MAPT R406W increases tau T217 phosphorylation in absence of amyloid pathology

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RESEARCH ARTICLE

**MAPT R406W increases tau T217 phosphorylation in absence of amyloid pathology**

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**Abstract**

**Objective:** Tau hyperphosphorylation at threonine 217 (pT217) in cerebrospinal fluid (CSF) has recently been linked to early amyloidosis and could serve as a highly sensitive biomarker for Alzheimer’s disease (AD). However, it remains unclear whether other tauopathies induce pT217 modifications. To determine if pT217 modification is specific to AD, CSF pT217 was measured in AD and other tauopathies.

**Methods:** Using immunoprecipitation and mass spectrometry methods, we compared CSF T217 phosphorylation occupancy (pT217/T217) and amyloid-beta (Aβ) 42/40 ratio in cognitively normal individuals and those with symptomatic AD, progressive supranuclear palsy, corticobasal syndrome, and sporadic and familial frontotemporal dementia.

**Results:** Individuals with AD had high CSF pT217/T217 and low Aβ42/40. In contrast, cognitively normal individuals and the majority of those with 4R tauopathies had low CSF pT217/T217 and normal Aβ 42/40. We identified a subgroup of individuals with increased CSF pT217/T217 and normal Aβ 42/40 ratio, most of whom were MAPT R406W mutation carriers. Diagnostic accuracies of CSF Aβ 42/40 and CSF pT217/T217, alone and in combination were compared. We show that CSF pT217/T217 alone and in combination were compared. We show that CSF pT217/T217 × CSF Aβ 42/40 is a sensitive composite biomarker that can separate MAPT R406W carriers from cognitively normal individuals and those with other tauopathies.

**Interpretation:** MAPT R406W is a tau mutation that leads to 3R+4R tauopathy similar to AD, but without amyloid neuropathology. These findings suggest that change in CSF pT217/T217 ratio is not specific to AD and might reflect common downstream tau pathophysiology common to 3R+4R tauopathies.
Introduction

Alzheimer’s disease (AD) is characterized by the plaque deposition of amyloid-beta 42 peptide (Aβ 42) and aggregation of hyperphosphorylated tau in neurofibrillary tangles, neuritic plaques, and neurofibril threads in the brain. Concomitant decrease in Aβ 42/40 ratio and increase of phosphorylated tau (ptau) species in the cerebrospinal fluid (CSF) have been used as biomarkers for AD amyloidosis and as surrogates of AD tau neuropathology, respectively.1,2 Increasing evidence suggests that either CSF tau phosphorylation at threonine 217 measured as absolute concentration (pT217) or as phosphorylation occupancy (pT217/T217) is a specific and more sensitive biomarker for AD, outperforming the well-established measure of CSF ptau level at threonine 181 (pT181).3–8 CSF pT181 level increase is strongly associated with the increase in total CSF tau concentration and is assumed to reflect tau neuropathology. However, CSF pT217 and pT217/T217 more strongly correlate with amyloid neuropathology measured by amyloid Pittsburgh compound B (PiB)-positron emission tomography (PET) imaging than total CSF tau concentration and is assumed to reflect tau neuropathology. Furthermore, some recent studies using immunoassays and mass spectrometry (MS) showed that an increase in CSF pT217 concentration is specific to AD and not observed in other neurodegenerative diseases.3,4,7,8 However, previous studies often do not take into account amyloid co-neuropathology that frequently increases with age and in many neurodegenerative diseases.

In order to evaluate the effect of tau phosphorylation in non-AD tauopathies, including PSP, CBS, and bvFTD, we measured CSF ptau and CSF Aβ using sequential immunoprecipitation (IP) and MS. CSF pT181/T217 and pT181/T181 ratios were calculated to differentiate tau phosphorylation changes from CSF total tau variation. CSF Aβ 42/40 ratio was calculated within the same participant and used as a surrogate for amyloid neuropathology. A cohort of cognitively normal age-matched controls (AMC) and individuals with symptomatic AD, PSP, CBS, and sporadic and familial FTD were analyzed. We assessed the correlation between CSF ptau and CSF Aβ 42/40 ratios in each disease group and evaluated diagnostic relevance of CSF ptau alone and in combination with CSF Aβ 42/40 to assess their ability to discriminate individuals with symptomatic AD from those with other neurodegenerative dementing illnesses.

Materials and Methods

Human studies

All studies were approved by the Institutional Review Board at Washington University in St. Louis, MO, USA and the Ethics Committee of the Montpellier University Hospital (CSF-NeuroBANK #DC-2008-417 at the certified NFS 96-900 CHU resource center BB-0033-00031 [http://www.biobanques.eu]). All participants or their delegates...
consented to the collection and sharing of biofluid samples. Exclusion criteria included contradiction to lumbar punctures (LPs) or lumbar catheters including a bleeding disorder, active anticoagulation, and active infection. Authorization to handle personal data was granted by the French Data Protection Authority (CNIL) under the number 1709743 v0.

AMC and individuals with mild AD were recruited at the Knight Alzheimer Disease Research Center (ADRC) at Washington University School of Medicine as part of Stable Isotope Labeling Kinetics (SILK) studies. AMC are volunteers who were enrolled for research purposes and are cognitively normal. This included two distinct cohorts of symptomatic participants (WashU-A, and WashU-B). Individuals from the WashU-A cohort participated in 36hr lumbar catheter studies. Individuals from the WashU-B cohort participated in the SILK study that involved five LPs over 4 months. Individuals were diagnosed by clinical assessment and classified according to the Clinical Dementia Rating (CDR)27; all AD participants had at least two abnormal CSF biomarkers of AD. Some PPA endophenotype AD cases were included in the AD focal phenotype (n = 5). CBS and PSP were diagnosed according to international criteria. bvFTD may be attributed to frontotemporal lobar degeneration (FTLD)-tau, FTLD-TDP, and FTLD-FUS. Some language endophenotype FTLD were included in bvFTD (n = 3). The CBS PSP continuum included patients with CBS clinical phenotypes that evolved into PSP during follow-up.31

**CSF collection**

CSF from individuals with AD and AMC in the WashU-A cohort were collected via a catheter as previously described. CSF from AMC and individuals with symptomatic AD, CBS, and bvFTD in the WashU-B cohort were obtained via LP with gravity collection and centrifugation as previously described. CSF from MAPT mutation families was collected according to the standardized protocol at the Biomarker Core at the Washington University School of Medicine.32 CSF from individuals with brain tumors was obtained via lumbar drain using a catheter before or after surgery.

