Glutamatergic dysfunction linked to energy and membrane lipid metabolism in frontal and anterior cingulate cortices of never treated first-episode schizophrenia patients

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A B S T R A C T

Background: Glutamatergic dysfunction and altered membrane lipid and energy metabolism have been repeatedly demonstrated in the frontal/prefrontal and anterior cingulate cortex (ACC) in schizophrenia. Though having been already studied in animals, the presumed link between glutamatergic function and structural plasticity has not been investigated directly in the human brain yet. We measured glutamate (Glu), focal energy metabolism, and membrane phospholipid turnover to investigate main pathologies in those key brain regions of schizophrenia.

Methods: 1H- and 31P-Chemical Shift Imaging (CSI) was combined in a single session to assess Glu and markers of energy (PCr, ATP) and membrane lipid (PME, PDE) metabolism in 31 neuroleptic-naïve first acute illness and possibly associated with negative symptoms and cognitive impairment. Our findings underline the importance of further research on neuroprotective treatment options during the early acute or even better for the ultra-high risk state of psychotic illness.

Conclusion: Frontal glutamatergic hyperactivity is disconnected from physiologically regulated energy metabolism and is associated with increased membrane breakdown in right and increased membrane restoration in left frontal and prefrontal cortical regions. As indicated by previous findings, this pathology is likely dynamic during the course of first acute illness and possibly associated with negative symptoms and cognitive impairment. Our findings underline the importance of further research on neuroprotective treatment options during the early acute or even better for the ultra-high risk state of psychotic illness.

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role in cortical projections to diverse subcortical regions (hippocampus, amygdala, basal ganglia), in inter-cortical projections and in thalamocortical tracts, such as the glutamatergic connections between thalamus and medial prefrontal and anterior cingulate cortices. In addition, corticofugal glutamatergic neurons control monoaminergic neurons and provide direct activation of dopaminergic, noradrenergic and serotonergic neurons. Furthermore, they inhibit monoaminergic neurons via activation of intermediary GABA-ergic inter-neurons enabling highly sensitive regulation of monoamines (Vogt, 1993).

In animal studies, the different regulation states of the glutamate/dopamine system were found to be important for early neurodevelopment and synaptic plasticity during adolescence/early adulthood (Bondi et al., 2012). Accordingly, regulation defects were identified to predispose disturbed synaptic plasticity in functionally important brain regions leading to the manifestation of symptoms summarized as “hypofrontality” in humans (Grace, 1993; Yin et al., 2012). Excess dopaminergic activity can enhance release of Glu, which in turn may cause excitotoxic cell or dendrite damage (Finlay and Zigmond, 1997; Reid et al., 1997) with crucial consequences in the adolescent/young adult brain.

Combining the notions of glutamatergic dysfunction, dysregulation of brain activity, and impaired membrane phospholipid turnover, we hypothesize that disease related glutamatergic dysfunction is linked to altered energy and membrane metabolism. However, so far it has been difficult to demonstrate this association in the human brain. Therefore, we investigated this link by means of combined proton and phosphorous MR spectroscopic (1H/31P-MRS) measurements.

In vivo proton spectroscopy (1H-MRS) allows quantification of several brain metabolites, including Glu. Glu is synthesized in axon terminals of glutamatergic neurons, either from α-ketoglutarate or from glutamine (Gln). It has been estimated that 80% of stimulus–release Glu is derived from Gln (Erecinska and Silver, 1990; Ross, 1991). A dynamic balance exists between Glu and Gln to maintain appropriate levels of Glu (Erecinska and Silver, 1990; Williamson et al., 1996).

A recent meta-analysis of 1H-MRS studies that focused on the Glu/Gln complex revealed decreased medial frontal Glu and increased Gln in first-episode schizophrenia patients (FEP) (Marshall et al., 2013). Reviewing findings in never-medicated and medicated patients separately, drug-naïve patients were reported with no changes of glutamatergic levels (measured by Glx, Gln) in the dorsolateral prefrontal cortex of never treated FEP and matched healthy controls (HC) to address the following main hypothesis.

1. Glu is dysregulated in the frontal/prefrontal and anterior cingulate cortex indicating glutamatergic dysfunction. If verified, this finding serves as the precondition to investigate the following main hypothesis.

2. In the frontal/prefrontal and anterior cingulate cortex of patients altered glutamatergic function is associated with focally altered PDE and PME and/or altered PCr and ATP.

