

The 28-amino acid form of an APLP1-derived A β -like peptide is a surrogate marker for A β 42 production in the central nervous system

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Surrogate markers for the Alzheimer disease (AD)-associated 42-amino acid form of amyloid- β (A β 42) have been sought because they may aid in the diagnosis of AD and for clarification of disease pathogenesis. Here, we demonstrate that human cerebrospinal fluid (CSF) contains three APLP1-derived A β -like peptides (APLP1 β) that are generated by β - and γ -cleavages at a concentration of \sim 4.5 nM. These novel peptides, APL1 β 25, APL1 β 27 and APL1 β 28, were not deposited in AD brains. Interestingly, most γ -secretase modulators (GSMs) and familial AD-associated presenilin1 mutants that up-regulate the relative production of A β 42 cause a parallel increase in the production of APL1 β 28 in cultured cells. Moreover, in CSF from patients with pathological mutations in *presenilin1* gene, the relative APL1 β 28 levels are higher than in non-AD controls, while the relative A β 42 levels are unchanged or lower. Most strikingly, the relative APL1 β 28 levels are higher in CSF from sporadic AD patients (regardless of whether they are at mild cognitive impairment or AD stage), than those of non-AD controls. Based on these results, we propose the relative level of APL1 β 28 in the CSF as a candidate surrogate marker for the relative level of A β 42 production in the brain.

INTRODUCTION

A key feature of the pathology of AD is the accumulation of amyloid- β peptides (A β) in senile plaques (Masters et al, 1985; Selkoe, 2001). A β is produced *via* endoproteolysis by BACE,

which cleaves β APP at the extracellular domain (Hussain et al, 1999; Sinha et al, 1999; Vassar et al, 1999; Yan et al, 1999), and by the presenilin (PS)- γ -secretase complex (Francis et al, 2002;

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Yu et al, 2000), which cleaves βAPP in the transmembrane domain (TM) (De Strooper, 2003; Edbauer et al, 2003; Kimberly et al, 2003; Takasugi et al, 2003). To date, no Aβ-like TM-containing peptides from other type-1 TM proteins have been found in brain. However, because *in vitro* studies indicate that Aβ-like peptides derived from Notch-1, CD44, βAPP like protein 1/2 (APLP1/2), alcadein, β-subunits of voltage-gated sodium channels and interleukin-1 receptor II are secreted by cultured cells (Araki et al, 2004; Eggert et al, 2004; Kuhn et al, 2007; Lammich et al, 2002; Okochi et al, 2002, 2006; Wong et al, 2005), we suspected that Aβ-like peptides may exist *in vivo*.

Aβ42 is a major constituent of senile plaques and is thought to induce the pathological process of AD (Selkoe, 2001). Thus the level of Aβ42 production in the brain, especially relative to total Aβ production, is a potential biomarker of the pathological process in AD. However, in patients with AD, the relative ratio of Aβ42 to total Aβ in CSF is lower (Andreasen et al, 1999; Jensen et al, 1999; Motter et al, 1995), probably because Aβ42 in the brain is being cleared more rapidly from the soluble pool by an enhanced rate of deposition/aggregation. To date, surrogate markers for estimating Aβ42 generation in the brain have not been identified. Such surrogate markers might reveal an increased ratio of Aβ42 production and is also associated with the pathology of sporadic AD cases.

In this study, we demonstrate that human CSF contains novel APLP1-derived APL1β species. Our data indicate that brain APL1β28 levels are a surrogate marker for the brain Aβ42 production, as the relative ratio of APL1β28 was up-regulated in CSF samples from patients with a variety of familial AD mutations and sporadic AD.

RESULTS

Identification of novel Aβ-like peptides (APL1β) derived from APLP1 in human CSF

APLP1 and APLP2 are similar to βAPP in the primary sequence and homologous in function (Coulson et al, 2000). To find an *in vivo* Aβ-like peptide, we focused on APLP1 and raised antibodies against the juxtamembrane domain (IQRDELA-PAGTGVSR for OA601 and DELAPAGTGVSR for OA663). Human CSF was obtained by lumbar puncture from non-demented patients, and proteins were immunoprecipitated using these antibodies or anti-Aβ antibody 4G8. The molecular masses of the precipitated proteins were analysed by matrix-assisted laser desorption/ionization-time of flight (MALDI-TOF) mass spectroscopy (MS). Experiments using OA601 or OA663 detected an identical set of three peptides of 2,329, 2,473 and

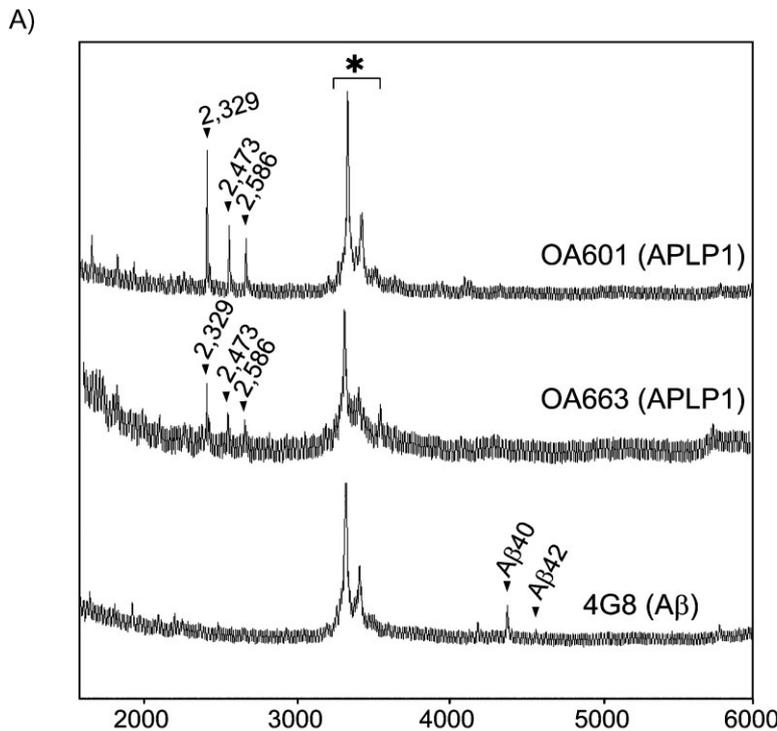
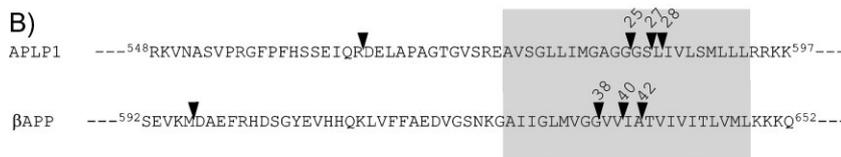


Figure 1. MALDI-TOF MS analysis of APLP1 peptides in human CSF.