CSF from the Montpellier cohort was collected using the standardized protocol for the collection, centrifugation, and storage at Memory Resources and Research Center of Montpellier. Briefly, the atraumatic needle was used for LP, with CSF collected into 10 mL polypropylene tube (ref 62.610.201, Sarstedt, Germany) and protein low binding Eppendorf (LoBind microtubes Eppendorf, ref 022431064, Hamburg, Germany). CSF was not centrifuged before aliquoting and storage at −80°C. CSF tau and pT181 concentrations were measured using the standardized commercially available INNOTEST sandwich ELISA X-MAP following Fujirebio instructions. CSF Aβ 42 and Aβ 40 were measured using INNOTEST sandwich ELISA from Fujirebio.

**Sequential IP and MS methods for CSF Aβ and Tau**

CSF Aβ was analyzed as previously described with the following modifications. Master mix containing detergent and chaotropic reagents (final 1% NP-40, 5 mmol/L guanidine, protease inhibitor cocktail) and internal standards for tau (15N labeled 2N4R recombinant tau) and Aβ (15N labeled synthetic Aβ 40, and 42) were prepared in low-binding Axygen tubes (Fisher Scientific, Pittsburgh, PA, USA, MCT-175). 500–1000 μL of CSF was added and immunoprecipitated with the HJ5.1 mid-domain Aβ antibody. After washing, samples were digested with LysN protease, desalted, and analyzed by Yevo TQ-S mass spectrometer (Waters Corporation, Milford, MA, USA).
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CSF tau and ptau were analyzed as previously described with the following modifications. Post-HJ5.1 immunoprecipitated CSF samples containing tau internal standards were sequentially immunoprecipitated with Tau1 mid-domain and HJ8.5 N-terminus tau antibodies. After washing, samples were digested with trypsin, desalted, and analyzed on Orbitrap Fusion mass spectrometer (Thermo Fisher Scientific, San Jose, CA, USA). MS method measuring pT217 and pT181 was described

**Amyloid and Tau PET imaging**

Amyloid PiB-PET, AV45-PET, and Tau AV1451-PET imaging measurements were performed in a subset of AD and AMC participants from the Knight ADRC at Washington University School of Medicine. Data were collected and processed as previously described.

**Statistics**

Receiver operating characteristic (ROC) and one-way ANOVA analyses were performed using GraphPad Prism software (GraphPad, San Diego, CA, USA, v8.3.0). After confirming the normal distribution of the data, one-way ANOVA followed by post hoc analyses (Tukey test) were performed. Data were represented as mean ± SEM.

**Results**

**Participants and study workflow**

Participants’ demographics and clinical characteristics are summarized in Table 1. For the purpose of the analyses, study cohorts were divided into several groups. The “AD” group (n = 80) included patients with amnestic-predominant clinically “typical” AD (n = 66) and those with focal variants (n = 14). bvFTD MAPT R406W mutation carriers (n = 5) were grouped as “R406W.” All neurodegenerative diseases other than AD, and MAPT R406W mutation carriers were grouped as “4R tauopathy” (n = 74). This group included individuals with PSP (n = 16), CBS (n = 15), CBS-PSP continuum (n = 7), sporadic bvFTD (n = 28), and FTD MAPT P301L mutation carriers (n = 3), which were primarily 4R tauopathies with 4R tau as primary isoform in the brain aggregates. Note that sporadic bvFTD was listed under “4R tauopathy” group; however, they were pathologically unconfirmed and might contain FTD-tau, FTLD-TDP43, FTLD-FUS, and small number of 3R tauopathy such as Pick’s disease. One of these participants was later found to have C9orf72 mutation. Cognitively normal controls was named “Control” (n = 98) and included AMC.

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**Table 1. Participants’ demographics and clinical characteristics.**

<table>
<thead>
<tr>
<th>Groups</th>
<th>AD (n = 80)</th>
<th>4R tauopathy (n = 74)</th>
<th>3R tauopathy (n = 3)</th>
<th>Control (n = 98)</th>
<th>AMC (n = 64)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subcategories</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AD, CBS, PSP</td>
<td>74.1 ± 1.9</td>
<td>66.7 ± 2.2</td>
<td>71.0 ± 2.6</td>
<td>70.7 ± 1.4</td>
<td>73.3 ± 0.9</td>
</tr>
<tr>
<td>Average age</td>
<td>73.2 ± 0.8</td>
<td>66.8 ± 1.6</td>
<td>64.5 ± 1.3</td>
<td>4.6</td>
<td>69.9</td>
</tr>
<tr>
<td>Sex (M/F)</td>
<td>41/39</td>
<td>0/0</td>
<td>0/0</td>
<td>14/36</td>
<td>14/12</td>
</tr>
<tr>
<td>WashU-A</td>
<td>11/14</td>
<td>0/0</td>
<td>0/0</td>
<td>0/0</td>
<td></td>
</tr>
<tr>
<td>Montpellier</td>
<td>14/12</td>
<td>0/0</td>
<td>0/0</td>
<td>0/0</td>
<td></td>
</tr>
</tbody>
</table>

For the purpose of analyses, all neurodegenerative diseases other than AD including PSP, CBS, CBS-PSP continuum, sporadic bvFTD, and FTD MAPT P301L mutation carriers, which are primarily 4R tauopathies, were grouped as “4R tauopathies.” Sporadic bvFTD was listed under “4R tauopathy” group. The use of sporadic bvFTD as an AD control is debatable; however, may contain undiagnosed FTLD-TDP43, FTLD-FUS, and 3R tauopathy cases. N = 1 was later found to have C9orf72 mutation.
n = 64), YNC (n = 26), and brain tumor patients (n = 8) who were cognitively normal.

