Longitudinal brain metabolic changes from amnestic mild cognitive impairment to Alzheimer's disease

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A sensitive marker for monitoring progression of early Alzheimer's disease would help to develop and test new therapeutic strategies. The present study is aimed at investigating brain metabolism changes over time, as a potential monitoring marker, in patients with amnestic mild cognitive impairment, according to their clinical outcome (converters or non-converters), and in relation to their cognitive decline. Seventeen amnestic mild cognitive impairment patients underwent magnetic resonance imaging and 18FDG-positron emission tomography scans both at inclusion and 18 months later. Baseline and follow-up positron emission tomography data were corrected for partial volume effects and spatially normalized using magnetic resonance imaging data, scaled to the vermis and compared using SPM2. ‘PET-PAC’ maps reflecting metabolic per cent annual changes were created for correlation analyses with cognitive decline. In the whole sample, the greatest metabolic decrease concerned the posterior cingulate-precuneus area. Converters had significantly greater metabolic decrease than non-converters in two ventro-medial prefrontal areas, the subgenual (BA25) and anterior cingulate (BA24/32). PET-PAC in BA25 and BA24/32 combined allowed complete between-group discrimination. BA25 PET-PAC significantly correlated with both cognitive decline and PET-PAC in the hippocampal region and temporal pole, while BA24/32 PET-PAC correlated with posterior cingulate PET-PAC. Finally, the metabolic change in BA8/9/10 was inversely related to that in BA25 and showed relative increase with cognitive decline, suggesting that compensatory processes may occur in this dorso-medial prefrontal region. The observed ventro-medial prefrontal disruption is likely to reflect disconnection from the hippocampus, both indirectly through the cingulum bundle and posterior cingulate cortex for BA24/32, and directly through the uncinate fasciculus for BA25. Altogether, our findings emphasize the potential of 18FDG-positron emission tomography for monitoring early Alzheimer's disease progression.

Keywords: amnestic mild cognitive impairment; 18FDG-PET monitoring; ventro-medial prefrontal cortex; longitudinal study

Abbreviations: aMCI = amnestic mild cognitive impairment; BA = Brodmann areas; 18FDG = 2-[18F]-Fluoro-2-Deoxy-D-Glucose; PAC = per cent annual change; VOI = volume of interest

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Introduction

To develop and test new therapeutic strategies for Alzheimer’s disease, sensitive markers for monitoring disease progression are urgently needed especially at its earliest stages, when neuropathological damage is still confined.

PET with 2-[¹⁸F]-Fluoro-2-Deoxy-o-Glucose (¹⁸FDG) is exquisitely sensitive to early Alzheimer’s disease-related brain changes. Significant hypometabolism can be detected in patients with amnestic Mild Cognitive Impairment (aMCI) that best represents the pre-dementia stage of Alzheimer’s disease (Petersen, 2005). The earliest metabolic changes involve the precuneus—posterior cingulate cortex and temporo-parietal areas (Salmon et al., 1994; Minoshima et al., 1997; Chételat et al., 2003b; Drzezga et al., 2003; Nestor et al., 2003a,b, 2004; Ishii et al., 2005; Mosconi, 2005; Kawachi et al., 2006). In contrast, the frontal cortex appears involved at the dementia stage (Minoshima et al., 1997; Desgranges et al., 1998; Alexander et al., 2002; Herholz et al., 2002), suggesting that metabolic changes should be detectable from aMCI to clinically probable Alzheimer’s disease, more specifically in this broad region. This progressive involvement of the frontal cortex may in turn parallel the worsening of cognitive deficits that eventually leads to the diagnosis of clinically probable Alzheimer’s disease.