- A. Determination of the molecular masses of APLP1 peptides in human CSF. Human CSF (300 μl) was immunoprecipitated with the indicated antibodies and analysed by MALDI-TOF MS. Numbers shown on top of the peaks are molecular masses. Asterisks (*) indicate nonspecific peaks.
- B. A diagram of the APL1β and Aβ domains in APLP1 and βAPP sequences, respectively. Arrowheads and the grey boxes indicate cleavage sites and the deduced TM, respectively. The numbers above the arrowheads indicate the number of amino acid residues in each fragment.



2,586 Da (Fig 1A). Under the same conditions, the A β species were recognized by 4G8 (Fig 1A). On the basis of the molecular weights and the epitopes recognized by the antibodies, we presumed the amino acid sequences of the set of APLP1 peptides. These peptides were named APL1 β 25 (calculated MW 2,327.2 Da), APL1 β 27 (calculated MW 2,471.3 Da) and APL1 β 28 (calculated MW 2,584.3 Da) to reflect the number of amino acid residues in each peptide (see Table S1 of Supporting Information). Finally, the amino acid sequences were determined by using a liquid chromatography-tandem MS (LC/MS/MS) system (see Fig S1 of Supporting Information). Similar to A β , the novel brain peptide species derived from APLP1 have a juxtamembrane region at their common N-terminus and a part of the hydrophobic TM at their variable C-termini (Fig 1B).

Sequential endoproteolytic processing by BACE and PS/ γ -secretase produces the APL1 β species in untransfected SH-SY5Y cells

We suspected that APL1 β is generated by a similar process as A β . Since naïve SH-SY5Y human neuroblastoma cells were found to secrete the same APL1 β species as those found in the human CSF (Fig 2A), degradation of endogenous APLP1 in the cells was then analysed by immunoprecipitation (IP)-MS analysis (Fig 2A). The cells were also radiolabelled with [³⁵S] methionine overnight (Fig 2B) and analysed by IP-autoradiography (Fig 2B; second and fourth panels). Both the IP-MS analysis and the pulse-chase experiments revealed that treatment with a BACE1/2 inhibitor, inhibitor IV, abolishes APL1 β secretion. In addition, recombinant BACE1/2 cleaved an APLP1 peptide (Nma-EIQRDELAK(Dnp)-RR-NH₂) containing the N-terminus of APL1 β as well as a wild-type (wt) β APP peptide (Nma-EVKMDAEFK(Dnp)-RR-NH₂), which contains the N-terminal sequence of A β (see Fig S2 of Supporting Information). These results suggest that BACE1/2 can participate in the generation of APL1 β which is reminiscent of A β generation (Farzan et al, 2000; Hussain et al, 2000).

To determine if PS/ γ -secretase is involved in the secretion of APL1 β , the cells were treated with the γ -secretase inhibitors DAPT (Fig 2A and B) and L685,458 (Fig 2B). Both compounds abolished APL1 β secretion and concomitantly induced intracellular accumulation of APLP1 C-terminal fragment (CTF) stubs, the substrate for γ -cleavage (Fig 2B; third and fourth panels). These results suggest that sequential endoproteolysis by BACE1/2 and PS/ γ -secretase mediates APL1 β generation.

APL1 β and A β levels are comparable in human CSF

We next determined how much APL1 β is present in the CSF. To do this, an LC/MS/MS system was established to measure the level of each APL1 β species. The LC/MS/MS analysis was first performed using synthetic APL1 β peptides to select optimal 'daughter (or product)' ions and conditions for quantification (b2, y20 and y21 for APL1 β 25/28; b2, y21 and y22 for APL1 β 27; see Fig S3 of Supporting Information). The peak areas of the three daughter ions were measured and the average of three calculated concentrations was defined as the concentration for each APL1 β species. Subsequently, various amounts of each synthetic peptide were added to the CSF (50 μ l) of patients with