2. Methods

2.1. Subjects

We investigated 31 FEP (16 males/15 females) and 31 HC (16 males/15 females), all right-handed and matched for age and gender (Table 1). All patients suffered their first schizophrenic episode, paranoid-hallucinatory sub-type, according to DSM-IV criteria for schizophrenia. All diagnoses were independently established by two board certified psychiatrists (S.St., H.S.) and confirmed by standardized structured clinical interviews (SCID-IV) (Wittchen et al., 1997). Psychopathology

<table>
<thead>
<tr>
<th>First episode patients (FEP)</th>
<th>Healthy controls (HC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>31</td>
</tr>
<tr>
<td>Gender (male)</td>
<td>16 (52%)</td>
</tr>
<tr>
<td>Age (years) mean (± SD)</td>
<td>25.97 (± 4.95)</td>
</tr>
<tr>
<td>Alcohol</td>
<td></td>
</tr>
<tr>
<td>Less than weekly</td>
<td>6 (19.4%)</td>
</tr>
<tr>
<td>1–6 drinks/week</td>
<td>23 (74.2%)</td>
</tr>
<tr>
<td>Daily</td>
<td>2 (6.4%)</td>
</tr>
<tr>
<td>Marijuana</td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>10 (32.3%)</td>
</tr>
<tr>
<td>Less or equal 2 g/week</td>
<td>18 (58.1%)</td>
</tr>
<tr>
<td>More than 2 g/week</td>
<td>3 (9.7%)</td>
</tr>
<tr>
<td>Psychiatric medication</td>
<td></td>
</tr>
<tr>
<td>Antipsychotic medication</td>
<td>Naive</td>
</tr>
<tr>
<td>Antidepressant</td>
<td>0</td>
</tr>
<tr>
<td>Benzodiazepine (sporadic)</td>
<td>6 (19.4%)</td>
</tr>
<tr>
<td>Duration of untreated psychosis (DUP)</td>
<td>5.2 ± 1.7 month</td>
</tr>
</tbody>
</table>

Data are mean (± standard deviation, SD) or n (%). PANSS denotes Positive and Negative Syndrome Scale.

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was assessed using PANSS scores (Kay et al., 1987). All patients were neuroleptic-naïve.

Healthy volunteers were recruited by newspaper advertisement. They were examined using a semi-structured interview to assess current mental status and to exclude personal or first-degree family history of psychiatric disorders or history of neurological or major medical conditions, possibly affecting brain metabolism. None of the volunteers suffered from concurrent substance dependence or had a history of substance dependence or abuse. The study was approved by the Ethics Committee of the Jena University Hospital. All subjects gave written informed consent to participate in the study.

2.2. Experimental setting, scan parameters and post-processing of data

All measurements were performed at the same time of day following the examination protocol in Table 2 (TA ≈ 85 min). The table also contains the data processing steps to quantify proton and phosphorous metabolic compounds.

The planning procedure to identically position the 1H- and 31P-CSI (Chemical Shift Imaging) slice is displayed in Fig. 1a–b. A region of interest was selected in the frontal part of the CSI slab including 8 voxels assigned to the frontal and prefrontal as well as the anterior cingulate cortex (Fig. 1c). Region specific metabolite measures were determined for 1H compounds (expressed as absolute concentrations in mmol/l and corrected for the individual GM, WM and CSF fractions in spectroscopic voxels (Gussew et al., 2012)) and as total phosphorous normalized intensities for 31P compounds (see Fig. 1d–e, respectively).

In case of 1H-MRS we focussed our analyses on Glu which can be measured with high accuracy at 3 T, and which represents a direct expression of glutamatergic function. As a number of previous studies used Glx as a measure of the glutamatergic regulation state, we also provide the respective results as Supplementary material.

2.3. Statistical analyses

2.3.1. Analysis of glutamate values, gray matter fraction and psychopathology

Focussing on Glu as independent variable, we initially tested Glu for group differences in each spectroscopic voxel using T-tests. Results were Bonferroni-corrected for multiple comparisons (n = 8, p = 0.00625). To assess partial volume effects caused by possible differences were Bonferroni-corrected for multiple comparisons (n = 8, p = 0.00625). To assess partial volume effects caused by possible differences in the examination protocol in Table 2 (TA = 45 min).

