, right PA, PR demonstrated significant heritability	
Hazlett et al. ¹⁹	30	41.4	FA reduced in left TL, RC and PC but not in AC, LC and PFR	Lower FA in C correlated with more severe negative symptoms	
Kyriakopoulos et al. ²⁰	17 17	16.6 23.7	Decreased FA in bilateral SLF, bilateral ILF, bilateral inferior FOF, bilateral corticopontine tracts, left CC and bilateral posterior TL in patients with adolescent-onset;		

(continued)

(continued) - Table 1.

Authors	Sample	Mean age (years)	Abnormalities	Correlations	Comments
			Decreased FA in bilateral ILF, bilateral inferior FOF, brain stem, cerebellum, right SLF, right CC, right UF, right C, right anterior CR, right posterior TL and corticopontine tract in patients with adult-onset		
Carletti et al. ²¹	32	23.4	FA, RD and AD intermediate in UHR between controls and FEP	Progressive reduction in FA in subjects who developed psychosis	
Benetti et al. ²²	46	24.3	Reduction of FA in left long segment in patients without verbal auditory hallucinations		The sample is composed by both patients UHR and FEP
Hoptman et al. ²³	22	20	Reduced FA in left posterior C, bilateral angular gyrus, left inferior frontal gyrus; increased FA in left subgenual anterior C and bilateral pontine tegmental WM and right middle/superior frontal gyri		
Smallman et al. ²⁴	12	21.0	Increased FA in left UF	Positive correlation between FA in right AF and hallucinatory experience	
Domen et al. ²⁵	93	29.4	Did not differ from HC		
Boos et al. ²⁶	123	26.7	Higher mean FA in left and right AF		
Epstein et al. ²⁷	21	16.1	Lower FA in left ILF, CST bilaterally, left inferior FOF		
Derosse et al. ²⁸	67	36.1	Lower FA in inferior FOF and greater asymmetry in UF		
Lener et al. ²⁹	49	36.5	Lower FA in CC compared with HC		This abnormality was more widespread in SZ
Lagopoulos et al. ³⁰	74	21.3	Lower FA in left anterior CR, anterior TL		
Jacobson et al. ³¹	11	11-13	WM decrease in inferior FOF, C, ILF		
Goghari et al. ³²	24	40.2	Increase in FA in right fimbria of the fornix	No significant association between FA and QI	
Hohenberg et al. ³³	28	20.6	Increased MD in SLF, posterior CR and CC, increased RD in posterior PL		

CC=corpus callosum; UF=uncinate fasciculus; SLF=superior longitudinal fasciculus; H=hippocampus; ILF=inferior longitudinal fasciculus; AF=arcuate fasciculus; PC=posterior cingulate; AC=anterior cingulate; CG=cingulate gyrus; LG=lingual gyrus; PA=pericaudate area; PR=perilenticular region; TL=temporal lobe; PFR=prefrontal region; TR=thalamic radiations; RC=right cingulum; LC=left cingulum; C=cingulum; FMJ=forceps major; FMN= forceps minor; CE=external capsule; CR= corona radiata; CST=corticospinal tract; FOF=fronto-occipital fasciculus; PL=parietal lobe; CP=cerebellar peduncles; PO=parietal-occipital; LDL=low-density lipoprotein; CI=internal capsule; PANSS=positive and negative syndrome scale; WCST= Wisconsin card sorting test; GF=frontal gyrus; BPRS=brief psychiatric rating scale; FL=frontal lobe; OL=occipital lobe; T=thalamus; I=insula.

Alterations of cerebral white matter structure in psychosis and their clinical correlations

Table 2. Main findings of DTI studies in people experiencing a first episode of psychosis.

Authors	Sample	Mean age (years)	Abnormalities	Correlations	Comments
Alvarado-Alanis et al. ⁴⁰	35	24.6	Abnormalities in projection fibers, association and commissural fibers (temporolimbic tract), bilateral fornix, superior and inferior CP		
Chan et al. ⁴¹	39	28.8	Lower FA values in right ILF	FA values correlated with severity of delusions	
Karlsgodt et al. ⁴²	12	20.9	Lower FA values in SLF	FA values in the left but not right SLF correlated with performance on a verbal task both in FEP and HC	
Mendelsohn et al. ⁴³	9	26	No FA differences		
Gasparotti et al. ⁴⁴	21	28.5	Lower FA values in the splenium but in the genu of CC		
Melicher et al. ⁴⁵	77	31.1	Decrease in FA in CC, SLF, ILF, inferior FOF, posterior TR		
White et al. ⁴⁶	31	25.2	No differences		
Wang et al. ⁴⁷	68	24.1	Reduced FA in CC, left TL, right PL, left OL		
Tang et al. ⁴⁸	38	16.3	Reduced FA in right anterior C	Negative correlation between mean FA and PANSS positive symptom score	
Begrè et al. ⁴⁹	7	22.6	No differences		
Cheung et al. ⁵⁰	34	25.4	Reduced FA in WM in left anterior and right middle CG, left superior and right middle temporal gyrus, left cuneus and right FL	Positive symptoms correlated positively with FA scores in these regions	
Moriya et al. ⁵¹	19	29.9	No differences		
Price et al. ⁵²	20	24.9	No differences in FA in CC		
Peters et al. ¹⁷	8	21.2	Reduced FA in bilateral PL, left superior TL, right TL, I and left FL		
Szesko et al. ⁵³	33	25.1	Lower FA in bilateral UF, left SLF, left inferior FOF	Lower FA in bilateral UF correlated with greater severity of negative symptoms, worse verbal/learning memory functioning	
Pérez-Iglesias et al. ⁵⁴	62	30.8	Lower FA in bilateral SLF, bilateral ILF, FMJ, CC and anterior and superior TL		

(continued)

(continued) - Table 2.

Authors	Sample	Mean age (years)	Abnormalities	Correlations	Comments
Bijanki et al. ⁵⁵	31	23.1		Significant correlation between global FA and negative symptoms (SANS)	This correlation became non-significant with adding age as a covariate
Price et al. ⁵²	19	23.8	FA reduced in left UF	No correlations between FA and clinical ratings	
Luck et al. ⁵⁶	32	23.6	FA reductions in the fornix	No significant correlation between FA and clinical or socio-demographic data	
Kong et al. ⁵⁷	15	24.3	No significantly decreased FA		
Schneiderman et al. ⁵⁸	23	16.1	Decreased FA in TL and SLF	Older age of onset tended to be associated with higher FA in ventral CI and ventral temporo-occipital WM	The study suggest that symptoms associated with the temporal lobe including auditory hallucinations would present before frontal associated symptoms including problem in executive functioning
Chen et al. ⁵⁹	20	46.9	Reduction in FA in left PL, right PC	No significant correlations between FA value and PANSS and cognitive test scores, age and antipsychotic medication dosages	Late-onset schizophrenia
Friedman et al. ⁶⁰	40	26	Lower FA in ILF		
Peters et al. ⁶¹	30	22.7	Lower FA in CC, bilateral PL, OL, FL, TL WM	FA correlated with polyunsaturated fatty acid concentration and negative correlated with negative symptoms	
Hao et al. ⁶²	21		Lower FA values in cerebral peduncle, frontal regions, inferior temporal gyrus, medial PL, hippocampal gyrus, I, right anterior C and right CR		
Carletti et al. ²¹	15	24.1	Widespread reduction in FA and increases in diffusivity compared to HC and UHR		
Cheung et al. ⁶³	25	29	Lower FA values in left FOF, left ILF, WM adjacent to right precuneus and right substantia nigra, CC, right posterior limb of CI and left cerebral peduncle		

(continued)

Alterations of cerebral white matter structure in psychosis and their clinical correlations

(continued) - Table 2.