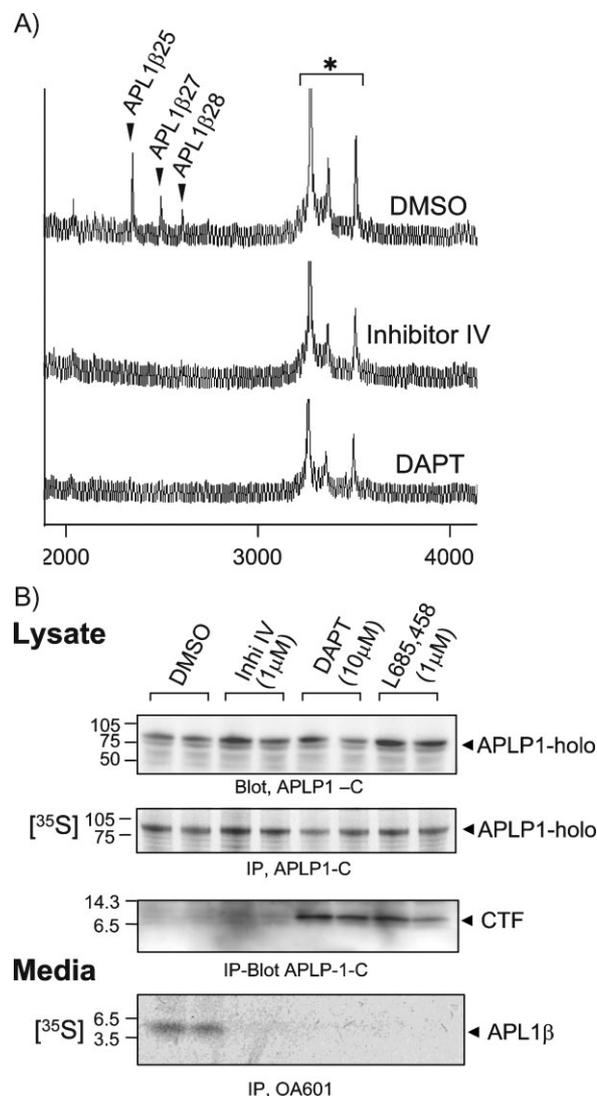


Figure 2. APL1 β secretion from naïve SH-SY5Y cells. Inhibition of APL1 β secretion from SH-SY5Y cells upon treatment with an inhibitor of BACE1/2 (1 μ M inhibitor IV) or PS/ γ -secretase (10 μ M DAPT or 1 μ M L685458).

- A.** Conditioned media were analysed by IP-MS. Asterisks (*) indicate non-specific peaks.
- B.** Cells were radiolabelled with [³⁵S] methionine overnight. APL1 β (detected via IP-autoradiography) was detected in the conditioned medium (fourth panel). Note that [³⁵S] incorporation in the APL1 β bands was abolished by the inhibitors. APLP1 holoprotein (detected via direct blotting and IP-autography; first and second panels) and APLP1-CTF stubs (detected via IP-blotting; third panel) were detected in the resultant cell lysates. Accumulation of APLP1-CTF stubs upon PS/ γ -secretase inhibitor treatment indicates inhibition of degradation of APLP1-CTF stubs, which are the final substrate for APL1 β generation following BACE cleavage. Experiments were performed in duplicate (two independent culture dishes).

(Fig 3B) or without AD (Fig 3A). The amounts of synthetic peptide and areas of the resultant daughter ions change in parallel in both the cases. Thus, the levels of each APL1 β species in CSF (200 μ l) were measured in this system. The APL1 β

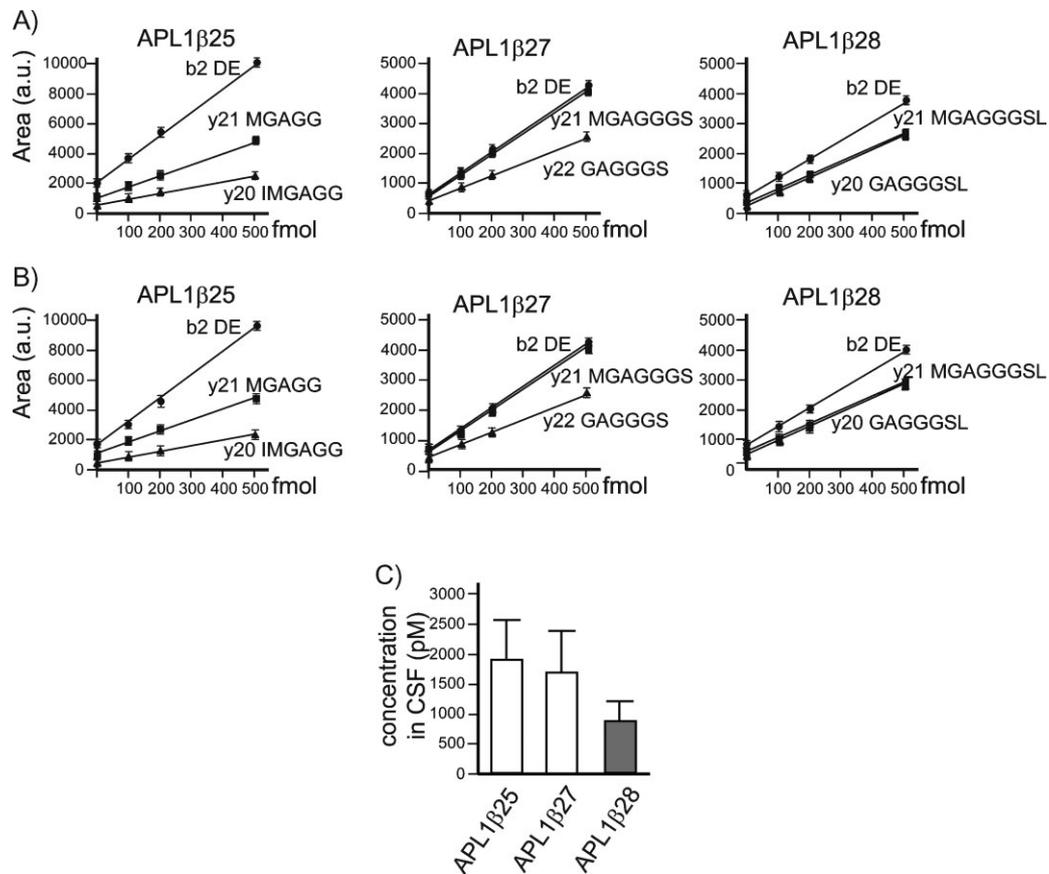


Figure 3. Quantification of APL1 β in human CSF by LC/MS/MS.

- A.** X-axis, levels of the synthetic APL1 β added to the CSF; Y-axis, areas of the indicated daughter ions. Note that none of the Y-intercepts is zero. This is due to the presence of APL1 β in CSF (C100; non-AD). The experiments were performed three times and values represent mean \pm SD.
- B.** The experiments were repeated using another CSF sample (C114; sporadic AD).
- C.** Comparison of the level of each APL1 β species in human CSF ($n = 17$).

level in CSF from non-demented patients was 4.5 ± 1.7 nM (mean \pm S.D. [$n = 17$]; see Table S2 of Supporting Information), and the concentrations of APL1 β 25, APL1 β 27 and APL1 β 28 were 1.9 ± 0.69 , 1.7 ± 0.72 and 0.94 ± 0.39 nM, respectively (Fig 3C). Thus, considering the total A β level in human CSF (500 pM to 4 nM, depending on the experimental methods for the measurement) (Fukuyama et al, 2000; Ida et al, 1996; Kauwe et al, 2007; Mehta et al, 2000; Southwick et al, 1996; Wiltfang et al, 2007), the results indicate that the level of APL1 β in the CSF is similar to or even higher than that of A β .