Individuals in YNC (42.3 ± 2.4), Brain tumor (50.2 ± 2.6), and MAPT P301L (37.2 ± 3.6) groups were younger than AMC (73.0 ± 0.8) and participants with neurodegenerative diseases including AD (73.3 ± 0.9), CBS (68.6 ± 2.6), CBS PSP continuum (70.7 ± 1.4), PSP (71.0 ± 2.6), and sporadic bvFTD (62.1 ± 1.3) (Table 1, Fig. S1).

All 252 CSF baseline samples and 8 CSF follow-up samples were measured with sequential IP/MS methods for CSF Aβ 42, Aβ 40, pT217, T217, pT181, and T181 concentrations. CSF Aβ 42/40, pT217/T217, pT181/T181 ratios were calculated. The workflow used to categorize the different clinical groups is described in Figure S2.

**Determining cutoffs for IP/MS CSF Aβ 42/40 and CSF pT217/T217**

To define amyloid positivity cutoff for CSF Aβ 42/40 measured by IP/MS, we used amyloid PiB-PET results from 48 participants in the WashU-A cohort (cutoff 0.18;
Table 2. Demographics and summary of biomarker values for MAPT R406W mutation carriers.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Quadrant</th>
<th>Symptomatic/Asymptomatic</th>
<th>Age</th>
<th>Sex</th>
<th>CSF Aβ 42/40 (cutoff = 0.086)</th>
<th>CSF pT217/T217 (cutoff = 4.76)</th>
<th>CSF pT217/T217 × CSF Aβ 42/40 (cutoff for R406W versus control = 0.50)</th>
<th>CSF pT217/T217 div CSF Aβ 42/40 (cutoff for R406W versus control = 39.9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>IV</td>
<td>No dementia</td>
<td>40</td>
<td>M</td>
<td>0.142</td>
<td>3.69</td>
<td>0.524</td>
<td>26.0</td>
</tr>
<tr>
<td>#2</td>
<td>I</td>
<td>No dementia</td>
<td>40</td>
<td>M</td>
<td>0.152</td>
<td>3.75</td>
<td>0.572</td>
<td>24.6</td>
</tr>
<tr>
<td>#3</td>
<td>I</td>
<td>No dementia</td>
<td>52</td>
<td>F</td>
<td>0.127</td>
<td>5.00</td>
<td>0.671</td>
<td>41.9</td>
</tr>
<tr>
<td>#4</td>
<td>I</td>
<td>No dementia</td>
<td>55</td>
<td>F</td>
<td>0.132</td>
<td>5.86</td>
<td>0.774</td>
<td>44.4</td>
</tr>
<tr>
<td>#5</td>
<td>IV</td>
<td>Symptomatic, other primary</td>
<td>64</td>
<td>F</td>
<td>0.121</td>
<td>5.47</td>
<td>0.659</td>
<td>45.4</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>73</td>
<td></td>
<td>0.102</td>
<td>5.14</td>
<td>0.522</td>
<td>50.5</td>
</tr>
<tr>
<td>(age &lt; 50)</td>
<td>I, 2 IV</td>
<td>No dementia</td>
<td>40.3 ± 0.40</td>
<td>-</td>
<td>0.142 ± 0.0064</td>
<td>4.2 ± 0.52</td>
<td>0.595 ± 0.049</td>
<td>30.4 ± 5.1</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>63.0 ± 4.1</td>
<td>-</td>
<td>0.118 ± 0.0056</td>
<td>5.3 ± 0.19</td>
<td>0.628 ± 0.049</td>
<td>45.2 ± 1.5</td>
</tr>
<tr>
<td>(age &gt; 50)</td>
<td>4 I, 1 IV</td>
<td>Symptomatic, other primary</td>
<td>54.5 ± 4.8</td>
<td>-</td>
<td>0.127 ± 0.0059</td>
<td>4.9 ± 0.28</td>
<td>0.615 ± 0.049</td>
<td>39.6 ± 3.3</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
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</tbody>
</table>

CSF, cerebrospinal fluid.

Fig. S2A, Table 1). CSF Aβ 42/40 was significantly decreased in the amyloid-PiB+ cohort (Fig. S3A). A ROC curve analysis was performed and a Youden’s index value of 0.086 was selected as a cutoff for CSF Aβ 42/40 to maximize discrimination between cohorts (area under the curve [AUC] = 0.921, p < 0.0001; Fig. S3B).

To determine ptau abnormality cutoff for CSF pT217/T217, we used CSF Aβ 42/40 values in amyloid-PiB+ patients from the Wash-U-A cohort (Fig. S2A). We added another subset of 37 participants with only MS CSF Aβ 42/40 measurements. CSF pT217/T217 was significantly increased in amyloid+ individuals based on PiB-PET and CSF Aβ 42/40 measurements (Fig. S3C). A ROC curve analysis was performed and a Youden’s index value of 4.76 was calculated as a cutoff for CSF pT217/T217 (AUC = 0.983, p < 0.0001; Fig. S3D).