The effect of Glu alterations on energy and membrane phospholipid metabolism in particular brain regions was investigated by multivariate analysis of covariance (MANCOVA) incorporating an “interaction term”. To analyze associations between Glu and energy metabolism, both PCr and ATP were included as dependent variables (since PCr and ATP are presumably correlated), whereas group (FEP vs. HC) was included as between-subject variable, and Glu was used as covariate. Concerning associations between Glu and phospholipid metabolism, PME and PDE were both treated as dependent variables (like PCr and ATP). We focussed on the group by Glu interactions, i.e., whether and how the illness’s impact on Glu affected the dependent variables PCr, ATP, PME, and PDE. The level of significance was set at p ≤ 0.05. Taken into account that patients were untreated at the time of measurement and that the scan time of each session was >1 h, the “n” of this population is comparably high among spectroscopy studies. Nevertheless, we estimated the a priori possibility to reveal significant results in a MANCOVA as low in this population. Therefore, and because our study is the first combined spectroscopy study in this field, we did not apodistically exclude results at trend level from further discussion. All statistical analyses were performed with IBM SPSS Statistics (Version 19).

3. Results

3.1. Demographics

FEPs were moderately ill according to the PANSS scores. Although alcohol and cannabis consumption was higher in FEP, none of them fulfilled the criteria of alcohol or drug abuse (Table 1).

3.2. Quality of MR spectra

All spectra in the predefined region-of-interest had sufficient SNR and narrow linewidth (1H-MRS: SNR > 25, linewidth < 7.5 Hz; 31P-MRS: SNR > 15, linewidth < 7.5 Hz). With Cramer–Rao-Lower-Bounds (CRLB) for PCr, PME and PDE being <10%, and <15% for Glu, spectra quality was considered adequate to quantify metabolic intensities with sufficient accuracy.

Table 2

<table>
<thead>
<tr>
<th>Experimental settings</th>
<th>MR scanner</th>
<th>RF coil</th>
<th>TI-weighted, 3D brain MRI</th>
</tr>
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<tr>
<td></td>
<td>3 T whole-body (Magnetom TIM Trio, Siemens Medical Solutions, Erlangen, Germany)</td>
<td>Double-resonance transmit/receive volume head coil providing acquisition of 1H/P-MRS data in the same session (Biomedical Rapid, Germany)</td>
<td>MP-RAGE, 192 sagittal slices TR/TE/TI: 2300/3.03/900 ms, FOVAP × HF: 25.6 × 25.6 cm2, 256 × 256 matrix</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PRESS, based, TE/TR: 30/2000 ms, Vol: 15 × 9 × 1.5 cm3, FOVAP × zi × zc: 24 × 24 × 24 cm3, 16 × 16 × 16 phase encoding steps, nominal voxel size: 15 × 15 × 15 mm3; manual shim; with and without water suppression; TA = 15 min</td>
</tr>
<tr>
<td></td>
<td>2D 1H-CSI</td>
<td></td>
<td>PRESS sequence with slice selective rf excitation and 8 × 8 × 8 phase encoding steps; TR: 3 s; FOVAP × zi × zc: 24 × 24 × 24 cm3; spatial extrapolation to 16 × 16 × 16 1.5 × 1.5 × 1.5 cm3 voxels; TA = 45 min</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data post-processing</th>
<th>MRI</th>
<th>1H-CSI</th>
<th>31P-CSI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Quantitation with LCM (Provencher, 1993) by using a vendor provided basis set including 15 model spectra of, e.g., NAA, creatine, total choline, myo-inositol, glutamate and glutamine</td>
<td>Determination of absolute concentrations (in mmol/l) by using water as internal concentration reference</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Quantitation of PME, PDE, PCr, Pi and ATP intensities with jMRUI (<a href="http://www.mrui.uab.es/mrui/">www.mrui.uab.es/mrui/</a>) (Stefan et al., 2009); AMARES tool (Vanhamme et al., 1997) and subsequent normalization with the total phosphorus amount in the spectrum. For an example of a 1H- and 31P-spectrum, see Fig. 1d and e, respectively</td>
<td></td>
</tr>
</tbody>
</table>
3.3. Correlations between metabolite values and psychopathology

No significant correlations were found between Glu and psychopathological measures (Glu/PANSS total score $r = 0.28$, $p = 0.572$; Glu/PANSS pos. $r = 0.32$; $p = 0.763$; Glu/PANSS neg. $r = 0.27$, $p = 0.543$).

