Altered brain high-energy phosphate metabolism in mild Alzheimer's disease: A 3-dimensional $^{31}$P MR spectroscopic imaging study

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A B S T R A C T

In Alzheimer's disease (AD), defects in essential metabolic processes for energy supply and phospholipid metabolism have been implicated in the pathological process. However, post-mortem investigations are generally limited to late stage disease and prone to tissue decay artifacts. In vivo assessments of high energy phosphates, tissue pH and phospholipid metabolites are possible by phosphorus MR spectroscopy ($^{31}$P-MRS), but so far only small studies, mostly focusing on single brain regions, have been performed. Therefore, we assessed phospholipid and energy metabolism in multiple brain regions of 31 early stage AD patients and 31 age- and gender-matched controls using $^{31}$P-MRS imaging. An increase of phosphocreatine (PCr) was found in AD patients compared with controls in the retrosplenial cortex, and both hippocampi, but not in the anterior cingulate cortex. While PCr/inorganic phosphate and pH were also increased in AD, no changes were found for phosphocholine (PCh) and phosphomonoesters (PME). This study showed that PCr levels are significantly increased in regions that show early degeneration in AD. Together with an increased pH, this indicates an altered energy metabolism in mild AD.

1. Introduction

Alzheimer's disease (AD) is the main cause of dementia in the elderly, responsible for about half of the nearly 47 million dementia cases worldwide (Report, 2015). Although the disease is defined by the accumulation of amyloid beta plaques and neurofibrillary tangle tangles in the brain (Braak and Braak, 1991), other pathological processes can be identified such as oxidative stress, vascular dysfunction, and inflammation (Akiyama et al., 2000; de la Torre, 2004; Markesbery, 1997). Additionally, defects in essential metabolic processes for energy supply and membrane function have been implicated in AD (Lynn et al., 2010; Nitsch et al., 1992).

The human brain is highly vulnerable to disturbances in energy metabolism, due to its relatively large energy consumption. Previous AD studies demonstrated alterations in global and cellular energy metabolism. FDG-PET studies have shown glucose hypometabolism in the retrosplenial cortex (RSC) and medial temporal lobe in people with mild cognitive impairment (MCI) and AD patients, as well as in cognitively normal carriers of the APOE ε4 allele (Nestor et al., 2003; Pietrini et al., 2000; Reiman et al., 2001; Reiman et al., 2005). Furthermore, the enzyme creatine kinase (CK), obtained from post-mortem AD tissue, shows reduced activity compared with samples that are free from neurological disease (Aksenov et al., 2000; David et al., 1998). The CK reaction, key to balance brain energy metabolism, can quickly replenish adenosine triphosphate (ATP) from the energy buffer phosphocreatine (PCr), when local energy demands suddenly increase (Lowe et al., 2015). This reaction also enhances the efficiency of mitochondrial oxidative phosphorylation (OXPHOS) by keeping adenosine diphosphate (ADP) sufficiently available (Schlattner et al., 2006) and prevents acidification by maintaining pH (for a review see...
One of the earliest pathological changes in AD is synaptic dysfunction, which correlates well with cognitive dysfunction and disease severity (Terry et al., 1991). Alterations in neuronal membrane composition, vital for synaptic transmission, have been linked to synaptic dysfunction in AD (Pomponi et al., 2008). For instance, post mortem studies found reduced levels of the major membrane components phosphatidylcholine, phosphatidylethanolamine and phosphatidylinositide (Nitsch et al., 1992; Pettetrew et al., 2001), as well as altered activity of catalytic and anabolic enzymes, suggesting compensatory metabolic changes to reduce the rate of neuronal membrane loss (Ross et al., 1998).

High energy phosphates, such as ATP and PCr, and metabolites of phospholipid membrane metabolism can be assessed in vivo by phosphorous magnetic resonance spectroscopy (31P-MRS). This technique has been applied in AD (e.g. Forlenza et al., 2002; Mandal et al., 2012; Pettetrew et al., 1994; Smith et al., 1995), but previous studies, essentially focusing on single brain regions, were severely hampered by small sample sizes and low spectral resolution, resulting in a wide disparity in findings. Furthermore, differences in the control groups that were used, in the brain regions that were studied and in the disease stages and medication statuses of the patients, may have contributed to apparent inconsistencies in the literature.