The same ROC analyses were performed for concentrations of CSF pT217, pT181, total tau, and phosphorylation occupancy at T181 (pT181/T181. Fig. S3E–L). AUC for each of these biomarkers was 0.949 (pT217), 0.816 (pT181), 0.698 (total tau), and 0.934 (pT181/T181), respectively, supporting the previous finding that CSF pT217/T217 is a superior discriminative AD biomarker.3,9

Association between IP/MS CSF Aβ 42/40 and CSF pT217/T217

To evaluate the relationship between IP/MS CSF Aβ 42/40 and pT217/T217, we plotted both ratios for each of the 255 participants. Based on the calculated 0.086 and 4.8 cutoffs for CSF Aβ 42/40 and CSF pT217/T217, respectively, we defined quadrants as follows: I (amyloid−, ptau−), II (amyloid+, ptau+), III (amyloid+, ptau−), and IV (amyloid−, ptau−) (Fig. 1A–E, Fig. S3B).

In quadrant II (amyloid+, ptau+), 88% (73/83) of individuals were clinically identified as AD (Fig. 1B). Overall, 91% (73/80) of individuals with AD were plotted in II (Fig. S4A). Seven participants clinically identified as AD were divided into quadrant I (n = 3), III (n = 1), and IV (n = 3, Fig. 1B–D). A subset of Controls (AMC [n = 5], CBS [n = 2], PSP [n = 2] and bvFTD [n = 1]) were also assigned to quadrant II (Fig. 1A and B).

Eighty four percent (82/98) of controls were plotted in IV and 55% (82/150) of individuals in IV were controls (Fig. 1E, Fig. S4B). Eighty percent (12/15) of CBS and 81% (13/16) of PSP were also in IV (Fig. S4C and D) as well as 71% (5/7) of the CBS PSP continuum.

CSF Aβ 42/40 and CSF pT217/T217 were negatively associated and displayed an L-shaped curve (Fig. 1). To better understand the dynamic association between CSF Aβ 42/40 and CSF pT217/T217 profile in the context of AD continuum, we assessed amyloid burden measured with PiB-PET and AV45-PET imaging and tau aggregation by AV1451-PET imaging in a subset of participants (Fig. S5). Aβ aggregation measured by both PET tracers gradually and significantly increased from quadrant IV, III to II (Fig. S5A and B). All the Controls in quadrant III were AMC (Fig. 1A) and...
none belonged to the YNC (age <64). However, within AMC, there was no significant difference in age in quadrant III (74.8 ± 2.4) and quadrant IV (72.4 ± 0.6). These suggest that individuals in quadrant III with amyloid positivity may be defined as presymptomatic AD without abnormal tau phosphorylation. In contrast, tau aggregation measured by Aβ1451-PET only increased in quadrant II (Fig. S5C), supporting CSF Aβ 42/40 and amyloid PET change before CSF pT217/T217 and tau PET. Importantly, a significant negative correlation between CSF Aβ 42/40 and CSF pT217/T217 was observed in quadrants III and IV (ptau-) including most controls, PSP, CBS, and bvFTD (Fig. S6).

**MAPT R406W carriers have increased pT217/T217 ratio without amyloid pathology**

Quadrant I (amyloid−, ptau+) was populated by individuals with bvFTD, PSP, AD, or CBS (Fig. 1C). Interestingly, 45% (5/11) were bvFTD, and all but one (80%, 4/5) were MAPT R406W mutation carriers (Fig. S4F, Table 2). All (5/5) MAPT R406W mutation carriers analyzed in this study were amyloid negative (quadrant I and IV), supporting the absence of amyloid neuropathology in MAPT R406W carriers (Table 2). Only one out of five MAPT R406W mutation carriers who were in their 40s and asymptomatic throughout the study was CSF pT217/T217 negative (quadrant IV) at both baseline and follow-up visit; all other MAPT R406W mutation carriers were CSF pT217/T217 positive (quadrant I) regardless of their pre/symptomatic status. One participant (#5) who was asymptomatic at baseline and developed dementia in follow-up visit 4 years later had CSF pT217/T217 just below the threshold at baseline (quadrant IV), but CSF pT217/T217 increased in the follow-up (quadrant I), suggesting that the longitudinal changes in this biomarker could reflect disease progression. In comparison, five other participants with follow-up visits within 1 year (1 PSP in quadrant I, 2 CBS, and 2 AMC in quadrant IV) remained in the same quadrant between baseline and follow-up (Table S1). These results suggest that increasing age and emergence of symptoms associate with increases in CSF pT217/T217 in MAPT R406W mutation carriers.

**Diagnostic values of IP/MS CSF Aβ 42/40, pT217/T217, and composite biomarkers in AD and MAPT R406W mutation carriers**

Next, we compared the diagnostic performance of IP/MS CSF Aβ 42/40 and CSF pT217/T217, with composite biomarkers consisting of pT217/T217 multiplied by CSF Aβ 42/40 and CSF pT217/T217 divided by Aβ 42/40 (Fig. 2, Table 3, Fig. S7). For this analysis, the four clinical groups previously defined ("AD," "R406W," “4R tauopathy,” and “Control”) were compared. CSF Aβ 42/40 ratio and CSF pT217/T217 used alone only separate AD from the other three groups (Fig. 2A and B). However, the R406W group had significantly increased CSF Aβ 42/40 × pT217/T217 composite biomarker compared to what was observed in the Control and 4R tauopathy groups (Fig. 2C). This composite biomarker demonstrated excellent ability to separate the R406W group from the 4R tauopathy (AUC = 0.948) and Control groups (AUC = 0.961). When this composite biomarker was used, 100% of MAPT R406W mutation carriers were above the cutoff of 0.50 for R406W versus control (Table 3). CSF pT217/T217 divided by CSF Aβ 42/40 performed similarly to CSF Aβ 42/40 and CSF pT217/T217 alone, and could not distinguish R406W from other groups (Fig. 2D, Table 3).