APL1 β is not a senile plaque component in AD

We investigated whether APL1 β accumulates in senile plaques, as is the case for A β . The majority of A β in senile plaques is highly insoluble but can be obtained by extraction of the sodium dodecyl sulphate (SDS)-insoluble fraction with 70% formic acid (FA; *i.e.*, FA fraction). Thus, we analysed how much APL1 β and A β are in the fraction of AD brain samples. The number of A β

(including smeared bands) levels was calculated by comparison of the densitometric values of the fractions and of synthetic A β (see Fig 4A and Fig S4 of Supporting Information). The FA fractions from 2.5 mg of AD brain samples ($n = 2$) contained 0.40–0.80 μ g of A β (Fig 4A). However, the FA fractions from 65 mg of the same AD brains contained less than 0.1 μ g of APL1 β (Fig 4B), indicating that the FA fraction of AD brains contains much less APL1 β than A β (<1%). Immunohistochemical analysis also indicated that neither of the anti-APL1 β antisera stain senile plaques in AD temporal lobe tissues (see Fig S5 of Supporting Information). To further characterize the non-aggregative nature of APL1 β , we incubated APL1 β *in vitro* under A β fibril/protofibril formation conditions, and analysed the solution by electron microscopy and size exclusion chromatography (SEC). Even though each APL1 β peptide was incubated much longer than A β 40, no APL1 β fibril/protofibril formation could be detected (see Fig 4C–F and Fig S6 of Supporting Information). Collectively, the data indicate a non-amyloidogenic character of APL1 β peptides.

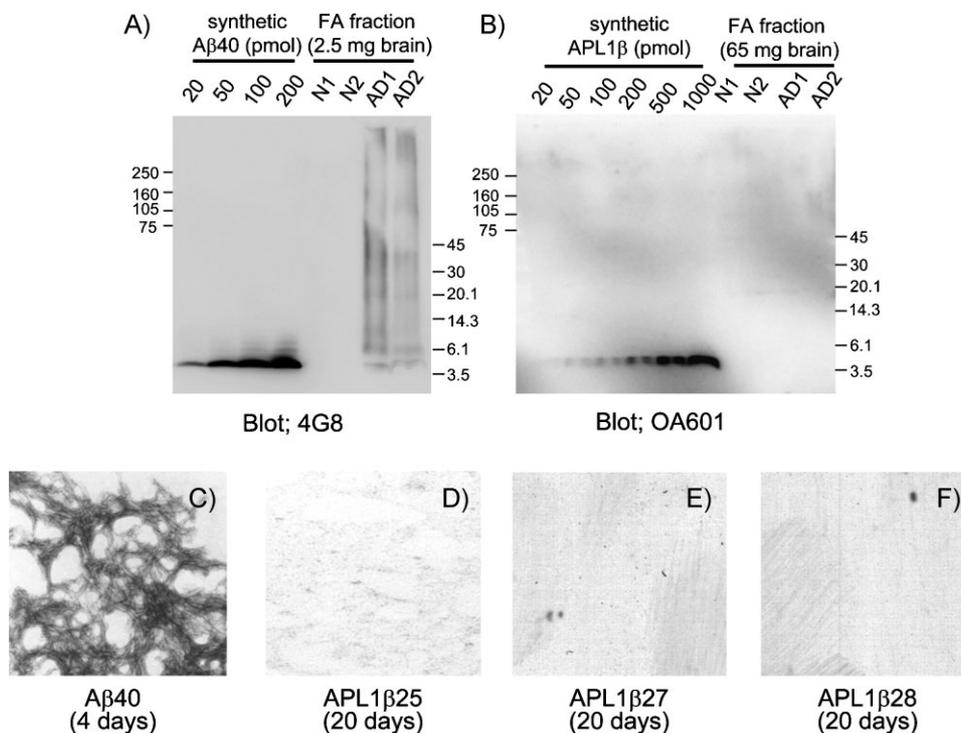


Figure 4. Biochemical and electron microscopic analysis of APL1β.

- A. Aβ in the FA fraction of sporadic AD brain samples. The indicated levels of synthetic Aβ40 and Aβ42 mixtures (1:1) and brain FA fractions (extracted from 2.5 mg of non-demented [N1 and N2] or sporadic AD [AD1 and AD2] brain tissue) were subjected to SDS-PAGE and analysed by immunoblotting with monoclonal antibody 4G8. Aβ levels in each FA fraction-containing lane were calculated from the optical densities by comparison with the optical densities of synthetic peptide bands (left four lanes) as a standard.
- B. APL1β in the FA fraction. Subsequently, the indicated levels of synthetic APL1β25, APL1β27 and APL1β28 mixtures (1:1:1) and much higher amounts of brain FA fraction (extracted from 65 mg of brain tissue) were immunoblotted with the antibody OA601. Note that OA601 detected a positive signal in the synthetic APL1β mixture but not in the FA fractions.
- C–F. Negative staining of Aβ/APL1β peptides incubated *in vitro*. Precipitated fibrils were observed when synthetic Aβ40 was incubated for four days (C). For synthetic APL1β25, 27 and 28 peptides, no fibrils were observed (D–F, respectively).