The aim of the current study was to investigate whether abnormal phospholipid and energy metabolism can be detected non-invasively in early stage AD patients by 31P MR spectroscopic imaging (31P-MRSI). This investigation was designed to overcome the limitations of previous studies. First, we performed the measurements at 3T field strength with proton (H1) decoupling to increase spectral resolution and sensitivity. Secondly, by applying 31P-MRSI in a 3-dimensional imaging mode we could investigate multiple brain regions simultaneously. We specifically addressed regions that are of interest in AD, namely, the hippocampus, the RSC, and the anterior cingulate cortex (ACC). Finally, we selected a well-defined drug-naïve patient group and an age- and gender-matched control group.

2. Materials and methods

2.1. Subjects and design

All visits of patients and controls to the Radboud university medical center (Nijmegen, the Netherlands) took place between 2012 and 2015. Patients aged ≥50 years with a diagnosis of possible or probable AD according to the revised National Institute of Neurological and Communicative Disorders and Stroke and the Alzheimer’s Disease and Related Disorders Association 2011 criteria (McKhan et al., 2011) with evidence of the pathophysiological process (i.e. from structural MRI or cerebrospinal fluid biomarker assays) and with a minimum Mini Mental State Examination (MMSE) score of 20, were recruited from the hospital’s memory clinic or by referral from regional hospitals. All AD patients participated in a randomized controlled trial on the effect of a medical food on brain phospholipid metabolism (Rijpma et al., 2017; Dutch Trial Register 3346). Only baseline data were used in the current study. Healthy control subjects, age- and gender-matched to the AD group, were screened by telephone before being invited to the clinic. All subjects were drug-naïve for AD medication (cholinesterase inhibitors and NMDA-antagonists) and were free from neurological or psychiatric disorders (other than dementia, for the AD patients). Patients nor healthy controls used nutritional supplements containing docosahexaenoic acid, eicosapentaenoic acid or > 200% of the recommended daily allowance of vitamins B, C, or E. All subjects were screened for MRI contra-indications before inclusion in the study.

Written informed consent was obtained from all subjects and from the informal caregivers of the AD patients. The local ethics committee reviewed and approved the protocol and the study was conducted in accordance with the Declaration of Helsinki.

Medical history, medication use and MMSE were recorded from all subjects, as well as date of birth, sex, ethnicity, smoking habits, alcohol consumption, and family history of AD. Level of education was classified according to Verhage (Verhage, 1964) (comparable with the International Standard Classification of Education) and categorized in three groups: primary education or lower (low), junior vocational training (middle), and senior vocational or academic training (high).

2.2. MR acquisition

MRI and MRS were performed on a Magnetom Tim Trio 3T MR system (Siemens, Erlangen, Germany) with a dual-tuned 1H-31P volume head coil (Rapid Biomedical, Wuerzburg, Germany). High resolution MR images were acquired with a T1-weighted magnetisation-prepared rapid gradient-echo sequence (TR = 2300 ms, TE = 3.16 ms, TI = 1100 ms, 15° flip-angle, 176 sagittal slices, slice-matrix size = 256 × 256 mm, slice thickness = 1 mm, voxel-size = 1 × 1 × 1 mm, TA = 6:25 min).