Nonetheless, little is known about the accuracy of ¹⁸FDG-PET to monitor the progression of early Alzheimer’s disease and only one previous longitudinal ¹⁸FDG-PET study in aMCI patients has been published so far (Drzezga et al., 2003). This study highlighted significantly greater metabolic decreases in the right middle frontal gyrus in those patients who converted to clinically probable Alzheimer’s disease as compared to non-converters over a one-year follow-up period. However, whilst clinically meaningful, the dichotomous approach used in this study (i.e. comparing rapid converters to non-converters) is limited by the fact that non-converters include patients who will later progress to Alzheimer’s disease. A comprehensive approach should also consider all aMCI patients, whether they rapidly convert or not, assessing, in a whole sample analysis, brain metabolic changes in relation to cognitive decline over time (Chételat et al., 2005a). Indeed, these two approaches would appear complementary as the former would allow the identification of specific changes occurring in aMCI patients while they convert to clinically probable Alzheimer’s disease while the latter would inform on changes characterizing rapid cognitive decline whatever the clinical outcome at the end of an arbitrary-defined follow-up period.

Our main objective with the present study was, therefore, to further investigate the brain pattern of metabolic changes over the course of aMCI to early Alzheimer’s disease using these two complementary approaches, i.e. comparing converters to non-converters in a standard fashion, but also across the whole sample in relation to cognitive decline, implementing methodology specially designed for this purpose. Furthermore, we assessed the discriminant accuracy of metabolic changes in monitoring the progression to Alzheimer’s disease, and we investigated the mechanisms underlying these metabolic changes.

Methods

Patients

The present study overlaps with those of our previous publications using baseline PET data (Chételat et al., 2003a,b, 2005a; Mevel et al., 2007) or longitudinal MRI data (Chételat et al., 2005b, 2008), although only those patients with both baseline and follow-up MRI and PET data were included in this study. Briefly, the 17 aMCI patients included here were all recruited through a memory clinic, and all complained of memory impairment. They were right-handed, aged over 55 years and had at least 7 years of education (see Table 1 for demographic and clinical characteristics). They underwent medical, neurological, neuropsychological and neuroradiological examinations, and were selected according to current criteria of aMCI, i.e. isolated episodic memory deficits (<1.5 SD of the normal mean for age and education), normal performances in other areas of cognition and in global cognition (assessed with MMSE and Mattis scales), and NINCDS-ADRDA criteria for probable Alzheimer’s disease (McKhann et al., 1984) not met (see Chételat et al., 2005a for details).

Using the same neuropsychological battery as used at inclusion, all aMCI patients were evaluated every 6 months over an 18-month follow-up period to assess whether they met NINCDS-ADRDA criteria of probable Alzheimer’s disease or not; at the end of the follow-up period, patients were classified as converters or non-converters, respectively. Patients were declared as converters if they had impaired performances (>1.5 SD below the normal means according to age and education when available) in at least one of general intellectual function scales as well as in at least two areas of cognition including memory, leading to impaired daily activities as judged by the clinicians from the consultation interviews. Moreover, as an index of cognitive decline, a Mattis-Per cent Annual Change (Mattis-PAC) was obtained for each patient. This index was calculated by first modelling a simple linear regression from Mattis scores collected at each neuropsychological examination (y = ax + b; where y = Mattis score and x = time from first evaluation). Then, estimated a and b values were used to calculate per cent change in Mattis scores over 12 months using the formula: [(12ax/b)*100] (Chételat et al., 2005a).

The study was approved by the Regional Ethics Committee. At the time of inclusion all recruited patients signed an informed consent for the whole 18-month longitudinal study including the two PET sessions, in the presence of a relative, and integrity of their decision capacity was controlled by the referring clinicians throughout the study.

Neuroimaging data acquisition

Each patient underwent MRI and ¹⁸FDG-PET scans within a few days of inclusion and after 18 months. The same scanners and the same acquisition parameters were used. MRI consisted of a set of 128 adjacent axial cuts parallel to the anterior–posterior commissure (AC–PC) line and with slice thickness 1.5 mm and pixel size 1 × 1 mm, using the SPGR (spin gradient recalled) sequence (TR = 10.3 ms; TE = 2.1 ms; FOV = 24 × 18 cm; matrix = 256 × 192). PET data were collected using the ECAT Exact HR+ device with isotropic resolution of 4.2 × 4.2 × 4.6 mm (FOV = 158 mm). A catheter was introduced in a vein of the arm to inject the radiotracer. Following ⁶⁸Ga transmission scans, three to five mCi of ¹⁸FDG were injected as a bolus at time 0, and a 10 min PET data acquisition started at 50 min post-injection period. Sixty-three planes were acquired with septa out
PET data processing and analysis