3.4. Group effects of Glu values and dependency on GM fraction

Glu was significantly increased in voxel 1 to 4, voxel 5 and voxel 8 (Table 3), though only the results of voxels 1–4 survived Bonferroni correction. Glu increases in the latter voxels were not associated statistically with possible group differences of GM fraction in these voxels (group by GM interaction of univariate ANCOVA: $\text{vox} 1 F_{(1,58)} = 0.053$, $p = 0.819$; $\text{vox} 2 F = 0.437$, $p = 0.511$; $\text{vox} 3 F = 0.021$, $p = 0.887$; $\text{vox} 4 F = 0.520$, $p = 0.474$). Group comparisons of PME, PDE, PCr, and ATP revealed no significant differences in none of the investigated voxels.

3.5. Associations between glutamate, energy and phospholipid metabolism

We performed two multivariate analyses of covariance (one using PCr and ATP, the other using PME and PDE as dependent variables) in each voxel that showed significantly increased Glu levels (vox 1–4, 5, and 8). We focussed on group by Glu interactions that indicate an influence of illness on the associations between Glu and PCr (or ATP), and PDE (or PME), respectively. Results of multivariate tests are presented in Table 4; corresponding results of univariate tests and mean values with standard deviations are summarized in Table 5.

The most pronounced effects (i.e., reaching significance levels in multivariate tests, see Table 4) were observed in voxels assigned to the right frontal and anterior cingulate cortex (vox 1 and 2). In voxel 1 (assigned to the right frontal/prefrontal cortex), illness affected the correlation between Glu and PCr (i.e., metabolites of phospholipid degradation) (Fig. 2a). While in healthy individuals higher Glu values were associated with lower PDE levels, the opposite held true in patients. In voxel 2 (assigned to the right ACC), illness affected the correlation between Glu and PDE; the main intermediate energy storage (Fig. 3b). While in HC higher Glu values were linked to lower Pcr levels, patients were lacking this association.

Weaker results (trend level in multivariate tests, see Table 4) were obtained in voxels assigned to the left frontal/prefrontal and dorsolateral prefrontal cortex (vox 4 and 8). Here, illness seemed to influence also the association between Glu and PME and PCr, i.e., metabolites of phospholipid synthesis and membrane restoration (Fig. 2c and d). While in healthy subjects Glu and PME were not observably associated, higher Glu values were connected with higher PME values in patients. Although not significant in the multivariate test, an effect similar to the finding in the right ACC (Fig. 3b) was observed for the energy metabolites in the left frontal/prefrontal cortex (Fig. 3c). The negative correlation between Glu and Pcr in healthy controls was absent in patients.

Finally, we considered general effects of Glu without taking into account group differences (i.e., group by Glu interactions in multivariate
In summary, Glu levels were increased in the frontal/prefrontal cortex bilaterally and in the anterior cingulate cortex of patients. These results are stable also if controlled for multiple comparisons (Bonferroni). In the patient group, higher Glu was associated with lower PCr or ATP values bilaterally in the frontal/prefrontal cortex and in the right ACC. These associations were not observed in patients in the right ACC and in the left frontal/prefrontal cortex. All results of the interaction analyses by MANCOVA do not survive adjustment for multiple comparisons.

4. Discussion

We hypothesized that glutamatergic functioning is impaired in never treated FEP. Indeed, we observed increased Glu levels in the frontal and prefrontal cortex bilaterally and in the anterior cingulate cortex. These results remained stable after adjustment for multiple comparisons. With about 80% of stimulus-released Glu being derived from Gln (Erecinska and Silver, 1990; Ross, 1991), increased Glu likely reflects increased glutamatergic activity. This corresponds to the increased glutamatergic levels reported in the medial frontal cortex (meta-analysis by Marsman 2013 (Marsman et al., 2013)) and in the medial prefrontal and anterior cingulate cortex (ACC) (Theberge et al., 2002, 2007) of never-medicated drug-naïve patients (review by Poels et al. (2014)).

The interpretation of focally increased Glu levels is supported by the associations with energy metabolites and membrane lipid compounds. These results are, although significant statistically less powerful as the Glu group differences, as they would not survive adjustment for multiple comparisons. However, concerning energy metabolites, higher Glu levels were bilaterally associated with lower PCr or ATP values in frontal/prefrontal regions and in the right ACC of healthy individuals. Higher glutamatergic activity is obviously associated with higher energy demands met by ATP and higher strain of intercellular phosphate buffer (reflected by decreased PCr). Of note, Glu transport, being part of the metabolic Glu/Gln cycling, is energy consuming and closely connected to the mitochondrial PCr/ATP metabolism (Faroqui et al., 2000; Kanai el al., 2013). The observation that patients did not show negative correlations between Glu and PCr or ATP in the right...
ACC and left frontal and prefrontal cortex points to a focal decoupling of glutamate and energy metabolism under the condition of illness, which might be clinically reflected as negative symptomatology or impaired cognitive function (Kato et al., 1995; Volz et al., 1998). Thus, increased glutamatergic activity seems to be ineffective in warranting adequate social/cognitive functioning. This is in line with the finding of Bartha and colleagues (Bartha et al., 1997) who also reported co-occurrence of increased medial frontal Gln and increased (instead of decreased) PCr.