31P-MR spectra were acquired with whole brain 3D MRSI (a pulse-acquire sequence with 40° flip-angle, acquisition delay of 0.7 ms including 0.3-ms gradient phase encoding time, 512 ms acquisition duration with WALTZ4H decoupling during the first 256 ms with γ1B = 250 Hz ensuring (γ1B)2 > (JppH)2, TR = 2000 ms, FOV 260 × 260 × 260 mm; matrix size = 10 × 10 × 10, acquisition time 13:08 min). Prior to acquisition, an automatic procedure was applied to optimize the magnetic field homogeneity of a rectangular shim volume maximizing brain coverage while bound by the skull. Subsequently, if necessary, the field homogeneity was further adjusted manually until a value of < 25 Hz was obtained for the full width at half maximum of the absolute-value 1H MR water signal. K-space was sampled with a weighted elliptical phase-encoding scheme with four averages. The volume of interest was centered on the midline and parallel to the line from the anterior commissure to the posterior commissure. Spatial post-processing consisted of zero-filling to a matrix size of 16 × 16 × 16. The nominal volume of the measured voxels is about 17.5 cm3, the effective voxel at 64% of the spatial response function has a spherical shape with a volume of about 40 cm3 (Pohmann and von Kienlen, 2001).

2.3. MRS and MRI data analyses

Four regions of interest (ROI) were selected for analysis from the 3D 31P-MRSI data: ACC, RSC, and left and right hippocampus (HL and HR). Guided by the T1-weighted images, the MRSI grid was shifted in the x, y and z dimension to position voxels in the ROI’s (by AR; Fig. 1). For the ACC, a voxel was selected anterior to the genu of the corpus callosum, with the inferior border aligned with the line from the anterior commissure to the posterior commissure (AC-PC line), and on the midsagittal plane. For the RSC, a voxel on the midsagittal plane was selected posterior to the splenium of the corpus callosum, with the inferior border aligned with the AC-PC line. For the HL and HR, a voxel was selected at the anterior end of each hippocampus, with the inferior and lateral border of the voxel aligned with the inferior and lateral side of the hippocampus.

The software package Metabolite Report (Siemens Healthcare, Erlangen, Germany) was used for post-processing (i.e. 100 ms exponential filter, zero-filling, phase correction, baseline correction) and for automatic fitting of the spectra in the time-domain using prior knowledge appropriate for 31P MR spectra (own spectral data and from de Graaf (2008)). Eleven well-resolved resonance peaks were fitted: the phospholipid metabolites phosphoethanolamine (PEth), phosphocholine (PCh), glycerophosphocholine (GPeth) and glycerophosphoglycerol (GPch), the high-energy phosphorus molecules PCr, ATP (α-ATP, β-ATP and γ-ATP), nicotinamide adenine dinucleotide (NAD) (H) and inorganic phosphate (Pi), and membrane-bound phospholipid (details of this procedure are described in the Appendix).

Both a quantitative evaluation of the fitting results and a visual quality control were performed. Quantitatively, only metabolite fits
with a Cramer–Rao lower bound of $\leq 30\%$ were considered reliable. Qualitatively, two MR spectroscopists (AR and MvdG) independently checked the spectra by visual inspection of the original spectra and the fitting results. If a metabolite peak was visually present, and its fit was assigned to the correct resonance—giving a minimal residue in the subtraction spectrum—the fitting result was accepted.

The integral of each metabolite resonance was expressed as a percent area of the total phosphorous signal in the corresponding spectrum. Hereby, the data were normalized, and corrected for cerebrospinal fluid (CSF) content and thus for differences in local atrophy. Phosphomonoesters (PME) were calculated from the sum of PEth and PCr; phosphodiesters (PDE) from GPeth and GPC and total ATP ($t$ATP) from the sum of $\alpha$-ATP, $\beta$-ATP and $\gamma$-ATP. In addition, the ratios PME/PDE, PE/GPE, PC/GPC and PCr/Pi were computed. Intracellular pH was determined from the chemical shift difference between the PCr and Pi resonance peaks (Petroff et al., 1985).

The T1-weighted images were segmented into grey matter (GM), white matter (WM) and CSF using automatic segmentation software (by AR; SPM8, Welcome Trust Centre for Neuroimaging, London, UK; VBM8, Structural Brain Mapping Group, Jena, USA). Binary tissue maps (matrices) of GM, WM, CSF were convolved with the, digitally sampled, mathematically-modelled three dimensional point-spread function of the MRSI, using Matlab 2012b (The Mathworks, Inc., Cary, NC, USA), to obtain theoretically correct values of the contribution of tissue type to each ROI (each consisting of one MRS voxel). GM-to-WM ratio (GM/WM) was calculated for each ROI for each subject.