To implement the two complementary analyses described in the Introduction, metabolic changes were first directly evaluated from baseline and follow-up PET data and compared between converters and non-converters. Secondly, maps reflecting metabolic per cent annual changes, called ‘PET-PAC’ maps in what follows, were generated for each patient and used to assess relationships with cognitive decline as well as for supplementary analyses. The following sections will briefly describe the common and specific processing steps for these analyses. Further details and illustration of these processing steps and analyses are provided as supplementary material.

Common processing steps

A co-registration was performed to place baseline and follow-up MRI and PET data of each patient in the same space. All PET data were then voxel-wise corrected for partial volume effects using the patient contemporary MRI and the ‘modified Muller-Gardner’ method (Quarantelli et al., 2004). Thirdly, PET data were scaled using a metabolically preserved brain region, namely the cerebellar vermis (Mevel et al., 2007), to control for inter- and intra-individual global variations in PET signal.

Optimal spatial normalization parameters, to be used in the subsequent specific procedures, were estimated from the spatial normalization of MRI data onto a customized aMCI template using optimal voxel-based morphometry (Good et al., 2001) as previously used in our laboratory (Chételat et al., 2005b). Note that a single set of normalization parameters was estimated for each patient so as to normalize baseline and follow-up PET data using the same parameters to avoid bias due to differential spatial normalization.

PET data processing and analyses for the comparison between baseline and follow-up PET

The optimal normalization parameters were applied to baseline and follow-up co-registered, corrected for partial volume effects and scaled PET data resulting from the common processing steps. Spatially normalized PET data were subsequently smoothed using a Gaussian kernel of 10 mm, and entered into the following statistical analyses.

First, a paired T-test with two conditions (baseline and follow-up) was performed to assess the pattern of metabolic evolution in all aMCI patients by comparing baseline to follow-up data. The resulting SPM-T map was projected onto the aMCI whole brain template.

Second, a repeated measures ANOVA with two groups (converters and non-converters) and two conditions (baseline and follow-up) was performed on the same data to assess the patterns of metabolic evolution in converters and in non-converters separately, by comparing baseline to follow-up data in each group. Resulting SPM-T maps were projected onto the customized aMCI whole brain template. Between-group comparison of baseline minus follow-up PET data was then performed onto the voxels exhibiting significant metabolic changes.

Table 1  Demographic and clinical data of aMCI patients at baseline ($t_0$) and at follow-up ($t_{18}$)

<table>
<thead>
<tr>
<th></th>
<th>aMCI patients</th>
<th>Converters</th>
<th>Non-converters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$t_0$</td>
<td>$t_{18}$</td>
<td>$t_0$</td>
</tr>
<tr>
<td>Number (female/male)</td>
<td>17 (11/6)</td>
<td>7 (5/2)</td>
<td>10 (6/4)</td>
</tr>
<tr>
<td>Follow-up duration (months; mean ± SD) (range)</td>
<td>17.9 ± 1.0 (17.0–20.6)</td>
<td>17.5 ± 0.91 (17.0–18.8)</td>
<td>18.2 ± 1.1 (17.0–20.6)</td>
</tr>
<tr>
<td>Age at $t_0$ (years; mean ± SD) (range)</td>
<td>71.6 ± 8.9 (55–87)</td>
<td>73.3 ± 4.3 (73–80)</td>
<td>70.4 ± 11.2 (55–87)</td>
</tr>
<tr>
<td>Education (years; mean ± SD) (range)</td>
<td>10.3 ± 3.9 (7–17)</td>
<td>11.0 ± 4.7 (7–17)</td>
<td>9.9 ± 3.6 (7–17)</td>
</tr>
<tr>
<td>MMSE (mean ± SD) (range)</td>
<td>27.5 ± 1.2 (25–29)</td>
<td>25.6 ± 3.9* (17–30)</td>
<td>26.7 ± 1.0 (25–28)</td>
</tr>
<tr>
<td>MMSE-PAC (mean ± SD) (range)</td>
<td>−4.3 ± 9.1 (−30.0–5.3)</td>
<td>−6.9 ± 12.3 (−30.0–3.0)</td>
<td>−2.5 ± 6.1 (−9.8–5.3)</td>
</tr>
<tr>
<td>Mattis (mean ± SD) (range)</td>
<td>137.1 ± 4.4 (129–144)</td>
<td>130.5 ± 10.1** (108–142)</td>
<td>135.7 ± 4.9 (129–141)</td>
</tr>
<tr>
<td>Mattis-PAC (mean ± SD) (range)</td>
<td>−3.3 ± 4.8 (−11.8–2.9)</td>
<td>−7.1 ± 3.4 (−11.8 to −2.5)</td>
<td>−0.7 ± 3.8 (−7.4–2.9)</td>
</tr>
</tbody>
</table>