Authors	Sample	Mean age (years)	Abnormalities	Correlations	Comments
Epstein et al. ³⁵	34	16.4	Lower FA in bilateral CST, bilateral ILF, bilateral inferior FOF compared to HC		
Epstein et al. ²⁷	55	16.9	Lower FA than HC in bilateral CST, left ILF, left inferior FOF		
Szesko et al. ⁶⁴	35	21.5	FA reductions within PL and OL WM	Greater overall FA increases in patients with greater increases in LDL	No significant FA increases among patients following treatment
Lee et al. ⁶⁵	17		Lower FA in genu and body of CC, UF, C, superior and inferior FOF, fornix, CE and CI, increased MD and RD in all WM regions; no difference for AD	FA in right inferior FOF had a positive correlation with negative, positive symptoms and all the items of WCST, FA of right CE showed positive correlation with category completed scores of WCST	
Price et al. ⁶⁶	18	23.6	Reduced FA in CC		
Qiu et al. ⁶⁷	32	28	No differences in FA	Left thalamic FA correlated with spatial working memory deficits	
Dekker et al. ⁶⁸	26	21.1	Reduced FA in CC in cannabis naïve FEP compared with FEP with early-onset cannabis use and with HC		
Quan et al. ⁶⁹	16	21.1	FA reduced in inferior GF-striatum tract, RD increased in bilateral rostral middle GF-striatum and bilateral inferior GF-striatum tracts	The number of WCST categories completed correlated positively with FA of right rostral middle GF-striatum tract and negatively with RD of right rostral middle GF-striatum tract, right inferior GF-striatum tract; BPRS score had no correlations	
Szesko et al. ⁷⁰	10	26.9	Reduced FA in left middle frontal gyrus, left posterior temporal gyrus, left CI		
Kiriakopoulos et al. ⁷¹	19	17.0	Lower FA in bilateral parietal association and left middle CP, no areas with higher FA		
Marques et al. ⁷²	63	27.7	Non responders to treatment at baseline showed lower FA in UF, C, CC		After 12 weeks increase in FA in responders and non responders positively correlated to antipsychotic exposure

(continued)

(continued) - Table 2.

Authors	Sample	Mean age (years)	Abnormalities	Correlations	Comments
Peters et al. ¹⁶	10	21.2	No differences		
Lu et al. ⁷³	21	22	Greater AD, RD, MD in CC, C, CR, posterior TL, CI, ILF, inferior FOF		
Luck et al. ⁷⁴	44	23.3	FA reduction in bilateral UF and bilateral SLF but not in C	Greater WM changes in these tracts with poor outcome as compared to patients with good outcome	

CC=corpus callosum; UF=uncinate fasciculus; SLF=superior longitudinal fasciculus; H=hippocampus; ILF=inferior longitudinal fasciculus; AF=arcuate fasciculus; PC=posterior cingulate; AC=anterior cingulate; CG=cingulate gyrus; LG=lingual gyrus; PA=pericaudate area; PR=perilenticular region; TL=temporal lobe; PFR=prefrontal region; TR=thalamic radiations; RC=right cingulum; LC=left cingulum; C=cingulum; FMJ=forceps major; FMN= forceps minor; CE=external capsule; CR= corona radiata; CST=corticospinal tract; FOF=fronto-occipital fasciculus; PL=parietal lobe; CP=cerebellar peduncles; PO=parietal-occipital; LDL=low-density lipoprotein; CI=internal capsule; PANSS=positive and negative syndrome scale; WCST= Wisconsin card sorting test; GF=frontal gyrus; BPRS=brief psychiatric rating scale; FL=frontal lobe; OL=occipital lobe; T=thalamus; I=insula.

higher MD in bilateral frontal regions, additionally the performance on some neuropsychological tests was related to frontotemporal FA reduction. Mao et al.¹¹² investigated interictal personality changes and white matter abnormalities in epilepsy patients: long disease duration and impairment of right AF integrity were independent risk factor of psychoticism.

Cocchi et al.¹¹³ studied the relationship between structural and functional deficits in schizophrenia patients: they showed decreased functional connectivity and impaired white matter integrity in a distributed network encompassing frontal, temporal, thalamic and striatal regions; in controls strong interregional coupling in neural activity was associated with well-myelinated white matter pathways.

Compared with Parkinson's disease patients without psychosis, those with psychosis had significantly lower FA in left frontal lobe, bilateral occipital lobe, left cingulate gyrus and left hippocampus¹¹⁴.

For an overview of the results see table 4.

DISCUSSION

The findings can be grouped into WM pathology affecting cortical regions, subcortical regions, inter-hemispheric fibers, association fibers and limbic system fibers. Corpus callosum consists of a commissural tract comprising the largest bundle of fibers connecting the two brain hemispheres.

Association fibers are: SLF which connects the frontal lobe with occipital and temporal areas, ILF, UF which are anterior temporo-frontal fiber tracts connecting orbito-frontal with anterior and medial temporal lobes, FOF which extends backward from the frontal lobe and spreading into the temporal and occipital lobes, AF is a fiber tract that stems from the caudal part of the superior temporal gyrus and extends to the lateral prefrontal cortex, the superior and the middle frontal regions. Limbic system fibers are the cingulum fibers that project both posteriorly from the cingulate gyrus to the

entorhinal cortex, temporal lobe, and anteriorly to the pre-motor, prefrontal regions and striatum. The fornix connects the hippocampus to the mamillary bodies, nucleus accumbens, medial prefrontal cortex, and septal regions, thus this fiber serves as the main output and input pathway for hippocampus. Thalamic radiations are projection fibers that provides a functional loop between the cerebral cortex and the thalamus; they converged into the internal capsule, located between the putamen and the thalamus-caudate nucleus regions⁵.

Changes in WM integrity were found in chronic psychosis, first-episode psychosis and patients at ultra-high risk for psychosis, they may play a role in the primary pathophysiology, as opposed to being a result of secondary disease processes. These changes have been correlated with specific cognitive deficits as well as clinical symptoms, suggesting that biological changes may underlie these clinical factors in patients.

Previous DTI studies assessing the impact of WM disruptions on the disease process have had mixed results. Our study adds to a growing body of literature emphasizing the need for treatments targeting white matter function and structure in psychosis patients.

The main findings in patients at ultra-high risk for psychosis were a decreased FA in inferior FOF, temporal lobe WM, frontal lobe WM. They seem to have predictive value of onset of psychosis in high-risk individuals. Other studies in ultra-high risk patients showed lower FA in anterior CR, corticospinal tracts, SLF, ILF, UF, CC and C. In addition, increase of FA values was seen in anterior C, left UF, AF, frontal lobe WM, right fornix and brain stem. The prediction of psychosis is a major topic in research and olds the hope for early intervention and prevention of full development of the illness, improving outcome and preserving WM integrity.

Decreases of FA in different tracts in patients at first-episode psychosis support notion of early disconnectivity between brain regions: the most burned were CC, UF, ILF, SLF, inferior FOF, temporal lobe WM, parietal lobe WM and left frontal lobe WM. White matter abnormalities were also observed in C, occipital lobe, CI, corticospinal tracts, cerebral

Alterations of cerebral white matter structure in psychosis and their clinical correlations

Table 3. Main findings of DTI studies in people affected by chronic schizophrenia.