Some GSMs increase the relative production of APL1β28 in parallel with that of Aβ42 in cell culture

Assuming that the ratio of Aβ42 to total Aβ production in the brain increases in AD, we reasoned that a surrogate marker for Aβ42 production would be a potential biomarker for progression of AD pathology. We studied whether the levels or production of any of the APL1β species might correlate with Aβ42 levels/production. The GSM, S2474, which increases the relative Aβ42 level (Kukar et al, 2005), was added to naïve SH-SY5Y cells, and the levels of secreted APL1β and Aβ species were measured. When the concentration of S2474 in the conditioned medium was increased to 30 μM, the ratio of APL1β28 to total APL1β increased ($R^2 = 0.983$, $t = 29.0$, $p = 1.35 \times 10^{-14}$; Fig 5A). By measuring Aβ40 and Aβ42 generation in conditioned media (Fig 5B), we were able to confirm that increasing the concentration of the compound resulted in an increase in the relative Aβ42 level ($R^2 = 0.9495$, $t = 16.7$, $p = 3.93 \times 10^{-11}$; Fig 5B). Importantly, S2474 increased the ratio of APL1β28 to total APL1β (sum of APL1β25, 27 and

28) in parallel with that of Aβ42 ($R^2 = 0.9578$, $t = 18.4$, $p = 1.02 \times 10^{-11}$; Fig 5C). Similar results were obtained with fenofibrate, another GSM (see Fig S7A of Supporting Information). Thus, the results suggest that APL1β28 generation increases in parallel with Aβ42 generation under these conditions. This is reminiscent of our previous results showing that, among the Nβ species secreted from mouse Notch-1 receptor, some compounds including S2474 and fenofibrate caused parallel changes in the ratios of the longer Nβ25 form to total Nβ and of Aβ42 to total Aβ (Okochi et al, 2006).

Recently, fenofibrate and flubiprofen have been reported to modulate the γ-cleavage by binding to βAPP (Kukar et al, 2008). Although sulindac sulfide (Weggen et al, 2001) and compound-W (Okochi et al, 2006) have been shown to lower the relative Aβ42 level to total Aβ, they did not cause a decrease in the relative APL1β28 level to total APL1β (see Fig S7B–D of Supporting Information). Our results demonstrate that some GSMs, but not all, affect intramembrane proteolysis of human APLP1 as well as βAPP/mNotch-1.

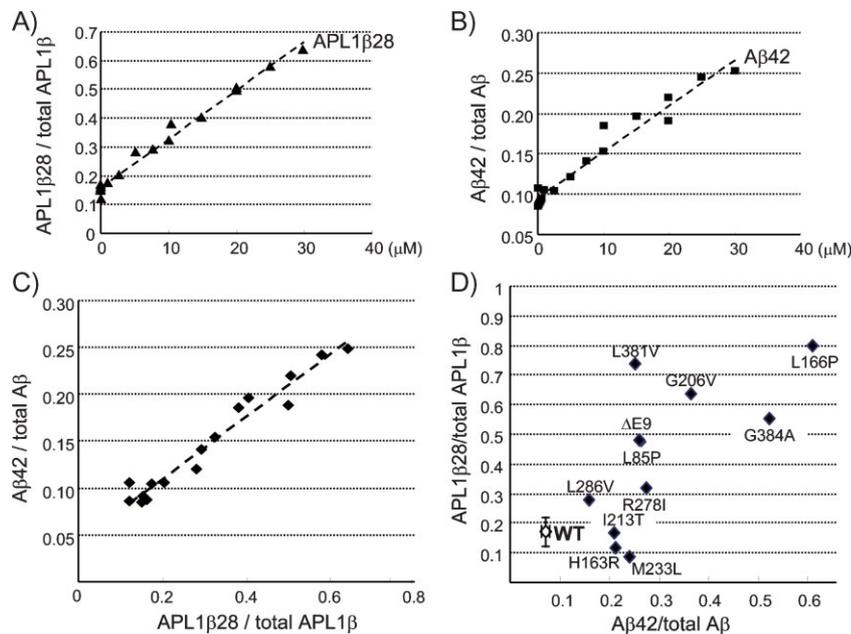


Figure 5. Effects of GSM and PS1 familial AD mutations on the relative ratio of APL1β28 production in cell culture. The levels of APL1β and Aβ in conditioned medium were determined using IP-LC/MS/MS or the sandwich ELISA system, respectively.

- A. Changes in relative APL1β28 levels after the addition of the indicated concentrations of S2474.
- B. Changes in relative Aβ42 levels after the S2474 addition. Note that the generation of Aβ42 increased as the dose of S2474 was increased.
- C. Relationship between the relative levels of APL1β28 versus Aβ42 upon S2474 treatment.
- D. Relationship between the relative levels of APL1β28 versus Aβ42 secreted from K293 cells stably expressing the indicated mutant forms of PS1 FAD. The values indicate means of two independent experiments without SEM.

Several FAD-associated presenilin 1 (PS1) mutants up-regulate the relative production of APL1β28 as well as that of Aβ42 in cell culture

We also examined whether FAD mutants in PS1 can cause, in addition to their effect on Aβ42, an increase in the ratio of APL1β28 to total APL1β. Previous studies using PS1 mutant-transgenic mice report that the magnitude of the increase in the relative Aβ42 level in cultured cells reflect the magnitude of increase in the brain (Borchelt et al, 1996; Citron et al, 1997). We chose the mutants PS1 L85P, H163R, L166P, G206V, I213T, M233L, R278I, L286V, L381V, G384A and ΔE9. We prepared human embryonic kidney 293 (HEK293) cells stably expressing βAPP Swedish (sw), wt APLP1, and each of the selected PS1 FAD mutant forms. In the stable cell lines, endogenous PS proteins in PS/γ-secretase complex were successfully displaced by the exogenous mutant form (see Fig S8 of Supporting Information). Analysis of conditioned media revealed that many of the PS1 mutants increase the relative level of APL1β28 and Aβ42 in parallel (Fig 5D).

However, three of the mutant forms, PS1 H163R, I213T and M233L, were exceptions and had very minor or no effects on the

rate of increase in relative APL1β28 production (wt PS background, mean ± SD = 0.163 ± 0.031) (Fig 5D). This is reminiscent of our previous finding that FAD-associated PS1 C92S does not increase the relative amount of Nβ25 generated from Notch1 (Okochi et al, 2006). Thus, there may be PS1 mutant forms that affect the interaction between βAPP and PS/γ-secretase but not the interaction between APLP1 and PS/γ-secretase.