Only the baseline ($t_0$) MMSE and follow-up ($t_{18}$) Mattis scores significantly differed between converters and non-converters ($P<0.01$).

*Significant difference between $t_0$ and $t_{18}$ $P<0.05$, **$P<0.01$, ***$P<0.001$. (volume acquisition), using a voxel size of $2.2 \times 2.2 \times 2.43$ mm (see Chételat et al., 2005a for further details).
decreases in converters (using the inclusive masking procedure of SPM2) so as to highlight areas of greater metabolic decrease in converters as compared to non-converters (i.e. significant Group x Condition interaction).

Clusters showing significant interaction in the above analysis were also used to define volumes of interest (VOI) for subsequent application onto PET-PAC maps (see below).

PET data processing and analyses with PET-PAC maps

The baseline and follow-up co-registered, corrected for partial volume effects and scaled PET data resulting from the common processing steps were used to create individual PET-PAC maps. These PET-PAC maps represent the voxel-wise calculation of per cent metabolic change over the 18-month follow-up period (i.e. the difference between follow-up and baseline scaled PET value divided by baseline PET value x 100) expressed in annual per cent change (i.e. multiplied by 12/18). Note that this calculation was performed only onto those voxels common to both baseline and follow-up PET data, identified using a masking procedure. The optimal spatial normalization parameters were then applied to these PET-PAC maps, which were subsequently smoothed using a Gaussian kernel of 10 mm.

A correlation analysis was then conducted onto these 17 PET-PAC maps using Mattis-PAC as covariate to assess the relationship between metabolism changes and global cognitive decline. Both positive and negative correlations were assessed.

To perform VOI-based discriminant and correlation supplementary analyses, mean PET-PAC values were extracted from each PET-PAC map in the VOI defined above.

To assess the accuracy of the metabolic changes in the VOI for monitoring the progression to Alzheimer’s disease in converters, a discriminant analysis was performed. Univariate analyses (t-test) of the mean PET-PAC value of each VOI independently were computed, and a multivariate F-statistic based on MANOVA analysis was performed on all VOI values combined using a Linear Discriminant analysis.

Finally, to highlight the brain networks whose dysfunction or relative preservation may be related to that of each VOI, correlation analyses were then performed by entering the mean PET-PAC value of each VOI as covariate in a voxel-based correlation analysis with PET-PAC maps, assessing both positive and negative correlations, respectively.

All data processing and voxel-based statistical analyses were performed using SPM2 running on MATLAB 6.5. The threshold for significance was set to P(uncorrected) < 0.005, which is identical (Alexander et al., 2002) or more severe (Drzezga et al., 2003) than previously used in longitudinal PET studies in Alzheimer’s disease and judged to provide the best compromise, neither too permissive nor over-conservative with risk of type 2 errors.

Results

Clinical data

Baseline and follow-up clinical characteristics are presented in Table 1. Over the 18 month follow-up period, 7 of the 17 aMCI patients converted to clinical diagnosis of probable Alzheimer’s disease. Baseline MMSE scores and follow-up Mattis scores were lower in converters than in non-converters. As already reported (Chételat et al., 2005a), the Mattis scores significantly decreased over the follow-up period in converters, but not in non-converters.