Authors	Sample	Mean age (years)	Abnormalities	Correlations	Comments
Palaniyappan et al. ⁷⁶	17	33.0	Reduction in FA in LG	Predicted impaired processing speed	
Munõz Maniega et al. ¹¹	31	37	Lower FA in bilateral UF, left AF, bilateral anterior limb of CI		
Nazeri et al. ⁷⁷	44	36.0	Reduced FA in left posterior PO cluster and left FL	FA in FL predicted attention, processing speed, working memory in HC but not in SZ	
White et al. ⁴⁶	83	36.4	Reduced FA in the whole brain		
Hoptman et al. ²³	23	36.8	Reduced FA in left superior and middle temporal giry, left ILF, left C, left inferior frontal gyrus, right perilentiform regions; higher FA in left LG, I and right deep frontal WM		
Schneiderman et al. ⁵⁸	35	43.1	Reduced FA in C, CC, right anterior TL, FOF		
Orfei et al. ⁷⁸	45	38.8	No significant results	No significant relationship for self-certainty and global cognitive insight	
Roalf et al. ⁷⁹	25	36.7	FA reduced in bilateral FL, TL, OL WM and CC		higher FA in LC and left FOF only in HC but not in SZ
Lener et al. ²⁹	22	33.2	Lower FA in C, CC, ILF, anterior limb of CI	Greater overall symptom severity correlated with lower FA in CC, left ILF and left anterior limb of CI	The abnormality in CC was more widespread than UHR
Hatton et al. ⁸⁰	42	22.7	Reduced FA and AD in left ILF, SLF and FMJ	The abnormalities in left ILF and FMJ correlated with worse symptom severity and worse levels of depression; those in SLF correlated with impaired neurocognitive performance	The patients were at early stage of disease
Cullen et al. ⁸¹	43	37.0	Lower FA in smoking SZ in total cortical, FL, total brain, OL	Among smoking and non smoking SZ FA was correlated with QI	Smoking SZ differed from non smoking SZ in FL, but these differences were no longer significant after QI correction
Marenco et al. ⁸²	15	30.6	Reduced total connectivity of the thalamus to PFR cortex	The total thalamo-cortical connectivity to PFR predicted working memory task performance	

(continued)

(continued) - Table 3.

Authors	Sample	Mean age (years)	Abnormalities	Correlations	Comments
Yan et al. ⁸³	33	23.1	Decreased FA in right AC	Correlated with stroop performance and symptom severity	
Camchong et al. ⁸⁴	29	41.3	Connectivity alteration in medial frontal e AC	Frontal connectivity is positively associated with symptoms and general cognitive ability measures	
Lagopoulos et al. ³⁰	69	22.4	Lower FA in left anterior CR, anterior TL		
Weijer et al. ⁸⁵	44	36.9	Decreased FA in CST, UF and C	Negative correlation between FA and age	The sample is composed by SZ with chronic severe hallucinations
Abdul-Rahman et al. ⁸⁶	33	39.4	Reduction in FA in bilateral fornix and left AC, increase in RD in left AC and bilateral fornix, increase in AD in anterior left middle C	Decreased FA in left fornix and increased AD in RC correlated with greater severity of psychotic symptoms	
Ardekani et al. ⁸⁷	50	30.3	FA and MD values can be used to distinguish between SZ and HC		
Choi et al. ⁸⁸	25	44.6	Decrease in mean FA in anterior commissure	Anterior commissure integrity correlated negatively with age and decision making and correlated positively with total positive symptom score	
Friedman et al. ⁶⁰	40		Lower FA in most regions compared to HC		
Antonius et al. ⁸⁹	36	37.4	Right superior GF, left middle GF, bilateral parahippocampal gyrus, right T, left I, left fusiform gyrus, bilateral PC and left lentiform nucleus, left AC, RC, left LG, bilateral claustrum	These abnormalities correlated with symptom unawareness; deficits of WM in right LG, left middle temporal gyrus and right precuneus related to misattribution of symptoms	No HC
Boos et al. ²⁶	126	26.6	No difference in mean FA between SZ and HC; excessive decline in mean FA in genu, left UF, left inferior FOF, left ILF with increasing age	Negative correlation between FA in bilateral AF and symptom severity	SZ were young adult
Filippi et al. ⁹⁰	43	29.3	Decreased MD and increased FA in right anterior and posterior limb of CI, bilateral interhemispheric and cortico-cortical connections, bilateral cerebellum and brain stem	These abnormalities related to a longer duration of the untreated psychosis and severity of positive symptoms	

(continued)

Alterations of cerebral white matter structure in psychosis and their clinical correlations

(continued) - Table 3.

Authors	Sample	Mean age (years)	Abnormalities	Correlations	Comments
Domen et al. ²⁵	85	28.3	Lower mean FA in CC, FMJ, FMN, bilateral CE, bilateral CR, bilateral posterior TR		
Sungranyes et al. ⁹¹	25	17.1	Reduced FA in splenium and PC		
Wagner et al. ⁹²	38	35.8	Lower FA in right anterior limb of CI, right T, right CC	FA in right anterior limb of CI correlated with cognitive performance	
Balevich et al. ⁹³	34 adults 17 adolescents	43.7 15.9	Adults most reduction in posterior region Adolescent most reduction in anterior region	Negative correlation between negative symptoms and FA in right posterior lateral body in adults and left medial anterior body in adolescents	
Bijanki et al. ⁵⁵	59	37.7		Global negative symptoms correlated with global FA , upon addition of age as a covariate the relationship became non-significant	
Goghari et al. ³²	25	41.3		No significant relationship between FA and QI, symptoms or global functioning	
Garver et al. ⁹⁴	13	33.7	Increase of diffusivity in SZ considered drug-responders	This pathological increase in diffusivity was reduced following treatment-associated reduction of psychotic symptoms	Diffusivity of SZ considered poor responders did not differ from HC at baseline and following treatment
Rosenberger et al. ⁹⁵	27	39.1	Decline in FA with age in SZ in C and UF but not in inferior FOF		
Skelly et al. ⁹⁶	25	34.2	FA reduction in multiple bilateral posterior limb of CI and bilateral CR (but stronger on the left hemisphere), in C (bilateral medial TL and right FL) , left ILF, left anterior TR, FMN and right inferior FOF	Inverse relationship of FA in left UF and left SLF with positive symptom score; positive correlation between negative symptoms and FA in right I	
Nestor et al. ⁹⁷	18	39.1		FA in left C correlated with orienting of attention	
Liu et al. ⁹⁸	10	25.6	Lower FA in left superior CP		
Caprihan et al. ⁹⁹	65	33.6	Abnormalities in TR, CST, FMJ, FMN, SLF, superior FOF		

(continued)

(continued) - Table 3.