In CSF from patients and in cultured cells, some PS1 FAD mutations cause a parallel increase in the ratio of APL1β28 to total APL1β

As APL1β28 is not detected in insoluble AD brain fractions (Fig. 4), we examined whether the relative APL1β28 level in CSF reflects the relative production of Aβ42 in the brain. We prepared CSF from patients bearing PS1 FAD mutants (PS1 L85P, H163R, G206V, M233L, L286V and L381V) (Table 1) and from non-demented patients (see Table S2 of Supporting Information), and measured the level of each APL1β and Aβ species in the samples (Fig. 6).

Table 1. Clinical information of the familial AD patients in this study

Mutation	Diagnosis	Age of onset (Year)	Age of CSF collection (Year)	Symptoms
PS1 L85P	Early onset AD with spastic paraplegia (variant type AD)	26	27	MMSE23/30
PS1 H163R	Early onset AD with parkinsonism	41	48	MMSE3/30
PS1 G206V	Early onset AD with psychosis	37	38	MMSE10/30
PS1 M233L-1	Early onset AD with parkinsonism	41	48	MMSE2/30
PS1 M233L-2	Early onset AD with spastic paraplegia	37	53	MMSE0/30, bed-ridden
PS1 L286V	Early onset AD	40	47	MMSE22/30, CDR1
PS1 G381V	Early onset AD with spastic paraplegia (variant type AD)	29	57	MMSE0/30, bed-ridden

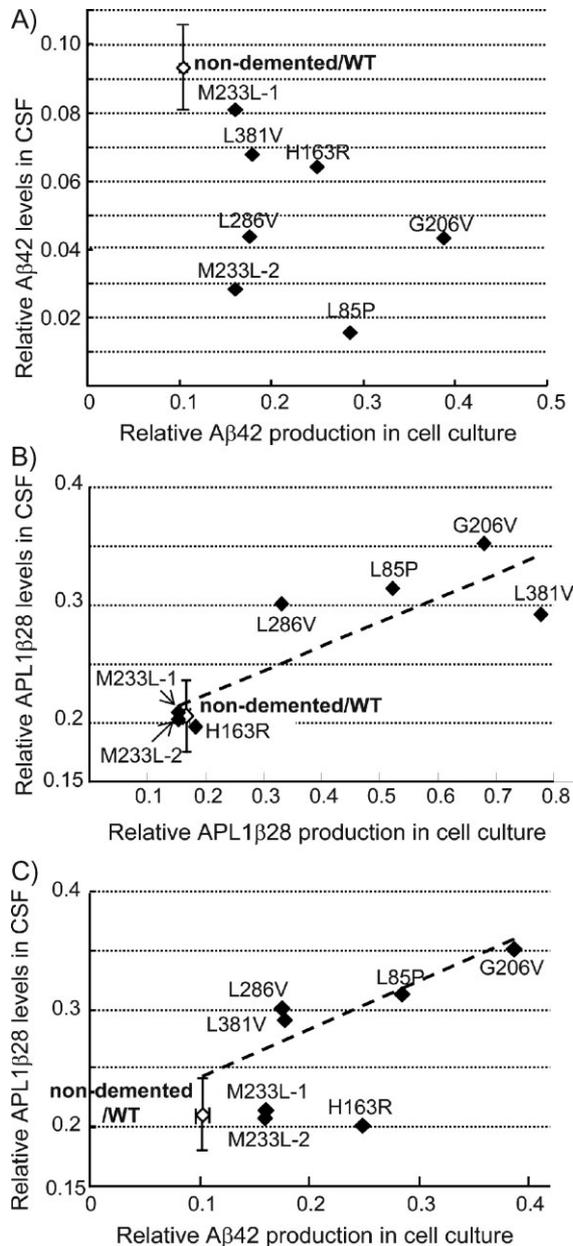


Figure 6. Relative APL1β28 levels in CSF of PS1 FAD patients.

- A.** Relationship between the relative ratio of Aβ42 level to total Aβ level in the CSF (for the non-demented patients with wt PS1 [$n = 17$] or patients with the indicated PS1 FAD mutations) and the relative ratio of Aβ42 production to total Aβ production in cell culture (K293 cells stably expressing wt PS1 or the indicated PS1 FAD mutants). For non-demented patients, the value is a mean, and the error bar represents the SD.
- B.** Relationship between the relative ratio of APL1β28 level to total APL1β level in the CSF and the relative ratio of APL1β28 production to total APL1β production in cell culture. Patients M233L-1 and M233L-2 are brothers.
- C.** Relationship between the relative ratio of APL1β28 level to total APL1β level in the CSF and the relative ratio of Aβ42 production to total Aβ production in cell culture.

We first calculated the relative Aβ42 levels in the CSF and then compared the values with those secreted from wt PS or the PS mutant-expressing cells (Fig 6A). As expected, although the relative levels of Aβ42 secreted from the mutant cells were elevated (wt PS background, mean \pm SD = 0.104 ± 0.004), the relative levels of Aβ42 in the CSF were unchanged or decreased (non-demented patients, mean \pm SD = 0.093 ± 0.010) (Fig 6A). Thus, it seems that the relative Aβ42 levels in CSF do not correspond to the relative generation of Aβ42 in FAD brains.

We, next, performed a similar study with APL1β (Fig 6B). More specifically, the relative APL1β28 levels in mutant CSF were compared with the levels secreted from mutant cells. PS1 L85P, L286V, G206V and L381V mutants were found to up-regulate the relative APL1β28 level in conditioned medium (Fig 5D). In contrast to what was found for Aβ42, the relative APL1β28 level is, indeed, up-regulated in CSF of the FAD patients bearing these mutants (non-demented patients, mean \pm SD = 0.208 ± 0.030) (Fig 6B). However, in CSF of patients bearing the mutations PS1 H163R and M233L, which do not increase the relative APL1β28 level in conditioned medium (Fig 5D), the relative level of APL1β28 is not up-regulated (Fig 6B). These results suggest that, as for the PS1 FAD mutations, the relative APL1β28 levels in CSF correlate with the relative generation of APL1β28 in the brain ($R^2 = 0.74$, $t = 4.10$, $p = 0.006$; Fig 6B). Collectively, we found that PS1 FAD mutations that increase the relative levels of Aβ42 and APL1β28 in cell culture, also elevate the relative CSF levels of APL1β28 but not Aβ42 (Fig 6C). Thus, APL1β28 is a potential surrogate marker for Aβ42. That is the relative level of APL1β28 in CSF correlated with the relative generation of Aβ42 in the brain ($R^2 = 0.79$, $t = 3.31$, $p = 0.04$; Fig 6C).