Comparison between baseline and follow-up PET

The patterns of metabolic changes from baseline to follow-up in the whole aMCI sample, and in converters and non-converters separately, are illustrated in Fig. 1. In the whole aMCI sample, metabolic decreases were largely bilateral and involved medially the posterior cingulate cortex and frontal areas (Brodmann areas BA 11 and 24/32), and laterally the temporoparietal cortex (with right predominance), insula and inferior temporal cortex. Assessing converters and non-converters separately, effects were similar but stronger in the former and lower in the latter, a difference that was particularly prominent in ventro-medial prefrontal regions (BA 25 and 24/32). Also, the posterior cingulate changes observed in the whole sample extended to the middle cingulate cortex in converters.

The repeated measures ANOVA comparing converters to non-converters revealed areas of significantly greater metabolism decrease in converters than non-converters, but not in the reverse contrast. These changes were located in two distinct ventro-medial prefrontal regions: the left anterior cingulate cortex (BA 24/32) and the subgenual area (BA 25; Fig. 2A). As described above, these two clusters were then made into VOI for the correlation and discriminant analyses.

PET-PAC maps

Positive correlation between PET-PAC maps and Mattis-PAC revealed a single significant cluster located in the subgenual area (BA 25; Fig. 2B). The reverse contrast (i.e. PET-PAC increases with Mattis-PAC decreases) disclosed a single cluster located in the right dorso-medial prefrontal cortex (BA 9/10; Fig. 3A).

While a partial overlap was observed between individual values of converters and non-converters using the mean PET-PAC in BA 24/32 \( (P = 0.001; \text{AUC} = 0.94) \) or in BA 25 \( (P = 0.006; \text{AUC} = 0.87) \) separately, the combination of the mean PET-PAC in these two VOI improved the between-group discrimination \( (P = 0.0001; \text{AUC} = 1) \; \text{Fig. 4} \).

Positive correlation between BA 24/32 mean PET-PAC value and PET-PAC maps highlighted surrounding medial prefrontal areas (BA 24/32/11) as well as the right posterior cingulate cortex including the retrosplenial cortex (BA 23/26/29; Fig. 5). The reverse contrast did not reveal any significant negative correlation.

Positive correlation between BA 25 mean PET-PAC value and PET-PAC maps revealed two clusters, the first encompassing surrounding prefrontal areas (BA 25/24) and right hippocampus and amygdala, and the second involving the left parahippocampal cortex (BA 20; Fig. 5). The reverse contrast (negative correlation) highlighted two close clusters in the right dorso-medial prefrontal cortex (BA 8 and BA 9; Fig. 3B).
Discussion

In the present study, we used a method specifically designed for the longitudinal assessment of PET changes, including voxel-based correction for partial volume effects and optimal normalization of each pair of PET data with the same parameters, as well as PET-PAC maps calculation restricted to common GM voxels. This method prevents, as far as possible, any confounding effects of brain tissue atrophy or methodological bias due to differential normalization and segmentation of baseline and follow-up data. The effects highlighted here are thus thought to reflect genuine metabolic changes taking place during the transition from aMCI to Alzheimer’s disease.

In the whole aMCI sample, we found progressive metabolic decreases over an 18-month follow-up period encompassing the temporo-parietal cortex and posterior medial parietal areas, consistent with numerous previous studies underlining the early involvement of these areas in Alzheimer’s disease (see Introduction section). Our results also disclosed significant changes in specific prefrontal areas, suggesting that prefrontal metabolic alterations are in fact initiated early in the course of Alzheimer’s disease. Most notably, the metabolic declines found to be significantly greater in converters relative to non-converters specifically and uniquely pointed to two medial prefrontal areas, namely the anterior cingulate cortex (BA24/32) and the subgenual area (BA25). A similar analysis also pointed to prefrontal areas in the Drzezga et al. study (2003), but involved lateral prefrontal rather than medial regions. In that study, the medial prefrontal areas were found to show similar decreases in converters and non-converters which was interpreted as reflecting a normal ageing process. Our findings disagree with this interpretation as the two groups did not differ in age or follow-up duration, and furthermore the metabolic changes in both medial prefrontal areas were found not to correlate with age (data not shown). In contradiction with Drzezga et al. (2003), therefore, the present study argues in favour of Alzheimer’s disease-related pathological processes in these two regions. In support of this contention, the same two medial prefrontal regions have been previously reported to show specific perfusion decreases from the entorhinal to the limbic neuropathologic Braak stages (Braak and Braak, 1991), corresponding to aMCI and early Alzheimer’s disease, respectively (Bradley et al., 2002).