Authors	Sample	Mean age (years)	Abnormalities	Correlations	Comments
Cui et al. ¹⁰⁰	25	25.8	Reduced FA in left posterior CR	Negative correlation between FA in left frontoparietal lobe and positive symptom score; no correlation with duration of illness	
Kong et al. ⁵⁷	15	24.3	Decreased FA in CC in SZ		
Levitt et al. ¹⁰¹	16	39.4	No differences	FA in anterior limb of CI correlated positively with performance on measures of spatial and verbal declarative/episodic memory	
Knochel et al. ¹⁰²	21	38.3	Changes in MD in bilateral C and right UF; lower FA and higher MD in fornix in comparison with HC; lower FA in bilateral UF; higher MD in bilateral UF in HC	No correlation with clinical parameters or with years of medication	
Whitford et al. ¹⁰³	24	39.6	Subnormal levels of FA in fibers connecting the rostral with the caudal anterior CG and the isthmus of C with parahippocampal cortex	FA in fibers connecting the rostral with the caudal anterior CG correlated with positive symptoms, FA in fibers connecting the isthmus of C with parahippocampal cortex correlated with negative symptoms	
McCarthy-Jones et al. ¹⁰⁴	113	39.1	Reduced FA and increased RD in left AF in patients with Auditory Verbal Hallucinations (AVH) compared to HC and SZ without AVH		
Sasamoto et al. ¹⁰⁵	35	36.6	Lower mean of FA in CC, bilateral UF, CST, left SLF and superior FOF in SZ	Mean FA showed positive correlation with mean cortical thickness	
Kawashima et al. ¹⁰⁶	15	24.5	Reduced FA in bilateral UF but not in C		Early stage of illness
Hatton et al. ¹⁰⁷	42	22.7	Reduced FA in short association fibres connecting the superior and the middle temporal gyri		Adolescent-onset psychosis subjects showed FA reductions in short association fibres connecting superior temporal gyrus and Heschl's gyrus when compared to adult-onset subjects

(continued)

Alterations of cerebral white matter structure in psychosis and their clinical correlations

(continued) - Table 3.

Authors	Sample	Mean age (years)	Abnormalities	Correlations	Comments
Zou et al. ¹⁰⁸	21		Reduced FA in bilateral anterior limb of CI		
Giezendanner et al. ¹⁰⁹	34	33.6	SZ born in summer had lower FA in CC, bilateral inferior FOF, bilateral UF, right anterior CR, left posterior C, bilateral posterior CR, left posterior TR, bilateral CST, bilateral SLF, FMJ	Later age of onset was found in SZ born in winter months	

CC=corpus callosum; UF=uncinate fasciculus; SLF=superior longitudinal fasciculus; H=hippocampus; ILF=inferior longitudinal fasciculus; AF=arcuate fasciculus; PC=posterior cingulate; AC=anterior cingulate; CG=cingulate gyrus; LG=lingual gyrus; PA=pericaudate area; PR=perilenticular region; TL=temporal lobe; PFR=prefrontal region; TR=thalamic radiations; RC=right cingulum; LC=left cingulum; C=cingulum; FMJ=forceps major; FMN= forceps minor; CE=external capsule; CR= corona radiate; CST=corticospinal tract; FOF=fronto-occipital fasciculus; PL=parietal lobe; CP=cerebellar peduncles; PO=parietal-occipital; LDL=low-density lipoprotein; CI=internal capsule; PANSS=positive and negative syndrome scale; WCST= Wisconsin card sorting test; GF=frontal gyrus; BPRS=brief psychiatric rating scale; FL=frontal lobe; OL=occipital lobe; T=thalamus; I=insula.

peduncles and fornix. None of the studies included showed increased FA in patients with first-episode psychosis.

DTI abnormalities in first-episode patients are less robust than in chronic patients, suggesting that progression to more extensive abnormalities occurs after illness onset; there are also indications for accelerated aging effects in psychosis.

FA reductions were found in patients with chronic psychosis in CC, C, UF, left ILF, inferior FOF, SLF, FMN, FMJ, CR, corticospinal tracts, anterior CI, TR, temporal lobe WM, occipital lobe WM and frontal lobe WM. Changes in WM integrity have been reported also in left AF, superior FOF, fornix and hippocampus.

White matter tracts that were reported to have increased FA in almost one study include brain stem, right frontal lobe WM, left occipital lobe WM, insula, CI, cerebellum, inter-hemispheric and cortico-cortical tracts.

Of the included studies, 13 did not report group differences in anisotropy measures between patients and controls (3 in ultra-high risk patients, 8 in first-episode psychosis, 2 in chronic psychosis).

38 of the included studies (7 in UHR, 12 in FEP, 19 in SZ) found significant correlations between clinical or cognitive variables and FA values in some WM tracts. 3 studies showed a negative correlation between the severity of positive symptoms and FA values in some WM tracts like temporal lobe WM, right anterior C, right frontal lobe WM, cingulate gyrus WM, left fornix, right anterior and posterior limb of CI, left UF, left SLF, fibers connecting the rostral with the caudal anterior CG, bilateral inter-hemispheric and cortico-cortical connections, cerebellum and brain stem. Regarding to hallucinatory experience a positive correlation was found with FA values in right AF, while severity of delusions was associated with FA values in right ILF.

In 3 studies negative symptoms were correlated negatively with FA values in some WM tracts including C, bilateral UF, CC, TL, OL, PL, FL and fibers connecting C with

parahippocampal cortex; in one paper a positive correlation was found between negative symptoms and WM integrity in right I.

FA values showed a relation with clinical symptoms in right UF, CC, left ILF, left anterior limb of CI, FMJ, right AC, frontal connectivity and bilateral AF.

Cognitive function was found to be related with WM deficits in left and right UF, right CE, SLF, right AC, frontal connectivity, right anterior limb of CI (this one was found to be proportional to performance on measures of spatial and verbal declarative/episodic memory). Left thalamic FA values correlated with spatial working memory deficits. Fractional anisotropy in right rostral middle GF-striatum tract correlated positively with the number of WCST categories completed; FA reduction in LG predicted impaired processing speed while FA in left C correlated with orienting of attention. According to Marenco et al.⁸² the total thalamo-cortical connectivity to PFR predicted working memory task performance.

On the contrary, according to Lee et al.⁶⁵ FA in right inferior FOF had a positive relation with negative, positive symptoms and all the items of WCST; similarly, according to Choi et al.⁸⁸ anterior commissure integrity correlated negatively with decision making and positively with total positive symptoms score. In UHR patients increase in FA in CC was found to be correlated with improvement in subthreshold positive symptoms while, in other samples, patients later developing psychosis had lower FA values in several tracts. In less numerous papers FA values did not differ between UHR patients that developed or not a psychotic disorder.

Functional deterioration in UHR was predicted by lower FA values in H and ILF, Goghari et al.³² didn't find significant relationship between FA and global functioning.

On the other side, no correlation with clinical/cognitive measures were found in 8 of the studies included (2 in UHR, 3 in FEP, 3 in SZ).

Table 4. Summary of DTI findings.

White matter tract or area	UHR		FEP		SZ	
	Decrease FA	Increase FA	Decrease FA	Increase FA	Decrease FA	Increase FA
Corpus callosum	2		9		9	
Left	2					
Right	1					
Cingulum	2		2		9	
Anterior		1	3		2	
Posterior	1		1		2	
Uncinate fasciculus	2		4		8	
Right						
Left		1	1			
Arcuate fasciculus		1				
Right						
Left					2	
Inferior longitudinal fasciculus	2				1	
Right			4			
Left	1		1			
Superior longitudinal fasciculus			5			
Right	2				3	
Left						
Fronto-occipital fasciculus			2		1	
Superior			1		2	
Inferior	4		5		3	
Temporal lobe	3		6		5	
Left	1		2			
Right					1	
Parietal lobe	1		5			
Right			1			
Left			1			
Occipital lobe			2		3	
Left			1			1
Right						
Frontal lobe	4	1	1		5	
Left			3		2	
Right			2			1
Hippocampus			1		2	
Thalamic radiations					3	
Posterior			1		2	
Anterior					1	
Internal capsule			2			1
Anterior	1				5	
Posterior			1		1	
External capsule			1		1	
Anterior						
Posterior						
Corona Radiata					3	
Anterior	2		1		2	
Posterior					2	

(continued)

Alterations of cerebral white matter structure in psychosis and their clinical correlations

(continued) - Table 4.