According to our hypothesis, effects of illness on Glu are also affecting those phospholipid compounds that maintain membrane structure. Higher Glu was associated with increased left frontal/prefrontal PME and right frontal/prefrontal PDE in patients, whereas healthy controls did not show such associations. We therefore argue that the previously reported increased PDE levels in frontal/prefrontal regions of neuroleptic-naïve patients (Keshavan et al., 1989; Pet tegrew et al., 1991; Shioiri et al., 1997; Stanley et al., 1994) and associations with cognitive impairment and increased negative symptoms (Deicken et al., 1995; Shioiri et al., 1994, 1997; Volz et al., 1998) are related to the glutamatergic regulation state. Taking into account the findings of animal studies mentioned before (Grace, 1993), enhanced “phasic” glutamatergic activity may predispose increased stress-induced dopamine release and concomitantly induce excitotoxicity and oxidative membrane damage (current literature on Glu induced excitotoxicity reviewed by (Plitman et al., 2014)). This pathway could explain focally increased membrane breakdown as indicated by higher PDE levels, or increased efforts of compensatory membrane regeneration and repair as reflected by increased PME levels.

Our direct group comparisons were unable to replicate the previously reported findings of increased prefrontal/frontal PDE or decreased PME (Keshavan et al., 1989; Pet tegrew et al., 1991; Stanley et al., 1995). We speculate that the extent of membrane damage and respective processes of restoration are dynamic and occur during the early course of acute illness. While in our patient population membrane turnover has been supposedly still in balance, it may progressively deteriorate with continuing active illness, as reported by other groups.

Regarding the left ACC we emphasize our observation that in all participants higher Glu levels were associated with higher PDE levels. This likely reflects a general close connection between brain activity and membrane lipid turnover in this brain region, which also implies high susceptibility to hyperexcitation and excitotoxicity. Again, in our population of early acute patients metabolism of the ACC did not differ (yet) from that of healthy individuals.

5. Limitations

Differing amounts of metabolites in gray or white matter (Hetherington et al., 2001; Jensen et al., 2006) or inter-individual variations of gray and white matter composition in voxels do influence spectroscopic measurements. To control for partial volume effects, we compared the gray matter fraction of each voxel between the groups and used it as a covariate in our group comparisons of Glu. Although we observed neither group differences in gray matter fractions nor significant group by GM interactions, we nevertheless stress that small partial volume effects cannot be completely ruled out.

As mentioned before, even significant results of our complex statistical model need to be interpreted with caution. While the highly significant increase of Glu in patients survived the conservative Bonferroni correction, this was not the case for the results of our interaction analyses. Despite this statistical weakness, we consider our results quite plausible and mainly in line with previous findings. Furthermore, we have combined for the first time 1H- and 31P-MRS in a clinical population, which explains its partly explorative character. Certainly, our results
need confirmation by independent replication presumably in a multi-center setting.

6. Conclusion

Glutamatergic activity is increased in never treated early course acute schizophrenic patients in the bilateral prefrontal/frontal and anterior cingulate cortex. This hyperactivity seems disconnected from physiologically regulated energy metabolism but associated with increased membrane breakdown in right frontal and increased membrane restoration in left frontal regions. Considering findings of other research groups, this pathology is likely dynamic during the course of first acute illness and might be associated with negative symptoms and impairment of cognitive performance. Our findings underline the importance of further research on neuroprotective treatment options, e.g., restoration of polyunsaturated fatty acid deficits by supplementation (Berger et al., 2008; Hoen et al., 2013), during the early acute or even better for the ultra-high risk state of psychotic illness.

Role of the funding source

The sponsor of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Author contributions

Drs Smesny and Gussew had full access to all the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis; all authors contributed to the writing of the paper and have approved the final version.

Conflict of interest statement

We declare that we have no conflict of interest.

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References