For reasons detailed in the Introduction, we also assessed metabolic changes in relation to global cognitive decline across the whole aMCI sample. Positive correlation between PET-PAC maps and Mattis-PAC highlighted a single ventro-medial...
prefrontal area encompassing the same BA25 region as that found in the between-group comparison, but surprisingly failed to highlight the BA24/32 cluster. As previously proposed (Chételat et al., 2005), patients expected to present with probable Alzheimer’s disease criteria at the end of the follow-up period (converters) include both patients with rapid cognitive decline, and patients with less rapid cognitive decline but who started from lower baseline cognitive status. Our findings thus suggest that the metabolic decrease in BA25 is specifically related to the slope of cognitive decline, while that in BA24/32 may instead be related to baseline cognitive performance. Consistent with this hypothesis, we found a significant positive correlation between baseline MMSE performances and BA24/32 PET-PAC values ($P=0.0006$; data not shown), while no significant correlation was found with BA25 PET-PAC values ($P=0.209$; data not shown). Overall, these two regions thus appear to serve complementary roles in expressing the metabolic decreases from aMCI to Alzheimer’s disease. This was also supported by our multivariate analysis showing improved discrimination between converters and non-converters when combining both BA25 and BA24/32 as compared to either VOI separately. While the complete discrimination found here would need to be validated from an independent and larger sample, our results strongly support the use of $^{18}$FDG-PET to monitor early Alzheimer’s disease progression.

To better understand the mechanisms underlying these metabolic changes, we also performed metabolic-metabolic correlations between PET-PAC in each VOI and whole-brain PET-PAC maps, thus exploring the whole brain networks whose metabolic changes relate to those in each of the two prefrontal VOI (i.e. BA24/32 and BA25). Interestingly, these analyses highlighted two distinct networks for BA24/32 and BA25, the former involving the posterior cingulate cortex and the latter the hippocampal region and temporal pole. These distinct relationships suggest that the medial prefrontal metabolic decreases characterizing the
progression from aMCI to clinically probable Alzheimer’s disease may result from disconnection from limbic structures, i.e. from the posterior cingulate cortex for BA24/32 and from the hippocampus for BA25. This so-called diaschisis hypothesis (Minoshima et al., 1997; Meguro et al., 2001; Bradley et al., 2002; Chételat et al., 2003b; Nestor et al., 2004) is consistent with recent functional MRI studies of functional connectivity showing, through a method similar to the correlation approach used here, altered hippocampal functional connectivity with the posterior cingulate and ventro-medial prefrontal cortex in early Alzheimer’s disease (Greicius et al., 2004; Allen et al., 2007; Wang et al., 2007). As the uncinate fasciculus directly connects the hippocampus, amygdala and temporal poles to the subgenual cortex (Kier et al., 2004; Schmahmann et al., 2007), disruption of this WM tract may lead to the specific relationships found here. Furthermore, alteration of this tract has been reported in Alzheimer’s disease (Taoka et al., 2006; Yasmin et al., 2008), and direct hippocampal projection fibres to BA25 were shown to mainly originate from the CA1 subfield (Zhong et al., 2006), i.e. the hippocampal subregion most involved by atrophic processes from aMCI to clinically probable Alzheimer’s disease (Chételat et al., 2008). The progressive metabolic decrease in BA25 is thus thought to directly reflect its disconnection from the hippocampus. In contrast, disruption of the rostral cingulum bundle relating the posterior cingulate cortex to the frontal cortex (Mufson and Pandya, 1984; Schmahmann et al., 2007; Mori et al., 2008) is probably responsible for the metabolic decrease observed in BA24/32. The caudal part of this tract, which connects the hippocampus to the posterior cingulate cortex, is also altered early in Alzheimer’s disease (Rose et al., 2000; Xie et al., 2005; Medina et al., 2006; Villain et al., 2008) probably accounting for early posterior cingulate hypometabolism (Rose et al., 2000; Chételat et al., 2003b; Nestor et al., 2004; Xie et al., 2005; Villain et al., 2008). Our findings suggest that, as aMCI progress to Alzheimer’s disease, posterior cingulate alterations progressively lead to medial prefrontal disruption through involvement of the rostral part of the cingulum bundle. Overall, therefore, BA24/32 metabolic decreases may reflect indirect
hippocampo-frontal disconnection processes, as already mentioned elsewhere (Grady et al., 2001; Bradley et al., 2002; Villain et al., 2008) probably mediated by the cingulum bundle which is the major path for fronto-hippocampal connectivity (Kobayashi and Amaral, 2003).

