Correlation of Cerebrospinal Fluid Levels of Tau Protein Phosphorylated at Threonine 231 With Rates of Hippocampal Atrophy in Alzheimer Disease

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**Background:** The microtubule-associated tau protein abnormally phosphorylated at threonine 231 (p-tau231) has been investigated as a potential marker of Alzheimer disease. Levels of cerebrospinal fluid (CSF) p-tau231 vary across patients with Alzheimer disease. We hypothesized that these variations partially reflect differences in the degree of neuronal damage and therefore may be used to predict structural disease progression.

**Objective:** To investigate whether CSF p-tau231 levels correlate with rates of hippocampal atrophy as an in vivo marker of regional neuronal loss.

**Design and Patients:** We measured hippocampal volumes on the basis of serial magnetic resonance image examinations in 22 patients with Alzheimer disease. In addition, we determined CSF p-tau231 levels at baseline.

**Results:** Levels of CSF p-tau231 were significantly correlated with baseline hippocampal volumes (P<.001) and rates of hippocampal atrophy (left hippocampus, P<.001; right hippocampus, P=.02), independent of disease duration and severity.

**Conclusion:** These findings suggest that variations in p-tau231 levels may be used to predict progression of brain atrophy in patients with Alzheimer disease.

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**METHODS**

We studied 22 patients (13 women and 9 men) with the clinical diagnosis of probable AD according to the criteria of National Institute of Neurological and Communicative Disorders and Stroke–Alzheimer’s Disease and Related Disorders Association. After describing the study to each subject, the holder of a durable power of attorney, or a legal guardian, written informed consent was obtained. Mean age was 67.8 years (SD, 7.9 years). Global cognitive functioning was assessed with the Mini-Mental State Examination (MMSE). The mean MMSE score was 23.1 (SD, 4.0). Twenty AD patients underwent MRI twice, and 2 underwent MRI 3 times. Length of observation time ranged from 11.3 to 41.0 months (mean, 18.4 months [SD, 18.4 months]). Originally, 25 patients had mild AD; for 2 patients the second and for 1 patient the first MRI from the series could not be used.

The MRIs were acquired on the same 1.5-T scanner (Magnetom Vision; Siemens AG, Er-
langer, Germany) for all patients, using a 3-dimensional, T1-weighted, sagitally oriented MRI sequence (repetition time, 11.6 milliseconds; echo time, 4.9 milliseconds; spatial resolution, 0.94 × 0.94 × 1.2 mm). Quantitative assessments of hippocampal volumes were performed with an anatomical protocol previously validated. Before volumetric measurements, a transformation algorithm was used to align MRIs between time points. First, for each patient the second (and for 2 patients, the third) MRI was aligned to the first MRI in the series using a 6-parameter rigid body transformation. Next, the first MRI in the series was transformed to match coordinates based on the Talairach atlas using a 12-parameter affine coregistration algorithm. Finally, this transformation was applied to the linearly aligned second (and third) MRIs. Because the rigid body and affine transformation matrices were combined, the entire transformation required only 1 interpolation of original data using a sinc-interpolation algorithm. Besides correction for differences in head positioning, this transformation corrects for differences in brain size across subjects and ensures that all scans are in the same orientation, ie, parallel to the anterior–posterior commissure line.

In addition to hippocampal volumes, we used an automated segmentation algorithm implemented in SPM2 (statistical parametric mapping) (Wellcome Department of Imaging Neuroscience, London, England) to determine volumes of CSF, gray matter, and white matter from the baseline MRIs. The SPM segmentation uses a mixture model cluster analysis (after correcting for nonuniformity in image intensity) to identify voxel intensities that match particular tissue types combined with a priori probabilistic knowledge of the spatial distribution of tissues derived from gray and white matter and CSF prior probability images (priors). Samples of CSF were obtained by means of lumbar puncture and processed immediately. Aliquots were stored at -80°C until further examination. The detailed CSF protocol has been described previously. Tau protein levels were measured using enzyme-linked immunosorbent assays (p-tau231, tau protein abnormally phosphorylated at threonine 231). The statistical significance of these findings remained unchanged when main and interaction effect terms for MMSE and disease duration were added to the model.

There was no significant correlation between p-tau231 and t-tau levels and CSF volume (Pearson r2 = 0.18 [P = .08] and r2 = 0.06 [P = .78], respectively), gray matter volume (r2 = -0.13 [P = .58] and r2 = -0.26 [P = .26], respectively), or white matter volume (r2 = 0.27 [P = .24] and r2 = 0.16 [P = .48], respectively).