White matter tract or area	UHR		FEP		SZ	
	Decrease FA	Increase FA	Decrease FA	Increase FA	Decrease FA	Increase FA
Corticospinal tracts	2		2		4	
Cerebellar peduncles			1		1	
Cerebral peduncles			2			
Insula			1		1	1
Cerebellum	1					1
FMN					3	
FMJ			1		4	
Fornix Right Left		1	2		2	
Anterior commissure					1	
Inter-hemispheric and cortico-cortical tracts						1
Brain stem	1	1				

Antonius et al.⁸⁹ studied the relation between symptoms unawareness and WM abnormalities, suggesting that misattribution of symptoms may be implied by loss of WM integrity in right LG, TL and right precuneus.

The impact of medications on WM integrity is far from well understood. The vast majority of patients participating in DTI studies to date have been on antipsychotic medication treatment. Although medication dose or cumulative exposure do not correlate with FA in most studies; some studies reported positive findings: according to Marques et al.⁷² patients non-responders to treatment at baseline showed lower FA in UF, C, CC; additionally, in the same sample after 12 weeks increase in FA positively correlated to antipsychotic exposure.

Interestingly, in 2 studies FA values have been associated with metabolic measures like greater levels of LDL or polyunsaturated fatty acid concentration.

Several studies have shown age-related reduction in FA in schizophrenia, whereas other studies did not replicate this relationship. While some studies that examined correlations with age failed to identify a significant effect, 5 of the included papers showed significant negative correlation between FA and age. Additionally, SZ adults showed most FA reduction in SNC posterior region, while SZ adolescents had most FA reduction in SNC anterior region. Karlsgodt et al.¹⁴ found the absence of age-associated increase in FA in H and ILF in UHR patients.

Some studies pointed out the effect of some socio-demographic variables like gender, duration of untreated psychosis, duration of illness and age of onset on WM changes. Older age of onset tended to be associated with higher FA in ventral CI and ventral temporo-occipital WM, while adolescent-onset psychosis subjects showed

WM anomalies in short association fibers connecting superior temporal gyrus and Heschl's gyrus; suggesting that symptoms associated with TL WM anomalies including auditory hallucinations would present before FL WM symptoms including problem in executive functioning. Later age of onset was found in SZ born in winter months, SZ born in summer had lower FA in CC, bilateral inferior FOF, bilateral UF, right anterior and bilateral posterior CR, left posterior C, left posterior TR, bilateral SLF, bilateral CST and FMJ. Filippi et al.⁹⁰ found abnormalities in right anterior and posterior limb of CI, bilateral inter-hemispheric and cortico-cortical connections, cerebellum and brain stem to be related with a longer duration of untreated psychosis. Cui et al.¹⁰⁰ showed no correlation of WM anomalies with duration of illness. No significant associations were found between FA and QI in 2 papers, but in another one SZ patients had FA values proportional to QI and differences between smoking and non-smoking SZ were no longer significant after QI correction.

Focusing particularly on patients outcome, increase in FA values in affected tracts was predictive of improvement in symptoms and good outcome, while greater WM changes in some of these tracts, like bilateral UF and bilateral SLF, were associated with poor outcome.

There is a need to better understand the relationship between neural changes with clinical manifestations, cognitive and social functioning and outcome. Understanding the progression of these changes over the span of the illness is important whilst taking into account the possible confounding effects of age, age of onset, duration of illness, sex, and treatment. This will potentially allow better staging of illness, identification of biomarkers for monitoring course of the illness as well as response to treatment.

CONCLUSIONS

In conclusion, despite heterogeneity of DTI findings in psychosis, there is mounting evidence of disruptions of white matter integrity in cortical-subcortical brain regions, as well as associative and commissural tracts, highlighting neural changes in patients affected by or at high-risk for psychosis.

Future studies need to validate these findings in larger samples of subjects and in different populations as well as chart the progress of these cerebral WM changes over time so as to better appreciate the trajectory with illness course, treatment and chronicity.

Particularly, it can be useful combining DTI studies to functional RMN methods in order to investigate mediating factors that will enhance our knowledge about pathophysiology of psychosis.