Intriguingly, most structures highlighted in the present study, namely the hippocampus, amygdala, posterior cingulate and medial prefrontal cortex, are key components of the episodic memory network (Cabeza and Nyberg, 2000). The role of the uncinate fasciculus and cingulum bundle in memory processes has also been highlighted (Levine et al., 1998; Gaffan and Wilson, 2008; Sepulcre et al., 2008), more specifically for autobiographical memory related to emotional events (Markowitsch et al., 2003). In addition, dysfunction in ventro-medial prefrontal areas has been related to depressive symptoms in healthy subjects (Steele et al., 2007) and apathy in Alzheimer’s disease (Marshall et al., 2007). Taken together, disruption of the brain networks leading to progressive decrease in ventro-medial prefrontal metabolism may underlie the worsening of memory impairments as well as the emergence of mood disorders reported as aMCI progresses to clinical Alzheimer’s disease (Assal and Cummings, 2002).

Finally negative correlations between PET-PAC maps and Mattis-PAC as well as BA25 PET-PAC, both highlighted a single and identical dorso-medial prefrontal region encroaching BA8/9/10. This suggests that, as the disease progresses and BA25 metabolism decreases, BA8/9/10 metabolism relatively increases, potentially reflecting functional compensatory

**Figure 5** VOI-based correlation analysis. Brain areas showing significant positive correlation between PET-PAC maps and PET-PAC values in BA25 (left), and BA24/32 (right), as illustrated in SPM2 ‘Glass brain’ representations and projection of the SPM-T maps (thresholded at $P < 0.005$; $k > 100$ voxels) onto sagittal sections of the aMCI whole-brain template. Peak and sub-peak MNI coordinates ($xyz$), size in voxels ($k$) and $T$- and $P$-values are indicated for each significant cluster and the corresponding plots and $R^2$ values are also provided. Hcp = hippocampus.
mechanism, as proposed in previous studies for the same dorso-medial prefrontal areas (Grady et al., 2001, 2003; Remy et al., 2005; Wang et al., 2007). Note that we failed to identify any significant relationship between this metabolic change and the neuropsychological declines over the 18-month follow-up (data not shown), preventing any clear conclusion regarding the potential consequence of BAB/9/10 relative metabolic increases on cognitive deficits. The striking difference between metabolic changes taking place in ventro- and dorso-medial prefrontal regions, both known to be connected to the hippocampus (Schmahmann et al., 2007) but showing either relative metabolic decreases or increases, respectively, would merit further investigation.

In summary, our findings highlight the specific metabolic changes associated with progression from aMCI to clinical Alzheimer’s disease, showing metabolic decrease in ventro-medial prefrontal BA24/32 and BA25 paralleled by relative increases in dorso-medial BAB/9/10. Prefrontal metabolic disruptions are likely to reflect disconnection from the hippocampus, both indirectly through the posterior cingulate cortex via cingulum bundle breakdown for BA24/32, and directly through uncinate fasciculus disruption for BA25. Metabolic decreases in these two areas combined specifically characterized rapid progression to Alzheimer’s disease, suggesting the potential of $^{18}$FDG-PET to monitor early Alzheimer’s disease progression and to test the effects of new therapies.

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