Higher rates of MMSE score decline correlated significantly with higher rates of atrophy of left and right hippocampal volumes (p = 0.52 [P < .02] and p = 0.47 [P < .03], respectively) (Figure 2). There was, however, no effect of p-tau231 levels on MMSE scores at baseline (F1,20 = 1.57 [P = .22]) or on rate of point loss in MMSE scores (F1,22 = 1.81 [P = .19]).

**RESULTS**

Mean levels of p-tau231 were 729.6 pg/mL (SD, 404.3 pg/mL). Hippocampal volumes were 2267 mm³ (SD, 640 mm³) for the left and 2263 mm³ (SD, 651 mm³) for the right side. As shown in the Table, the mixed general linear model yielded a significant effect of p-tau231 on rates of hippocampal atrophy and left and right hippocampal volumes. Higher p-tau231 levels corresponded to higher rates of atrophy and higher baseline volumes (Figure 1). There was a significant effect of t-tau levels on baseline volumes of the left hippocampus (β = 0.50 [P < .01]) and right hippocampus (β = 0.46 [P = .03]), with higher t-tau levels corresponding to higher baseline hippocampal volumes. There was no significant effect of t-tau levels on rates of left and right hippocampal atrophy (β = -0.27 [P = .14] and β = -0.10 [P = .51], respectively).

**COMMENT**

In AD patients, higher CSF p-tau231 levels were significantly correlated with higher rates of hippocampal atrophy progression, even after controlling for disease duration and severity. This finding is consistent with the hypothesis that increased levels of CSF p-tau231 reflect more extensive neuronal damage, leading to higher rates of hippocampal atrophy.

Rates of hippocampal atrophy may reflect reduction of hippocampal neuron density as found in postmortem studies of AD. The significant correlations between p-
tau$_{231}$ levels and rates of hippocampal atrophy suggest that CSF levels of p-tau$_{231}$ can serve as a marker for the degree of neuronal destruction and may be used to predict structural disease progression. The results were independent from disease duration and severity, indicating that the correlations do not reflect the effects of disease stage on rates of atrophy and p-tau$_{231}$ levels.

Levels of p-tau$_{231}$ and t-tau were positively correlated with baseline hippocampal volumes. There is no conclusive interpretation of this correlation at present. In a study of 8 patients with mild cognitive impairment, CSF p-tau$_{231}$ levels were decreased with larger ventricle size, suggesting a dilution of p-tau$_{231}$. In our patients, however, p-tau$_{231}$ levels were not correlated with CSF volume, indicating that tau proteins are not simply diluted in CSF with larger ventricle size (which is inversely correlated with hippocampal volume). The baseline effect, however, was modeled in the mixed-effects regression analysis to ensure that the correlations between p-tau$_{231}$ and rates of hippocampal atrophy were independent of the p-tau$_{231}$ effects on baseline volumes. Our study did not examine the rate of delivery of p-tau$_{231}$ into the CSF and did not address any changes in the rate of CSF turnover. It is expected that these factors may contribute to the interpretation of the results, and further studies are warranted.

Rates of hippocampal atrophy were correlated with rates of change in MMSE scores, suggesting a functional consequence of progressive hippocampal atrophy. Levels of p-tau$_{231}$ were not correlated with rates of change in MMSE scores, suggesting that the significant correlations between p-tau$_{231}$ levels and hippocampal volume

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**Figure 1.** Rates of hippocampal atrophy and levels of tau protein abnormally phosphorylated at threonine 231 (p-tau$_{231}$) in Alzheimer disease (AD). Higher cerebrospinal fluid p-tau$_{231}$ levels at baseline correlate with higher annual rates of left (A) and right (B) hippocampal atrophy derived from a mixed-effects regression model in AD patients.

**Figure 2.** Rates of hippocampal atrophy and rates of point loss in Mini-Mental State Examination (MMSE) scores in Alzheimer disease. Rates of point loss in the MMSE scores correlate with rates of atrophy of right (B) and left (A) hippocampal volume.
Our data agree with the notion that variations in p-tau231 levels reflect differences in the degree of neuronal damage across AD patients. Although the strength of the correlations presently suggests no sufficient clinical utility to individual patients, p-tau231 levels may be used to predict progression of brain atrophy in AD. To draw more definite conclusions, replication of our findings is needed in larger studies.

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