Even at the mild cognitive impairment (MCI) stage, the relative level of APL1β28 in the CSF of sporadic AD patients is higher than that of non-AD controls

Given that APL1β28 may be a non-aggregating surrogate marker for Aβ42, we examined whether the relative ratio of APL1β28 in the CSF changes in sporadic AD patients. We measured APL1β and Aβ species in CSF of patients with sporadic AD ($M = 43$) including those who were at the MCI stage ($n = 9$) and in demented patients without AD ($n = 35$) as well as in non-demented individuals ($n = 17$) (Supplementary Table 2). The relative ratios of APL1β28 are plotted against those of Aβ42 in Fig 7A. As clearly shown, results for many of the sporadic AD patients were located in the lower-right part (a location where APL1β28 ratio is high and Aβ42 ratio is low) of the plot. Statistically, even when the patients were at the MCI stage (mean \pm SEM = 0.248 ± 0.003), the relative APL1β28 level in the CSF of sporadic AD patients (0.263 ± 0.001) was higher than that of non-demented (0.208 ± 0.002) or non-AD patients (0.212 ± 0.002) with significant differences between non-demented and sporadic AD patients ($p < 0.0001$), non-demented and MCI-stage patients ($p < 0.01$), non-AD and sporadic AD patients ($p < 0.001$), and non-AD and MCI-stage patients ($p < 0.05$), according to the Kruskal-Wallis and Wilcoxon-Mann-Whitney tests (Fig 7B). In addition, we also observed the lowered tendency of the relative Aβ42 level in the CSF of

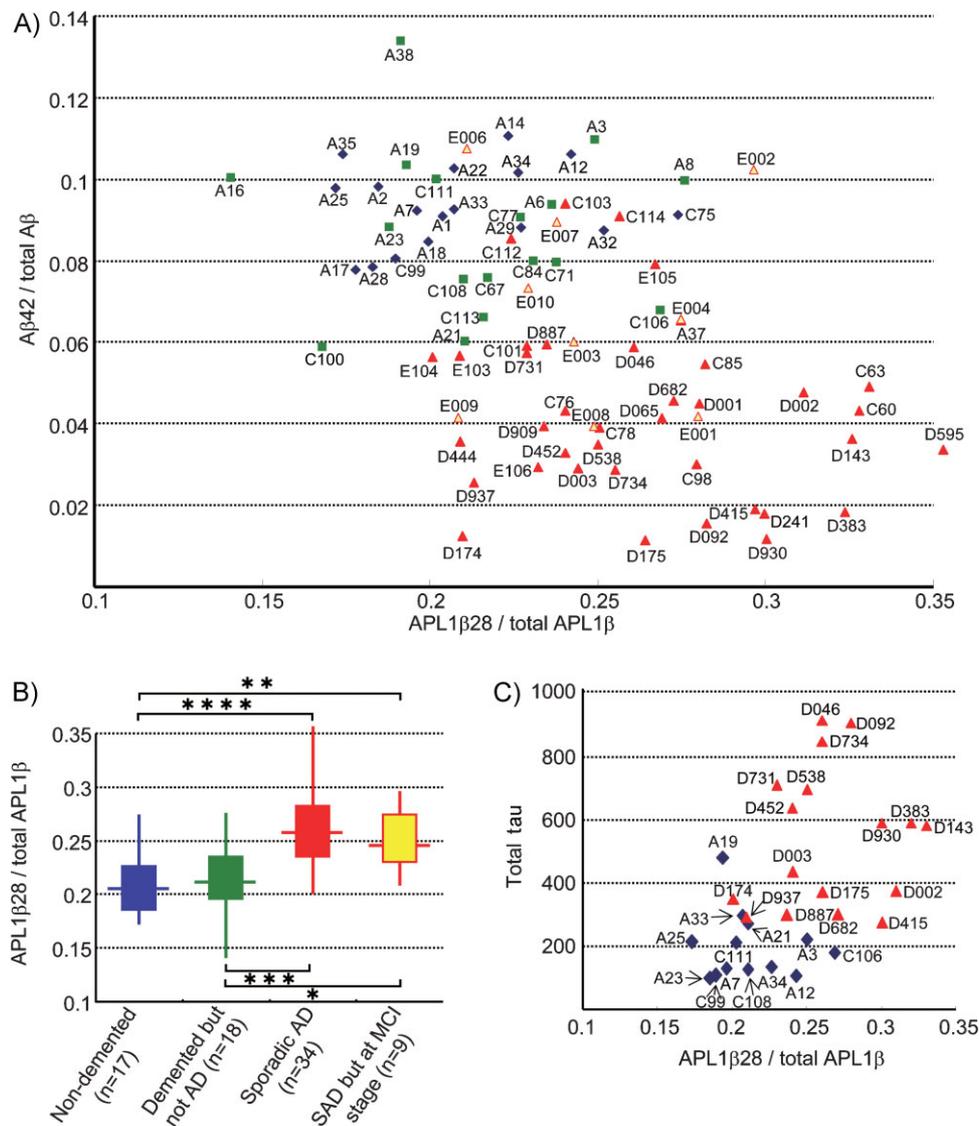


Figure 7. Relative APL1β28 levels in the CSF of sporadic AD and other patients.