REFERENCES

1. Picchioni M, Murray RM. Schizophrenia. *BMJ* 2007; 335: 91-5.
2. Miguel-Hidalgo JJ. Brain structural and functional changes in adolescents with psychiatric disorders. *Int J Adolesc Med Health* 2013; 25: 245-56.
3. Benes F, Turtle M, Khan Y, Farol P. Myelination of a key relay zone in the hippocampal formation occurs in the human brain during childhood, adolescence and adulthood. *Arch Gen Psychiatry* 1994; 51: 477-84.
4. Lenroot RK, Giedd JN. Brain development in children and adolescents: insights from anatomical magnetic resonance imaging. *Neurosci Biobehav Rev* 2006; 30: 718-29.
5. Kuswanto CN, Teh I, Lee TS, Sim K. Diffusion tensor imaging findings of white matter changes in first episode schizophrenia: a systematic review. *Clin Psychopharmacol Neurosci* 2012; 10: 13-24.
6. Peters BD, Blaas J, de Haan L. Diffusion tensor imaging in the early phase of schizophrenia: what have we learned? *J Psychiatr Res* 2010; 44: 993-1004.
7. Pierpaoli C, Jezzard P, Bassar PJ, Barnett A, Di Chiro G. Diffusion tensor MR imaging of the human brain. *Radiology* 1996; 201: 637-48.
8. Kyriakopoulos M, Bargiotas T, Barker GJ, Frangou S. Diffusion tensor imaging in schizophrenia. *Eur Psychiatry* 2008; 23: 255-73.
9. Katagiri N, Pantelis C, Nemoto T, et al. A longitudinal study investigating sub-threshold symptoms and white matter changes in individuals with an 'at risk mental state' (ARMS). *Schizophr Res* 2015; 162: 7-13.
10. Bloemen O, de Koning MB, Schmitz N, et al. White-matter markers for psychosis in a prospective ultra-high-risk cohort. *Psychol Med* 2010; 40: 1297-304.
11. Muñoz Maniega S, Lymer GK, Bastin ME, et al. A diffusion tensor MRI study of white matter integrity in subjects at high genetic risk of schizophrenia. *Schizophr Res* 2008; 106: 132-9.
12. Camchong J, Lim KO, Sponheim SR, Macdonald AW. Frontal white matter integrity as an endophenotype for schizophrenia: diffusion tensor imaging in monozygotic twins and patients' nonpsychotic relatives. *Front Hum Neurosci* 2009; 3: 35.
13. Nakamura M, McCarley RW, Kubicki M, et al. Fronto-temporal disconnectivity in schizotypal personality disorder: a diffusion tensor imaging study. *Biol Psychiatry* 2005; 58: 468-78.
14. Karlsgodt KH, Niendam TA, Bearden CE, Cannon TD. White matter integrity and prediction of social and role functioning in subjects at ultra-high risk for psychosis. *Biol Psychiatry* 2009; 66: 562-9.
15. Peters BD, Dingemans PM, Dekker N, et al. White matter connectivity and psychosis in ultra-high-risk subjects: a diffusion tensor fiber tracking study. *Psychiatry Res* 2010; 181: 44-50.
16. Peters BD, de Haan L, Dekker N, et al. White matter fiber tracking in first-episode schizophrenia, schizoaffective patients and subjects at ultra-high risk of psychosis. *Neuropsychobiology* 2008; 58: 19-28.
17. Peters BD, Schmitz N, Dingemans PM, et al. Preliminary evidence for reduced frontal white matter integrity in subjects at ultra-high-risk for psychosis. *Schizophr Res* 2009; 111: 192-3.
18. Bertisch H, Li D, Hoptman MJ, Delisi LE. Heritability estimates for cognitive factors and brain white matter integrity as markers of schizophrenia. *Am J Med Genet B Neuropsychiatr Genet* 2010; 153B: 885-94.
19. Hazlett EA, Goldstein KE, Tajima-Pozo K, et al. Cingulate and temporal lobe fractional anisotropy in schizotypal personality disorder. *Neuroimage* 2011; 55: 900-8.
20. Kyriakopoulos M, Perez-Iglesias R, Woolley JB, et al. Effect of age at onset of schizophrenia on white matter abnormalities. *Br J Psychiatry* 2009; 195: 346-53.
21. Carletti F, Woolley JB, Bhattacharyya S, et al. Alterations in white matter evident before the onset of psychosis. *Schizophr Bull* 2012; 38: 1170-9.
22. Benetti S, Pettersson-Yeo W, Allen P, et al. Auditory verbal hallucinations and brain dysconnectivity in the perisylvian language network: a multimodal investigation. *Schizophr Bull* 2015; 41: 192-200.
23. Hoptman JM, Nierenberg J, Bertisch HC, et al. A DTI study of white matter microstructure in individuals at high genetic risk for schizophrenia. *Schizophr Res* 2008; 106: 115-24.
24. Smallman RP, Barkus E, Azadbakht H, et al. MRI diffusion tractography study in individuals with schizotypal features: a pilot study. *Psychiatry Res* 2014; 221: 49-57.
25. Domen PA, Michielse S, Gronenschild E, et al. Microstructural white matter alterations in psychotic disorder: a family-based diffusion tensor imaging study. *Schizophr Res* 2013; 146: 291-300.
26. Boos HB, Mandl RC, van Haren NE, et al. Tract-based diffusion tensor imaging in patients with schizophrenia and their non-psychotic siblings. *Eur Neuropsychopharmacol* 2013; 23: 295-304.
27. Epstein KA, Cullen KR, Mueller BA, Robinson P, Lee S, Kumra S. White matter abnormalities and cognitive impairment in early-onset schizophrenia-spectrum disorders. *J Am Acad Child Adolesc Psychiatry* 2014; 53: 362-72. e1-2.
28. DeRosse P, Nitzburg GC, Ikuta T, Peters BD, Malhotra AK, Szeszko PR. Evidence from structural and diffusion tensor imaging for frontotemporal deficits in psychometric schizotypy. *Schizophr Bull* 2015; 41: 104-14.
29. Lener MS, Wong E, Tang CY, et al. White matter abnormalities in schizophrenia and schizotypal personality disorder. *Schizophr Bull* 2015; 41: 300-10.
30. Lagopoulos J, Hermens DF, Hatton SN, et al. Microstructural white matter changes are correlated with the stage of psychiatric illness. *Transl Psychiatry* 2013; 3: e248.
31. Jacobson S, Kelleher I, Harley M, et al. Structural and functional brain correlates of subclinical psychotic symptoms in 11-13 year old schoolchildren. *Neuroimage* 2010; 49: 1875-85.
32. Goghari VM, Billiet T, Sunaert S, Emsell L. A diffusion tensor imaging family study of the fornix in schizophrenia. *Schizophr Res* 2014; 159: 435-40.
33. von Hohenberg CC, Pasternak O, Kubicki M, et al. White matter microstructure in individuals at clinical high risk of psychosis: a whole-brain diffusion tensor imaging study. *Schizophr Bull* 2014; 40: 895-903.
34. Pettersson-Yeo W, Benetti S, Marquand AF, et al. Using genetic, cognitive and multimodal neuroimaging data to identify ultra-high risk and first-episode psychosis at the individual level. *Psychol Med* 2013; 43: 2547-62.
35. Epstein KA, Kumra S. White matter fractional anisotropy over two time points in early onset schizophrenia and adolescent

Alterations of cerebral white matter structure in psychosis and their clinical correlations