### 2.4. Statistical analyses

Two-factorial mixed ANOVAs were used to test differences in tissue content (GM, WM, and CSF) and GM/WM in each ROI between mild AD patients and controls. Group and brain region (ROI) differences were analyzed for each spectroscopy outcome parameter using a mixed model with group (AD or control), sex, brain region and its interaction as fixed factors, considering brain region as a within subject factor, and adjusting for age. Two AD patients had MR spectra of low quality (due to severe motion and a dental implant) and four control subjects were found to meet an exclusion criterion during or after the visit (two subjects took nutritional supplements, two subjects presented with structural neurological damage from ischemic infarcts and trauma). Therefore, 31 AD patients and 31 controls were included in the final analysis. The groups were similar with respect to age and gender (see Table 1 for subject characteristics).

### 3. Results

#### 3.1. Subjects

A total of 33 mild AD patients and 35 healthy control subjects were enrolled in the study and subjected to MRI and MRS measurements. Two AD patients had MR spectra of low quality and four control subjects were found to meet an exclusion criterion during or after the visit. Therefore, 31 AD patients and 31 controls were included in the final analysis. The groups were similar with respect to age and gender (see Table 1 for subject characteristics).

#### 3.2. ROI tissue contribution

The interaction between group and brain region for GM and CSF contributions to the total volume of each ROI was not significant, but GM and CSF differed significantly between groups, and between brain regions (all $p < 0.001$). GM was lower and CSF was higher in AD patients than in healthy control subjects (mean $\% \pm$ SD, GM: 36.3 $\pm$ 4.7 vs. 40.5 $\pm$ 4.0; CSF: 22.5 $\pm$ 4.7 vs. 18.1 $\pm$ 3.5). Overall, GM was highest in the right hippocampus, followed by left hippocampus, and then followed by equal amounts in RSC and ACC (data not shown). CSF in RSC and ACC was higher than in both hippocampi. There was a significant interaction between group and brain region for WM...
3.5. Differences in phosphorus metabolites and pH between brain regions

Brain region significantly affected all outcome parameters (all \( p < 0.05 \)), except PCh and PME (\( p > 0.05 \)). The normalized signals of total ATP, \( \alpha \text{ATP} \), \( \beta \text{ATP} \), \( \gamma \text{ATP} \), NAD(H), Pi, GPe, GPE, GPCh, and PDE were lower in the RSC than in the ACC and both hippocampi (all \( p < 0.05 \)), while the pattern was reversed for the ratios PCh/GPCh and PME/PDE (\( p < 0.001 \)). We found no difference between the left and right hippocampus for any of the energy and phospholipid metabolites or pH (\( p > 0.05 \)), except for \( \alpha \text{ATP} \) (LS mean difference = 0.65, SEM = 0.26, \( p = 0.015 \)). See Table 3 for an overview of the differences between brain regions.

3.6. Differences in phospholipid metabolites and pH between groups

In this study we acquired high-quality \(^{31}\text{P-MRSI} \) data of the brain in a large group of mild AD patients and in a well-matched healthy elderly population. High spectral resolution enabled us to gather information on high-energy phosphates, as well as on specific phospholipid metabolites. MR spectra of the four brain regions that are among the most studied in AD were investigated and for the first time, these areas were measured simultaneously by \(^{31}\text{P-MRSI} \). We detected increased phosphocreatine and pH, but no changes in phospholipid metabolite signals in mild AD patients. Interestingly, the increase in PCr was observed in the RSC and in the hippocampi, regions that both show early pathological changes in AD, but not in ACC, a region known to be involved in the disease at a later stage. This suggests that the PCr abnormality expands across brain regions in a similar fashion as other AD pathologies, such as tau (Braak and Braak, 1991). Furthermore, in both groups pH, high energy phosphates, and most phospholipid metabolites differed across brain regions.