**Discussion**

**MAPT R406W mutation carriers have increased pT217/T217 without amyloid pathology**

Neither CSF pT217, pT181, total tau, nor phosphorylation occupancy at T181 (pT181/T181) were as efficient as the composite biomarker CSF pT217/T217 × CSF Aβ 42/40 at separating MAPT R406W mutation carriers from individuals with other neurodegenerative dementing illnesses (Figs. S8, S9). CSF pT181/T181 was significantly decreased in sporadic bvFTD (including FTLD-tau, FTLD-TDP43, and FTLD-FUS) compared to AD, AMC, and MAPT R406W mutation carriers (Figs. S8D, S9D). When regrouped, CSF pT181/T181 was able to separate sporadic bvFTD group from AD (AUC = 0.959), Control (AUC = 0.752), and other tauopathies including CBS, PSP, and FTD-MAPT including R406W and P301L (AUC = 0.707. Fig. S10). However, the specificity and sensitivity of CSF pT181/T181 to separate sporadic bvFTD from other tauopathies and control were not as high as that of CSF pT217/T217 in identifying MAPT R406W mutation carriers.

**IP/MS CSF total tau and ptau concentrations are not efficient biomarkers for MAPT R406W carriers**

Neither CSF pT217, pT181, total tau, nor phosphorylation occupancy at T181 (pT181/T181) were as efficient as the composite biomarker CSF pT217/T217 × CSF Aβ 42/40 at separating MAPT R406W mutation carriers from individuals with other neurodegenerative dementing illnesses (Figs. S8, S9). CSF pT181/T181 was significantly decreased in sporadic bvFTD (including FTLD-tau, FTLD-TDP43, and FTLD-FUS) compared to AD, AMC, and MAPT R406W mutation carriers (Figs. S8D, S9D). When regrouped, CSF pT181/T181 was able to separate sporadic bvFTD group from AD (AUC = 0.959), Control (AUC = 0.752), and other tauopathies including CBS, PSP, and FTD-MAPT including R406W and P301L (AUC = 0.707. Fig. S10). However, the specificity and sensitivity of CSF pT181/T181 to separate sporadic bvFTD from other tauopathies and control were not as high as that of CSF pT217/T217 in identifying MAPT R406W mutation carriers.

**MAPT R406W mutation carriers have increased pT217/T217 without amyloid pathology**

CSF pT217/T217 strongly correlates with amyloid pathology measured by amyloid PET in AD, but it was unproven whether pT217/T217 was a readout for CSF amyloid pathology or tau pathology. In this study, we first showed a specific correlation between CSF Aβ 42/40 and CSF pT217/T217 in individuals with symptomatic AD. Even in presymptomatic AD, CSF Aβ 42/
40 and CSF pT217/T217 correlate when slight changes in phosphorylation are observed, consistent with previous reports showing a correlation between PiB-PET and CSF pT217/T217. Neither CSF Aβ42/40 nor CSF pT217/T217 were altered in other tauopathies, including PSP, CBS, and most sporadic and familial FTD. However, we found that MAPT R406W mutation carriers have increased CSF pT217/T217 independent of amyloid pathology, demonstrating that increased CSF pT217/T217 is, indeed, a biomarker of pathological tau modification common to AD and MAPT R406W associated dementia and that amyloid pathology is not a prerequisite to this modification. This suggests that there is a common tau pathology downstream of AD and MAPT

Figure 2. CSF Aβ42/40, CSF pT217/T217, and composite biomarkers for diagnosis of AD, and MAPT R406W mutation carriers. (A) CSF Aβ42/40 is significantly decreased in AD (ANOVA, \( p < 0.0001 \)). (B) CSF pT217/T217 is significantly increased in AD (ANOVA, \( p < 0.0001 \)). (C) CSF pT217/T217 \( \times \) CSF Aβ42/40 is significantly increased in AD compared to Control and 4R tauopathy group consisting mostly of 4R tauopathy (PSP, CBS, FTD-MAPT P301L) and a subset of sporadic bvFTD (may contain FTD-TDP, FTD-FUS and 3R tauopathy. ANOVA, \( p < 0.0001 \)). This is also significantly increased in MAPT R406W carriers compared to control (ANOVA, \( p < 0.0001 \)) and 4R tauopathy group (ANOVA, \( p = 0.0001 \)). (D) CSF pT217/T217 divided by CSF Aβ42/40, is significantly increased in AD (ANOVA, \( p < 0.0001 \)). CSF, cerebrospinal fluid; AD, Alzheimer’s disease; PSP, progressive supranuclear palsy; CBS, corticobasal syndrome; bvFTD, behavioral variant frontotemporal dementia.
R406W mutation carriers, which results in specific tau phosphorylation changes in the brain, leading to an increase in CSF pT217/T217. Alternatively, two distinct upstream mechanisms, one involving amyloid deposition and the second involving MAPT R406W mutation, could lead to the activation of a similar pathway,

### Table 3. Diagnostic accuracy of combinations of CSF Aβ 42/40 and CSF pT217/T217 biomarkers for AD and FTD-MAPT R406W.