- cannabis use disorder: a naturalistic diffusion tensor imaging study. *Psychiatry Res* 2015; 232: 34-41.
36. Mittal VA, Dean DJ, Bernard JA, et al. Neurological soft signs predict abnormal cerebellar-thalamic tract development and negative symptoms in adolescents at high-risk for psychosis: a longitudinal perspective. *Schizophr Bull* 2014; 40: 1204-15.
 37. DeRosse P, Ikuta T, Peters BD, Karlsgodt KH, Szeszko PR, Malhotra AK. Adding insult to injury: childhood and adolescent risk factors for psychosis predict lower fractional anisotropy in the superior longitudinal fasciculus in healthy adults. *Psychiatry Res* 2014; 224: 296-302.
 38. Skranes J, Vangberg TR, Kulseng S, et al. Clinical findings and white matter abnormalities seen on diffusion tensor imaging in adolescents with very low birth weight. *Brain* 2007; 130 (Pt 3): 654-66.
 39. Gilmore J, Kang C, Evans DD, et al. Prenatal and neonatal brain structure and white matter maturation in children at high risk for schizophrenia. *Am J Psychiatry* 2010; 167: 1083-91.
 40. Alvarado-Alanis P, León-Ortiz P, Reyes-Madriral F, et al. Abnormal white matter integrity in antipsychotic-naïve first-episode psychosis patients assessed by a DTI principal component analysis. *Schizophr Res* 2015; 162: 14-21.
 41. Chan WY, Yang GL, Chia MY, et al. White matter abnormalities in first-episode schizophrenia: a combined structural MRI and DTI study. *Schizophr Res* 2010; 119: 52-60.
 42. Karlsgodt KH, van Erp TG, Poldrack RA, Bearden CE, Nuechterlein KH, Cannon TD. Diffusion tensor imaging of the superior longitudinal fasciculus and working memory in recent-onset schizophrenia. *Biol Psychiatry* 2008; 63: 512-8.
 43. Mendelsohn A, Strous RD, Bleich M, Assaf Y, Hendler T. Regional axonal abnormalities in first episode schizophrenia: preliminary evidence based on high b-value diffusion-weighted imaging. *Psychiatry Res* 2006; 146: 223-9.
 44. Gasparotti R, Valsecchi P, Carletti F, et al. Reduced fractional anisotropy of corpus callosum in first-contact, antipsychotic drug-naïve patients with schizophrenia. *Schizophr Res* 2009; 108: 41-8.
 45. Melicher T, Horacek J, Hlinka J, et al. White matter changes in first episode psychosis and their relation to the size of sample studied: a DTI study. *Schizophr Res* 2015; 162: 22-8.
 46. White T, Magnotta VA, Bockholt HJ, et al. Global white matter abnormalities in schizophrenia: a multisite diffusion tensor imaging study. *Schizophr Bull* 2011; 37: 222-32.
 47. Wang Q, Deng W, Huang C, et al. Abnormalities in connectivity of white matter tracts in patients with familial and non-familial schizophrenia. *Psychol Med* 2011; 41: 1691-700.
 48. Tang J, Liao Y, Zhou B, et al. Abnormal anterior cingulum integrity in first episode, early-onset schizophrenia: a diffusion tensor imaging study. *Brain Res* 2010; 1343: 199-205.
 49. Bégre S, Federspiel A, Kiefer C, Schroth G, Dierks T, Strik WK. Reduced hippocampal anisotropy related to anteriorization of alpha EEG in schizophrenia. *Neuroreport* 2003; 14: 739-42.
 50. Cheung V, Chiu CP, Law CW, et al. Positive symptoms and white matter microstructure in never-medicated first episode schizophrenia. *Psychol Med* 2011; 41: 1709-19.
 51. Moriya J, Kakeda S, Abe O, et al. Gray and white matter volumetric and diffusion tensor imaging (DTI) analyses in the early stage of first-episode schizophrenia. *Schizophr Res* 2010; 116: 196-203.
 52. Price G, Cercignani M, Parker GJ, et al. White matter tracts in first-episode psychosis: a DTI tractography study of the uncinate fasciculus. *Neuroimage* 2008; 39: 949-55.
 53. Szeszko PR, Robinson DG, Ashtari M, et al. Clinical and neuropsychological correlates of white matter abnormalities in recent onset schizophrenia. *Neuropsychopharmacology* 2008; 33: 976-84.
 54. Pérez-Iglesias R, Tordesillas-Gutiérrez D, Barker GJ, et al. White matter defects in first episode psychosis patients: a voxelwise analysis of diffusion tensor imaging. *Neuroimage* 2010; 49: 199-204.
 55. Bijanki KR, Hodis B, Magnotta VA, Zeien E, Andreasen NC. Effects of age on white matter integrity and negative symptoms in schizophrenia. *Schizophr Res* 2015; 161: 29-35.
 56. Luck D, Malla AK, Joobor R, Lepage M. Disrupted integrity of the fornix in first-episode schizophrenia. *Schizophr Res* 2010; 119: 61-4.
 57. Kong X, Ouyang X, Tao H, et al. Complementary diffusion tensor imaging study of the corpus callosum in patients with first-episode and chronic schizophrenia. *J Psychiatry Neurosci* 2011; 36: 120-5.
 58. Schneiderman JS, Buchsbaum MS, Haznedar MM, et al. Age and diffusion tensor anisotropy in adolescent and adult patients with schizophrenia. *Neuroimage* 2009; 45: 662-71.
 59. Chen L, Chen X, Liu W, et al. White matter microstructural abnormalities in patients with late-onset schizophrenia identified by a voxel-based diffusion tensor imaging. *Psychiatry Res* 2013; 212: 201-7.
 60. Friedman J, Tang C, Carpenter D, et al. Diffusion tensor imaging findings in first-episode and chronic schizophrenia patients. *Am J Psychiatry* 2008; 165: 1024-32.
 61. Peters BD, Machielsen MW, Hoen WP, et al. Polyunsaturated fatty acid concentration predicts myelin integrity in early-phase psychosis. *Schizophr Bull* 2013; 39: 830-8.
 62. Hao Y, Liu Z, Jiang T, et al. White matter integrity of the whole brain is disrupted in first-episode schizophrenia. *Neuroreport* 2006; 17: 23-6.
 63. Cheung C, Cheung C, McAlonan GM, et al. A diffusion tensor imaging study of structural dysconnectivity in never-medicated, first-episode schizophrenia. *Psychol Med* 2008; 38: 877-85.
 64. Szeszko PR, Robinson DG, Ikuta T, et al. White matter changes associated with antipsychotic treatment in first-episode psychosis. *Neuropsychopharmacology* 2014; 39: 1324-31.
 65. Lee SH, Kubicki M, Asami T, et al. Extensive white matter abnormalities in patients with first-episode schizophrenia: a Diffusion Tensor Imaging (DTI) study. *Schizophr Res* 2013; 143: 231-8.
 66. Price G, Cercignani M, Parker GJ, et al. Abnormal brain connectivity in first-episode psychosis: a diffusion MRI tractography study of the corpus callosum. *Neuroimage* 2007; 35: 458-66.
 67. Qiu A, Zhong J, Graham S, Chia MY, Sim K. Combined analyses of thalamic volume, shape and white matter integrity in first-episode schizophrenia. *Neuroimage* 2009; 47: 1163-71.
 68. Dekker N, Schmitz N, Peters BD, van Amelsvoort TA, Linszen DH, de Haan L. Cannabis use and callosal white matter structure and integrity in recent-onset schizophrenia. *Psychiatry Res* 2010; 181: 51-6.
 69. Quan M, Lee SH, Kubicki M, et al. White matter tract abnormalities between rostral middle frontal gyrus, inferior frontal gyrus and striatum in first-episode schizophrenia. *Schizophr Res* 2013; 145: 1-10.
 70. Szeszko P, Ardekani BA, Ashtari M, et al. White matter abnormalities in first-episode schizophrenia and schizoaffective disorder: a diffusion tensor imaging study. *Am J Psychiatry* 2005; 162: 602-5.
 71. Kyriakopoulos M, Vyas NS, Barker GJ, Chitnis XA, Frangou S. A diffusion tensor imaging study of white matter in early-onset schizophrenia. *Biol Psychiatry* 2008; 63: 519-23.
 72. Reis Marques T, Taylor H, Chaddock C, et al. White matter integrity as a predictor of response to treatment in first episode psychosis. *Brain* 2014; 137: 172-82.
 73. Lu HL, Zhou XJ, Keedy SK, Reilly JL, Sweeney JA. White matter microstructure in untreated first episode bipolar disorder with psychosis: comparison with schizophrenia. *Bipolar Disord* 2011; 13: 604-13.
 74. Luck D, Buchy L, Czechowska Y, et al. Fronto-temporal disconnection and clinical short-term outcome in first episode psychosis: a DTI-tractography study. *J Psychiatr Res* 2011; 45: 369-77.
 75. Peters BD, de Haan L, Vlieger EJ, Majoie CB, den Heeten GJ, Linszen DH. Recent-onset schizophrenia and adolescent cannabis use: MRI evidence for structural hyperconnectivity? *Psychopharmacol Bull* 2009; 42: 75-88.