As in vivo human \(^{31}\text{P} \) MRS brain studies are nearly always performed under signal saturating conditions, changes in T1 relaxation time may affect metabolite signal intensities (Longo et al., 1993). Although we cannot exclude that such an effect has contributed to the increased PCr signal, it would require a rather drastic decrease in PCr's T1 value from about 3 to 2 s. Moreover, no increases in PME and PDE signals were detected, while those would be affected more severely by a T1 decrease (Klomp et al., 2008). A potential cause for relaxation enhancement is a higher brain iron accumulation in AD patients (Tao et al., 2014), but this would increase the signal linewidth, which was not observed. Thus, the most likely explanation for the increased PCr signal is a higher tissue concentration of this compound.

Elevated PCr signals have been reported before for AD patients in comparison with young controls (Mandal et al., 2012), but as PCr also increases with age in healthy persons (Chiu et al., 2015; Forester et al., 2010; Longo et al., 1993) it is unclear whether this finding was due to an aging effect. The current results showed increased PCr, and PCr/Pi, in AD patients compared with elderly controls of the same age. In contrast, two earlier studies showed a decrease in prefrontal PCr in mild, but not severe, AD (Pettegrew et al., 1994) and decreased PCr/Pi in the frontal lobe (Smith et al., 1995). However, these studies were performed at 1.5 T with only surface coil localization and involved small sample sizes.

As the concentration of high energy phosphates depends on the

### Table 1

| Subject characteristics. | AD \( n = 31 \) | Controls \( n = 31 \) |
|--------------------------|----------------|------------------|
| Age                      | 73.4 years (6.8) | 73.5 years (6.3) |
| Gender (%)               | 13 males (42%) | 15 males (48%) |
| MMSE                     | 23.2 (2.0) | 28.1 (1.4) |
| Time since AD diagnosis  | 1.6 months [0.2–15.3] | – |
| BMI                      | 25.4 kg/m\(^2\) (3.8) | 26.3 kg/m\(^2\) (4.5) |
| Educational level         | 9/16/6 | 4/9/18 |
| Smoking (never/past/current) | 13/17/1 | 6/22/3 |

\( \leq 1 \) relatives with AD (n) 19 7

MMSE, mini mental state examination; AD, Alzheimer’s disease; BMI, body mass index.

Data are presented as mean (standard deviation) or median [range] unless otherwise indicated.

\( p = 0.004 \) and GM/WM (\( p = 0.021 \)). WM was higher in AD patients compared with controls in the right hippocampus (41.5 ± 3.0 vs. 40.0 ± 2.6), but not in the other brain regions. GM/WM was lower in AD patients than in controls in ACC, and both hippocampi, but not in RSC (data not shown).

### 3.3. MRS results

High quality MR spectra were obtained with well-resolved PME, PDE, Pi, PCr and ATP signals for the brain regions evaluated in this study (Fig. 2). The linewidth of PCr varied between 8 and 13 Hz in the different brain regions (ACC: mean ± SD 13.5 ± 3.3 Hz, RSC: 8.1 ± 2.6 Hz, HL: 11.2 ± 2.6 Hz, HR: 12.5 ± 3.0 Hz). We did not observe a difference in the linewidth of PCr between AD and controls (mean ± SD 11.5 ± 3.9 Hz and 11.1 ± 3.0 Hz, not tested). ROI tissue contributions showed typical differences with lower GM and higher CSF in AD patients compared with controls.

In the statistical analysis, the interaction between group and brain region was kept in the model for PCr, \( \gamma \text{ATP} \) and \( \beta \text{ATP} \), because it survived our criterion of \( p < 0.10 \). For all other outcome parameters, the interaction term had a \( p \)-value > 0.10 and was removed from the model.