<table>
<thead>
<tr>
<th>Test</th>
<th>Diagnostic groups</th>
<th>n per group</th>
<th>AUC</th>
<th>95% CI</th>
<th>p value</th>
<th>Sensitivity %</th>
<th>Specificity %</th>
<th>Cutoff</th>
</tr>
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<tr>
<td>CSF Aβ 42/40</td>
<td>AD versus R406W</td>
<td>80 versus 5</td>
<td>0.978</td>
<td>0.947–1.000</td>
<td>0.0004</td>
<td>100.0</td>
<td>96.3</td>
<td>&gt;0.0985</td>
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<td>AD versus 4R tauopathy</td>
<td>80 versus 69</td>
<td>0.946</td>
<td>0.905–0.988</td>
<td>&lt;0.0001</td>
<td>94.2</td>
<td>90.0</td>
<td>&gt;0.0768</td>
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<td>Control versus AD</td>
<td>98 versus 80</td>
<td>0.925</td>
<td>0.882–0.969</td>
<td>&lt;0.0001</td>
<td>91.3</td>
<td>87.8</td>
<td>&gt;0.0798</td>
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<td>98 versus 5</td>
<td>0.588</td>
<td>0.384–0.791</td>
<td>0.5094</td>
<td>60.0</td>
<td>66.3</td>
<td>&gt;0.1302</td>
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<td>4R tauopathy versus R406W</td>
<td>69 versus 5</td>
<td>0.548</td>
<td>0.329–0.767</td>
<td>0.7223</td>
<td>55.4</td>
<td>62.5</td>
<td>&lt;0.1298</td>
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<td>Control versus 4R tauopathy</td>
<td>98 versus 69</td>
<td>0.543</td>
<td>0.454–0.631</td>
<td>0.3459</td>
<td>56.5</td>
<td>55.1</td>
<td>&gt;0.1231</td>
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<tr>
<td>CSF pT217/T217</td>
<td>Control versus AD</td>
<td>98 versus 80</td>
<td>0.951</td>
<td>0.916–0.987</td>
<td>&lt;0.0001</td>
<td>96.3</td>
<td>92.9</td>
<td>&gt;4.325</td>
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<td>AD versus 4R tauopathy</td>
<td>80 versus 69</td>
<td>0.945</td>
<td>0.907–0.983</td>
<td>&lt;0.0001</td>
<td>88.4</td>
<td>96.3</td>
<td>&lt;4.338</td>
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<td>Control versus R406W</td>
<td>98 versus 5</td>
<td>0.908</td>
<td>0.829–0.987</td>
<td>0.0021</td>
<td>100.0</td>
<td>76.5</td>
<td>&gt;3.678</td>
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<td>AD versus R406W</td>
<td>80 versus 5</td>
<td>0.878</td>
<td>0.799–0.956</td>
<td>0.0048</td>
<td>100.0</td>
<td>80.0</td>
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<td>4R tauopathy versus R406W</td>
<td>69 versus 5</td>
<td>0.875</td>
<td>0.797–0.954</td>
<td>0.0053</td>
<td>81.2</td>
<td>100.0</td>
<td>&lt;3.675</td>
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<td>Control versus 4R tauopathy</td>
<td>98 versus 69</td>
<td>0.525</td>
<td>0.435–0.615</td>
<td>0.5895</td>
<td>65.2</td>
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<td>CSF pT217/T217 × CSF Aβ 42/40</td>
<td>Control versus R406W</td>
<td>98 versus 5</td>
<td>0.961</td>
<td>0.924–0.998</td>
<td>&lt;0.0001</td>
<td>100.0</td>
<td>94.9</td>
<td>&gt;0.522</td>
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<td>4R tauopathy versus R406W</td>
<td>69 versus 5</td>
<td>0.948</td>
<td>0.897–0.999</td>
<td>0.0009</td>
<td>92.8</td>
<td>100.0</td>
<td>&lt;0.522</td>
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<td>Control versus AD</td>
<td>98 versus 80</td>
<td>0.814</td>
<td>0.748–0.880</td>
<td>&lt;0.0001</td>
<td>66.3</td>
<td>90.8</td>
<td>&gt;0.448</td>
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<td>AD versus 4R tauopathy</td>
<td>80 versus 69</td>
<td>0.793</td>
<td>0.719–0.868</td>
<td>&lt;0.0001</td>
<td>85.5</td>
<td>68.8</td>
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<td>AD versus R406W</td>
<td>80 versus 5</td>
<td>0.733</td>
<td>0.602–0.863</td>
<td>0.0824</td>
<td>100.0</td>
<td>60.0</td>
<td>&gt;0.515</td>
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<tr>
<td></td>
<td>Control versus 4R tauopathy</td>
<td>98 versus 69</td>
<td>0.521</td>
<td>0.432–0.611</td>
<td>0.6375</td>
<td>73.9</td>
<td>36.7</td>
<td>&gt;0.332</td>
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<td>CSF pT217/T217 divided by CSFAβ42/40</td>
<td>AD versus R406W</td>
<td>80 versus 69</td>
<td>0.963</td>
<td>0.922–1.000</td>
<td>0.0005</td>
<td>100.0</td>
<td>95.0</td>
<td>&lt;61.1</td>
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<tr>
<td></td>
<td>AD versus 4R tauopathy</td>
<td>80 versus 5</td>
<td>0.953</td>
<td>0.915–0.990</td>
<td>&lt;0.0001</td>
<td>92.8</td>
<td>95.0</td>
<td>&lt;67.6</td>
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<td></td>
<td>Control versus AD</td>
<td>98 versus 80</td>
<td>0.950</td>
<td>0.912–0.987</td>
<td>&lt;0.0001</td>
<td>95.0</td>
<td>94.9</td>
<td>&gt;69.8</td>
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<tr>
<td></td>
<td>4R tauopathy versus R406W</td>
<td>69 versus 5</td>
<td>0.817</td>
<td>0.701–0.934</td>
<td>0.0184</td>
<td>85.5</td>
<td>80.0</td>
<td>&lt;38.0</td>
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<td></td>
<td>Control versus R406W</td>
<td>98 versus 5</td>
<td>0.804</td>
<td>0.694–0.914</td>
<td>0.0222</td>
<td>80.0</td>
<td>82.7</td>
<td>&gt;39.9</td>
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<td></td>
<td>Control versus 4R tauopathy</td>
<td>98 versus 69</td>
<td>0.533</td>
<td>0.443–0.623</td>
<td>0.4746</td>
<td>14.5</td>
<td>94.9</td>
<td>&lt;17.0</td>
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</table>

CSF, cerebrospinal fluid; AD, Alzheimer’s disease; AUC, area under the curve; FTD, frontotemporal dementia.
ultimately leading to tau hyperphosphorylation and aggregation.