76. Palaniyappan L, Al-Radaideh A, Mouglin O, Gowland P, Liddle PF. Combined white matter imaging suggests myelination defects in visual processing regions in schizophrenia. *Neuropsychopharmacology* 2013; 38: 1808-15.
77. Nazeri A, Chakravarty MM, Felsky D, et al. Alterations of superficial white matter in schizophrenia and relationship to cognitive performance. *Neuropsychopharmacology* 2013; 38: 1954-62.
78. Orfei MD, Piras F, Macci E, Caltagirone C, Spalletta G. The neuroanatomical correlates of cognitive insight in schizophrenia. *Soc Cogn Affect Neurosci* 2013; 8: 418-23.
79. Roalf DR, Ruparel K, Verma R, Elliott MA, Gur RE, Gur RC. White matter organization and neurocognitive performance variability in schizophrenia. *Schizophr Res* 2013; 143: 172-8.
80. Hatton SN, Lagopoulos J, Hermens DF, Hickie IB, Scott E, Bennett MR. White matter tractography in early psychosis: clinical and neurocognitive associations. *J Psychiatry Neurosci* 2014; 39: 417-27.
81. Cullen KR, Wallace S, Magnotta VA, et al. Cigarette smoking and white matter microstructure in schizophrenia. *Psychiatry Res* 2012; 201: 152-8.
82. Marengo S, Stein JL, Savostyanova AA, et al. Investigation of anatomical thalamo-cortical connectivity and fMRI activation in schizophrenia. *Neuropsychopharmacology* 2012; 37: 499-507.
83. Yan H, Tian L, Yan J, et al. Functional and anatomical connectivity abnormalities in cognitive division of anterior cingulate cortex in schizophrenia. *PLoS One* 2012; 7: e45659.
84. Camchong J, MacDonald AW 3rd, Bell C, Mueller BA, Lim KO. Altered functional and anatomical connectivity in schizophrenia. *Schizophr Bull* 2011; 37: 640-50.
85. de Weijer AD, Mandl RC, Diederer KM, et al. Microstructural alterations of the arcuate fasciculus in schizophrenia patients with frequent auditory verbal hallucinations. *Schizophr Res* 2011; 130: 68-77.
86. Abdul-Rahman MF, Qiu A, Sim K. Regionally specific white matter disruptions of fornix and cingulum in schizophrenia. *PLoS One* 2011; 6: e18652.
87. Ardekani BA, Tabesh A, Sevy S, Robinson DG, Bilder RM, Szeszko PR. Diffusion tensor imaging reliably differentiates patients with schizophrenia from healthy volunteers. *Hum Brain Mapp* 2011; 32: 1-9.
88. Choi H, Kubicki M, Whitford TJ, et al. Diffusion tensor imaging of anterior commissural fibers in patients with schizophrenia. *Schizophr Res* 2011; 130: 78-85.
89. Antonius D, Prudent D, Rehani Y, et al. White matter integrity and lack of insight in schizophrenia and schizoaffective disorder. *Schizophr Res* 2011; 128: 76-82.
90. Filippi M, Canu E, Gasparotti R, et al. Patterns of brain structural changes in first-contact, antipsychotic drug-naïve patients with schizophrenia. *AJNR Am J Neuroradiol* 2014; 35: 30-7.
91. Sugranyes G, Kyriakopoulos M, Dima D, et al. Multimodal analyses identify linked functional and white matter abnormalities within the working memory network in schizophrenia. *Schizophr Res* 2012; 138: 136-42.
92. Wagner G, De la Cruz F, Schachtzabel C, et al. Structural and functional dysconnectivity of the fronto-thalamic system in schizophrenia: a DCM-DTI study. *Cortex* 2015; 66: 35-45.
93. Balevich EC, Haznedar MM, Wang E, et al. Corpus callosum size and diffusion tensor anisotropy in adolescents and adults with schizophrenia. *Psychiatry Res* 2015; 231: 244-51.
94. Garver DL, Holcomb JA, Christensen JD. Compromised myelin integrity during psychosis with repair during remission in drug-responding schizophrenia. *Int J Neuropsychopharmacol* 2008; 11: 49-61.
95. Rosenberger G, Kubicki M, Nestor PG, et al. Age-related deficits in fronto-temporal connections in schizophrenia: a diffusion tensor imaging study. *Schizophr Res* 2008; 102: 181-8.
96. Skelly LR, Calhoun V, Meda SA, Kim J, Mathalon DH, Pearlson GD. Diffusion tensor imaging in schizophrenia: relationship to symptoms. *Schizophr Res* 2008; 98: 157-62.
97. Nestor PG, Kubicki M, Spencer KM, Niznikiewicz M, McCarley RW, Shenton ME. Attentional networks and cingulum bundle in chronic schizophrenia. *Schizophr Res* 2007; 90: 308-15.
98. Liu H, Fan G, Xu K, Wang F. Changes in cerebellar functional connectivity and anatomical connectivity in schizophrenia: a combined resting-state functional MRI and diffusion tensor imaging study. *J Magn Reson Imaging* 2011; 34: 1430-8.
99. Caprihan A, Abbott C, Yamamoto J, et al. Source-based morphometry analysis of group differences in fractional anisotropy in schizophrenia. *Brain Connect* 2011; 1: 133-45.
100. Cui L, Chen Z, Deng W, et al. Assessment of white matter abnormalities in paranoid schizophrenia and bipolar mania patients. *Psychiatry Res* 2011; 194: 347-53.
101. Levitt JJ, Kubicki M, Nestor PG, et al. A diffusion tensor imaging study of the anterior limb of the internal capsule in schizophrenia. *Psychiatry Res* 2010; 184: 143-50.
102. Knöchel C, Stäblein M, Storchak H, et al. Multimodal assessments of the hippocampal formation in schizophrenia and bipolar disorder: evidences from neurobehavioral measures and functional and structural MRI. *Neuroimage Clin* 2014; 6: 134-44.
103. Whitford TJ, Lee SW, Oh JS, et al. Localized abnormalities in the cingulum bundle in patients with schizophrenia: a Diffusion Tensor tractography study. *Neuroimage Clin* 2014; 5: 93-9.
104. Mc-Carthy Jones S, Oestreich LK, Australian Schizophrenia Research Bank, Whitford TJ. Reduced integrity of the left arcuate fasciculus is specially associated with auditory verbal hallucinations in schizophrenia. *Schizophr Res* 2015; 162: 1-6.
105. Sasamoto A, Miyata J, Kubota M, et al. Global association between cortical thinning and white matter integrity reduction in schizophrenia. *Schizophr Bull* 2014; 40: 420-7.
106. Kawashima T, Nakamura M, Bouix S, et al. Uncinate fasciculus abnormalities in recent onset schizophrenia and affective psychosis: a diffusion tensor imaging study. *Schizophr Res* 2009; 110: 119-26.
107. Hatton SN, Lagopoulos J, Hermens DF, Hickie IB, Scott E, Bennett MR. Short association fibres of the insula-temporoparietal junction in early psychosis: a diffusion tensor imaging study. *PLoS One* 2014; 9: e112842.
108. Zou L, Xie JX, Yuan HS, Pei XL, Dong WT, Liu PC. Diffusion tensor imaging study of the anterior limb of internal capsules in neuroleptic-naïve schizophrenia. *Acad Radiol* 2008; 15: 285-9.
109. Giezendanner S, Walther S, Razavi N, et al. Alterations of white matter integrity related to the season of birth in schizophrenia: a DTI study. *PLoS One* 2013; 8: e75508.
110. Tang CY, Friedman J, Shungu D, et al. Correlations between Diffusion Tensor Imaging (DTI) and agnetic Resonance Spectroscopy (1H MRS) in schizophrenic patients and normal controls. *BMC Psychiatry* 2007; 7: 25.
111. Flügel D, Cercignani M, Symms MR, et al. Diffusion tensor imaging findings and their correlation with neuropsychological deficits in patients with temporal lobe epilepsy and interictal psychosis. *Epilepsia* 2006; 47: 941-4.
112. Mao LY, Ding J, Peng WF, et al. Disease duration and arcuate fasciculus abnormalities correlate with psychoticism in patients with epilepsy. *Seizure* 2011; 20: 741-7.
113. Cocchi L, Harding IH, Lord A, Pantelis C, Yucel M, Zalesky A. Disruption of structure-function coupling in the schizophrenia connectome. *Neuroimage Clin* 2014; 4: 779-87.
114. Zhong J, Wu S, Zhao Y, et al. Why psychosis is frequently associated with Parkinson's disease? *Neural Regen Res* 2013; 8: 2548-56.