### 3.4. Differences in energy metabolites and pH between groups

A significant interaction between group and brain region was found for PCr, showing that normalized PCr signals were higher in mild AD patients compared with healthy control subjects in the RSC (Least Square (LS) mean difference = 0.86, SEM = 0.29, \( p = 0.004 \)), HL (LS mean difference = 1.52, SEM = 0.52, \( p = 0.005 \)) and HR (LS mean difference = 1.47, SEM = 0.38, \( p < 0.001 \)), but not in the ACC (\( p = 0.947 \)) (Fig. 3A). The interaction between group and brain region was not significant for \( \gamma \text{ATP} \) and \( \beta \text{ATP} \). A main effect of group was found for PCr/Pi, showing that this ratio was higher in mild AD patients compared with healthy controls (LS mean difference = 0.22, SEM = 0.11, \( p = 0.046 \)) (Fig. 3B). Also pH was increased in AD patients compared with controls (LS mean difference = 0.008, SEM = 0.004, \( p = 0.032 \)) (Fig. 3C). No group differences were found for \( \gamma \text{ATP} \), \( \beta \text{ATP} \), \( \alpha \text{ATP} \), total ATP, Pi, and NAD(H) (all \( p > 0.05 \)). For a summary of group effects see Table 2.

### 3.5. Differences in phospholipid metabolites between groups

No interaction or group difference between mild AD patients and healthy control subjects were found for any of the phospholipid metabolites (PEth, PCh, GPE, GPCh, PME, and PDE; Table 2) or their ratios (PEth/GPE, PCh/GPCh, and PME/PDE) (all \( p > 0.05 \)).
balance between energy production and energy utilization, increases in steady state PCr levels and PCr/Pi reflect a redistribution in the content of metabolites involved in the connected CK and ATPase pseudo-equilibria (Du et al., 2007). This may be the consequence of reduced utilization of ATP (Forester et al., 2010), caused by synaptic dysfunction or loss of other energy requiring functionalities (Chandrasekaran et al., 1996; Rapoport et al., 1996). Although these changes are expected to lower ATP production and thus PCr, the final balance between reduced energy production and consumption may still result in a higher PCr level. To maintain equilibrium, the increased PCr should be accompanied by changes in the levels of other substrates of the CK reaction, such as a higher ATP concentration. Previous studies reported an increase in (γ)ATP (Mandal et al., 2012; Mecheri et al., 1997; Pettegrew et al., 1994), although no alterations in ATP levels were found in the current nor in several other studies (e.g. Forlenza et al., 2002; Gonzalez et al., 1996; Smith et al., 1995). Alternatively, a higher PCr may result from an increased total amount of cellular creatine (Cr). However, in vivo measurements of total Cr content in MCI and AD patients provide no clear evidence that Cr is increased in the disease (Graff-Radford and Kantarci, 2013; Tumati et al., 2013). Finally, decreases in ADP and/or H+ concentration may accompany the PCr increase. Indeed, a slight increase in pH was detected in mild AD patients, but it does not fully compensate for the increase in PCr when equilibrium is assumed. Changes in PCr levels have also been associated with decreased CK activity in the AD brain (Forester et al., 2010; Mandal et al., 2012). However, it is unlikely to be a direct effect of this decrease as even in cytosolic CK knockout mice the remaining CK activity (< 20%) is sufficient to preserve equilibrium (in ’t Zandt et al., 2004). Clearly, a strongly affected reaction rate will affect processes that require rapid (local) energy supply, and a higher PCr level may represent a flux adaptation to this condition.

There is some evidence for involvement of PCr in processes beyond the PCr-CK system. Since glutamate uptake by synaptic vesicles is stimulated by PCr, independent of ATP or CK (Xu et al., 1996), increased PCr may prevent glutamate excitotoxicity (Bender et al., 2005). Furthermore, PCr may be able to bind to and stabilize phospholipid membranes (Tokarska-Schlattner et al., 2005) and may function as an osmolyte (Bothwell et al., 2001) and a neurotransmitter (Almeida et al., 2006). In addition, differences in metabolite levels may be explained by variations in tissue and cell type (Gribn et al., 2002; Urenjak et al., 1993), although our results remained unchanged when adjusting for grey and white matter. A prominent neuropathological feature in AD is astrogliosis (Osborn et al., 2016). As this alters the neuron-to-glia ratio within grey and white matter (Beach et al., 1989), it is possible that morphological differences between AD patients and healthy aged controls play a role in the alterations in PCr and pH. Furthermore, atrophy may introduce slight differences in the brain area that the measured volumes encompass, which effect may not be entirely captured by