**MAPT R406W mutation’s similarity to AD**

MAPT R406W mutation-related pathology shares multiple clinical and neuropathological similarities with AD. Unlike other MAPT mutation carriers, MAPT R406W mutation carriers have later ages-at-symptomatic onset, with clinical symptoms including memory loss emerging, on average, in the mid-50s with slow progression.37 Most pathological MAPT mutations such as P301L are located in or around exon 10 and typically lead to 4R tau isoform aggregation, resulting in 4R tauopathies. In contrast, the MAPT mutations such as R406W and V337M are located in the C-terminus of the tau protein in a domain common to both 3R and 4R tau isoforms, resulting in 3R+4R mixed brain pathologies.38,39 The MAPT R406W mutation, like AD, can thus be categorized as a 3R+4R tauopathy and is differentiated from other 4R (CBS, PSP, bvFTD related to MAPT mutations located on exon 10) or 3R (Pick’s disease) tauopathies.

Filament structures in tau aggregates have been recently resolved by cryo-electron microscopy for different tauopathies such as AD and chronic traumatic encephalopathy (CTE) (3R+4R), CBS (4R), and Pick’s disease (3R).40–44 Consistent with neuropathological findings, tau domains shared by 3R and 4R isoforms are involved in AD and CTE tau aggregates, while 4R and 3R specific domains are, respectively, involved in corticobasal degeneration and Pick’s disease aggregates. Though no such structural data is available for MAPT R406W, AD, MAPT R406W, and V337M have paired helical filament structures,37,45 and AD Tau PET tracers such as AV1451 bind to some extent in presymptomatic MAPT R406W and V337M mutation carriers but not in other tauopathies,45–49 suggesting that tau aggregates in these 3R+4R tauopathies have similar characteristics. However, how hyperphosphorylation at T217 contributes to or associates with paired helical filament formation remains to be addressed. Previous studies suggest that CSF T217 is hyperphosphorylated in the early presymptomatic stages of AD, and is detectable more than 20 years before the emergence of clinical symptoms, while tau aggregates detected by PET imaging increase near symptom onset.9 We speculate that in 3R+4R tauopathies including MAPT R406W mutation carriers, (1) CSF pT217/T217 becomes abnormal prior to symptom onset when tau paired helical filament formation begins but it is below the detection limit by tau PET imaging followed by evident changes in Tau PET imaging; or, (2) CSF T217 hyperphosphorylation is not directly associated with the formation of neurofibrillary tangles but reflects an abnormal cellular metabolism affecting tau and leading ultimately to tau aggregation.

**Composite biomarker of CSF pT217/ T217 × CSF Aβ 42/40 serves as a sensitive biomarker for MAPT R406W mutation carriers**

We evaluated diagnostic values of CSF pT217/T217 and CSF Aβ 42/40 alone and in combination. CSF pT217/T217 and T217 levels were increased in MAPT R406W mutation carriers. However, the degree of increase was much smaller compared to that of AD and we could not separate MAPT R406W mutation carriers from the Control or 4R tauopathy groups including PSP, CBS, sporadic bvFTD, and FTD-MAPT P301L by CSF pT217/T217 alone (Fig. 2A, 2B, Fig. S6). Previous studies have indicated an increase of CSF and plasma pT181 concentrations in some cases of MAPT R406W mutation carriers, but the increase was mild.50–52 These are consistent with the insufficient sensitivity obtained from this study using only CSF concentrations of pT181, pT217, or phosphorylation occupancies at T181 and T217 (pT181/T181 and pT217/T217) as R406W biomarkers. Through quadrant analysis, we demonstrated that both CSF pT217/T217 and CSF Aβ 42/40 are necessary to distinguish MAPT R406W mutation carriers with high accuracy. We also demonstrated that a composite biomarker, CSF pT217/ T217 × CSF Aβ 42/40, contained sufficient sensitivity and specificity to distinguish MAPT R406W mutation carriers from the controls and 4R tauopathies (Fig. 2C, Fig. 5C. AUC = 0.934, 0.960, respectively). This is comparable to the high specificity and sensitivity of CSF Aβ 42/40 and CSF pT217/T217 to distinguish AD from the controls (AUC = 0.926, 0.952, respectively). A combination of CSF Aβ 42/40 and pT217/T217 ratios could be used in future trials to select for presymptomatic MAPT R406W mutation carriers and possibly other 3R+4R tauopathies such as V337M. Moreover, longitudinal measures of CSF pT217/T217 could reflect disease progression, suggesting that CSF Aβ 42/40, CSF pT217/ T217, and composite biomarkers may serve as new sensitive readouts in drug clinical trials against tauopathies that can assess target engagement in MAPT R406W mutation carriers.

**CSF pT181/T181 may decrease in sporadic bvFTD**

Previous studies using immunoassays showed mixed results in bvFTD, PSP, and CBS patients showing no or mild changes in CSF total tau or pT181.16–18,53–57 Consistent with multiple reports, our study did not show
significant differences in CSF total tau or CSF pT181 concentrations alone between bvFTD, PSP, CBS, and Control groups. However, by calculating the phosphorylation occupancies within the same participant, we showed that CSF pT181/T181 significantly decreases in sporadic bvFTD. This may be achieved by normalizing the changes in pT181 by T181, accounting for any physiological increase in pT181 as total tau increases, and individual variabilities such as age, sex, and genotype. Specificity and sensitivity of CSF pT181/T181 biomarker in identifying sporadic bvFTD from Controls or other tauopathies (AUC <0.8) were not as high as a composite biomarker, CSF pT217/T217 × CSF Aβ 42/40, in identifying MAPT mutation carriers (AUC >0.9). This may be due to the heterogeneity of the sporadic bvFTD cohort including FTLD-tau, FTLD-TDP, and FTLD-FUS. Previous studies showed that FTLD-TDP has lower CSF pT181/T181, 58,59 which could be consistent with our results if the sporadic bvFTD cohort included FTLD-TDP.