Fig. 2. Representative spectra from the anterior cingulate cortex (ACC), retrosplenial cortex (RSC), left hippocampus (HL) and right hippocampus (HR) of an Alzheimer’s disease patient (73 years old). Zero filling to 4096 data points and an 8 Hz Gaussian filter were applied for display purposes. PEth, phosphoethanolamine; PCr, phosphocreatine; PCh, phosphocholine; Pi, inorganic phosphate; GPEth, glycerophosphoethanolamine; GPCh, glycerophosphocholine; MP, membrane phospholipids; PCr, Phosphocreatine; ATP, adenosine triphosphate; NAD(H), nicotinamide adenine dinucleotide; ppm, parts per million.
adjusting for grey and white matter. However, ROIs were placed such that volume of the actual area of interest was maximized and the measured signals are dominated by the reported brain regions of interest.

Contrary to our expectation, we did not observe differences between mild AD patients and controls in any of the phospholipid metabolites, although preclinical and post-mortem studies show alterations in membrane function and lipid composition in AD (Nitsch et al., 1992; Ross et al., 1998). No previous in vivo studies have reported on PEth, phosphodiester systems are a differential expression of phosphatidylethanolamine and phosphatidylcholine species across hippocampal subfields was recently shown in AD (Mendis et al., 2016).

MRSS revealed that high energy phosphates, pH and most phospholipid metabolites vary extensively across brain regions that are of interest in AD. These differences existed in both mild AD patients and controls, and were not explained by regional variation in grey and white matter content, with the ratio PCr/Pi as the sole exception. This indicates that the investigated regions are metabolically different from each other. It also underlines that regional differences should be taken into account in any cross-sectional or longitudinal metabolic study. Moreover, as shown here for PCr, changes in metabolite levels in disease may not be the same for all brain regions.

The current study only reports on relative metabolite levels, as obtaining absolute quantifications requires several assumptions, which adds complexity and reduces reliability. Moreover, when the variation in atrophy between and within groups is large, relative measurements are preferred over absolute. A second limitation may be that our results have not been corrected for multiple testing, because of the exploratory nature of this study. Replication of these results in an independent population would strengthen our findings. In future research it would be valuable to include preclinical AD patients or an at-risk population to clarify the disease stage in which abnormalities in PCr and pH appear, as well as perform longitudinal (intervention) studies to follow these abnormalities. In addition, magnetization transfer experiments to determine the CK and ATPase reaction rates with measurements of absolute concentrations of PCr and ATP to determine fluxes (Du et al., 2007), would elucidate whether the dynamics of the PCr-CK and ATPases systems are affected in AD.

4.1. Conclusion

To the best of our knowledge, this is the largest study to date investigating brain phospholipid and energy metabolism in AD by $3^{1}P$ MRS. Increased PCr levels were found in regions that show early degeneration in AD, but not in the ACC, a region known to be involved in this disease at a later stage. Together with an increased pH, this indicates that energy metabolism is altered in mild AD. Although most
LS means ± SEM of metabolite levels, as percentage of total phosphorus signal in the corresponding spectrum, in anterior cingulate cortex, retrosplenial cortex and hippocampi. Significant (p < 0.05) main effect of brain region indicated in bold. ∗PCr also has a significant interaction between group and brain region. p < 0.05, ACC vs RSC, HL, or HR; RSC vs HL, or HR; LS, least squares; SEM, standard error of the mean; n, number of observations; ACC, anterior cingulate cortex; RSC, retrosplenial cortex; HL, left hippocampus; HR, right hippocampus; PCr, Phosphocreatine; Pi, inorganic phosphate; ATP, adenosine triphosphate; NAD(H), nicotinamide adenine dinucleotide; PEth, phosphoethanolamine; PCh, phosphocholine; GPEth, glycerylphosphoethanolamine; GPC, glycerylphosphocholine.

phospholipid metabolites, like the high energy phosphates, differed between the investigated brain regions in both groups, no alterations in phospholipid metabolism were found specific to mild AD.

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Declaration of interest

Conflicts of interest: none

Appendix A. Supplementary data

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