Limitations of this study and future directions

The relatively small number of participants in some subgroups and the inclusion of pathologically unconfirmed tauopathy and sporadic bvFTD cases may have decreased diagnostic accuracies. MAPT V337M mutation carriers may also be interesting to evaluate in the context of 3R+4R tauopathy. Future studies utilizing pathologically confirmed cases, longitudinal samples with clinical and PET assessments, and a larger cohort may facilitate additional analyses in ptau or tau that may be specific to MAPT R406W mutation carriers, sporadic bvFTD, or other subgroups of tauopathies.

Acknowledgments

We thank the participants and families for their contribution to this study. We thank Megan Arb, Theresa Arb, Melissa Sullivan, Wendy Sigurdson, Tamara Donahue for IRB protocol development and recruitment at Washington University, and Dr. Sylvain Lehmann, Karim Bennys, Cecilia Marelli, Christophe Hirtz at Montpellier. We thank Kathryn Draege for the brain tumor CSF collection. We thank Drs. Robert Swarm, Lesley Rao, Jacob Aubuchon for performing lumbar punctures. We thank members of the Bateman lab for discussion, especially Dr. Kanta Horie for initial feedback and Andrew Espeland for the initial analyses and exploration of the data. We thank the Clinical, Biomarker, and Imaging Cores at the Washington University School of Medicine for participant evaluation, samples, and data collection.

Author Contributions

CS, NRB, and AG conceived the project. NRB, CS, and NM developed tau and Aβ sequential IP/MS methods. CS, NRB, and NM designed and performed IP/MS experiments. CS and NRB analyzed and interpreted the data. CS developed IRB protocols and collected the majority of non-AD tauopathy CSF in the WashU-B cohort. NG, BAW, GSD, AAD referred bvFTD and tauopathy patients at Washington University. CS and GSD recruited YNCS. AHK and GJZ referred brain tumor patients. AG collected CSF at University of Montpellier. RJB provided CSF from the entire WashU-A cohort and part of the WashU-B cohort, mass spectrometry resources, and mentorship. CS, NRB, AG, NG, RJB wrote the initial draft of the paper; all authors made substantial contributions to the subsequent version of the manuscript and approved the final version for submission.

Conflict of Interests

Washington University, with CS, NRB, and RJB as co-inventors, have submitted the U.S. provisional patent application “Methods to detect novel tau species in CSF and use thereof to track tau neuropathology in AD and other tauopathies.” “CSF phosphorylated tau and Amyloid beta profiles as biomarkers of tauopathies” to Washington University. RJB and NRB as co-inventors, have submitted the non-provisional patent application “Methods of Diagnosing and Treating Based on Site-Specific Tau Phosphorylation.” RJB has received honoraria from AC Immune, Janssen, Pfizer, and Roche as a speaker, from AC Immune, Amgen, Eisai, and Janssen as a consultant, and from Roche as an advisory board member. RJB has an equity ownership interest in C2N Diagnostics and receives royalty income based on technology licensed by Washington University to C2N Diagnostics. RJB receives income from C2N Diagnostics for serving on the scientific advisory board. NG has participated or is currently participating in clinical trials of anti-dementia drugs sponsored by the following companies: Bristol Myers Squibb, Eli Lilly/Avid Radiopharmaceuticals, Janssen Immunotherapy, Novartis, Pfizer, Wyeth, SNiFF (The Study of Nasal Insulin to Fight Forgetfulness) study, and A4 (The Anti-Amyloid Treatment in Asymptomatic Alzheimer’s Disease) trial. She receives research support from NIH, Tau Consortium, and the Association for Frontotemporal Dementia. BAW participates in research sponsored by Acadia, Biogen, Global Kinetics, Neurocrine, Roche, Vaccinex, and Wave Biosciences. GSD is supported by grants from NIH/NIA (K23AG064029); personal fees from Parabon NanoLabs, Inc, personal fees from DynaMed (EBSCO Health), outside the submitted...
work; and is the clinical director for the Anti-NMDA Receptor Encephalitis Foundation (uncompensated). AHK is a consultant for Monteris Medical and has received research funding from Monteris Medical, Stryker, and Collagen Matrix.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

**Figure S1.** Age of the participants in each subgroup.

**Figure S2.** Flowchart of cohort analyzed in this study.

**Figure S3.** ROC analyses of IP/MS CSF Aβ 42/40, CSF tau, and ptau.

**Figure S4.** Quadrant analyses by diagnosis.

**Figure S5.** Amyloid and tau PET Imaging by quadrant.

**Figure S6.** CSF Aβ 42/40 and CSF pT217/T217 correlate in quadrants III and IV.

**Figure S7.** Subcategory of diagnosis are shown from Figure 2.

**Figure S8.** Quadrant analyses using CSF Aβ 42/40 and CSF total tau and ptau.

**Figure S9.** IP/MS CSF total tau and ptau in subgroups of tauopathies.

**Figure S10.** Sporadic bvFTD containing FTLD-tau, FTLD-TDP, FTLD-FUS may be separated from Control, AD and other tauopathies with CSF pT181/T181.

**Table S1.** Demographics and summary of biomarker values for participants with follow-up visits.