- A.** Relationship between the APL1β28 and the Aβ42 ratio in the CSF. Non-demented, blue rhombus; non-AD, green squares; sporadic AD, red triangles; and sporadic AD at the MCI stage, yellow-filled red triangles.
- B.** Box plot of the APL1β28 ratio in the CSF of the non-demented, non-AD, sporadic AD and sporadic AD at the MCI stage. Nonparametric statistical analysis was performed (**** $p < 0.0001$, *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$).
- C.** Relationship between the APL1β28 ratio and total tau levels in the CSF. Non-AD, blue rhombus; SAD patients, red triangles.

sporadic AD patients (Andreassen et al, 1999; Jensen et al, 1999; Motter et al, 1995). Finally, the total tau levels, another CSF biomarker of AD, were plotted against the APL1β28 ratios in the CSF of sporadic AD patients and non-demented controls (Fig 7C). Interestingly, the results for sporadic AD patients were located in the upper-right part of the plot. These results indicate that relative APL1β28 levels in CSF are useful for segregating sporadic AD patients. Additionally, no evidence was found for an altered rate of APL1β28 species degradation in CSF (Supplementary Fig 9). Therefore, the relative production of APL1β28 may be up-regulated in the brains of sporadic AD patients.

DISCUSSION

In this study, we identified a novel APLP1-derived peptide species in human CSF. Like AD-associated Aβ, the APL1β are a group of Aβ-like peptides (Okochi et al, 2002) secreted during sequential endoproteolysis by BACE and PS/γ-secretase. Although the APL1β level in CSF is comparable to that of Aβ, we detected the APL1β species in neither senile plaques nor insoluble fractions of AD brain. In cultured cells expressing endogenous wt PS1, some GSMs caused a parallel increase in the relative levels of Aβ42 and APL1β28, the C-terminally elongated

species. Several PS1 FAD mutants also induced such effects. APL1 β and A β peptide levels were measured in the CSF of patients with PS1 FAD pathological mutations. We found that, although the relative A β 42 levels in CSF decreased in most of the cases, the relative APL1 β 28 levels in CSF and the relative APL1 β 28 generation by mutant-expressing cells increased in parallel. Thus, the results indicate that the level of the novel peptide APL1 β 28 in CSF is a candidate surrogate marker for brain A β 42 production.

Disturbances in A β 42 degradation/clearance are thought to play important roles in the emergence of sporadic AD pathologies (Saido and Iwata, 2006). So far, no study has reported whether there are abnormalities in A β 42 production in sporadic AD. In this study, we found that APL1 β 28 and A β 42 are secreted *in vivo* via similar processes. Thus, we investigated whether the relative level of APL1 β 28 in the CSF changes in patients with sporadic AD to address whether A β 42 production changes in the brains of these patients. Strikingly, in sporadic AD, the relative APL1 β 28 levels in CSF were higher than that of non-AD controls. Moreover, we did not find any evidence for altered degradation of APL1 β 28 species in the CSF. Collectively, we suggest that (i) relative A β 42 production in the brain may increase in some sporadic AD patients, as is the case of patients with familial AD, and (ii) that an elevated relative APL1 β 28 level in the CSF is a potential biomarker for sporadic AD. In the future, we plan to construct an assay system for measuring plasma APL1 β and to perform large-scale/cohort studies to determine whether the relative APL1 β level in CSF is useful for clinical diagnosis of AD. It will be interesting to determine when the ratio of APL1 β 28 production starts to rise in the pathological process of sporadic AD.

Using β APP (Okochi et al, 2006; Weggen et al, 2001), mNotch-1 (Okochi et al, 2006) and APLP1, we found that fenofibrate and S2474 affect the γ -cleavage of multiple substrates. Whether GSMs bind to the TM of APLP1 remains to be determined. If this is the case, although some GSMs may target β APP (Kukar et al, 2008), their binding would not be specific to β APP.

Previously, we reported that N β , a Notch-1 A β -like peptide, is secreted (Okochi et al, 2006), and, in this study, we demonstrated that CSF contains as much APL1 β as A β . This suggests that a novel group of physiological peptides (*i.e.* a group of A β -like peptides) may exist in the human brain. It seems possible that A β was identified first because high levels of A β accumulation are associated with AD. Because small brain peptides often have a variety of physiological roles, for example serving as neurotransmitters and ligands, it is important to further investigate the physiological functions of A β -like peptides such as APL1 β and N β .

MATERIALS AND METHODS

Antibodies and reagents

Rabbit antisera OA601 and OA663 were raised against the synthetic peptides IQRDELAPAGTGVRSRE and DELAPAGTGVRSRE, respectively (MBL, Japan). The peptide sequences correspond to the sequence of the

human APLP1 juxtamembrane domain (GenBank accession number, U48437). The monoclonal antibody 4G8 against A β was purchased from Signet, and the antiserum against APLP1 CTF was purchased from Calbiochem. HRP-conjugated anti-rabbit or anti-mouse IgG (Promega) was used as a secondary antibody. For detection of the biotinylated antibodies, we used neutravidin-HRP (Pierce). The A β 40 peptide and the peptides DELAPAGTGVRSREAVSGLLIMGAGG (APL1 β 25), DELAPAGTGVRSREAVSGLLIMGAGGGS (APL1 β 27) and DELAPAGTGVRSREAVSGLLIMGAGGGS (APL1 β 28) were synthesized by Peptide Institute. Each peptide was dissolved in 1,1,1,3,3,3-hexafluoro-2-propanol, stored, and pretreated before use as described previously (Okochi et al, 2006). S2474 was synthesized by Shionogi. The secretase inhibitors L685458 and DAPT were purchased from Peptide Institute, and inhibitor IV and TAPI-1 were from Calbiochem.

Collection of human CSF

Human CSF samples were collected in six facilities. All the experiments using CSF were approved by the ethical committee of Osaka University Hospital (Nos. 07139 and 07212). Lumbar punctures were performed using standard methods. Briefly, CSF (5–10 mL) was collected into sterile polypropylene tubes using atraumatic cannulas (21–23G) placed in the L3/L4 or L4/L5 intervertebral space. CSF was centrifuged for 10 min at 4,000 $\times g$, and aliquots of the remaining CSF supernatants were frozen immediately at 80°C. The CSF samples were frozen and thawed once or twice before measurements.

cDNA constructs

A cDNA encoding human APLP1 (Toyobo) was subcloned into pcDNA3.1 Hygro(+). The FAD mutant versions of PS1 were generated by PCR-based mutagenesis using the QuikChange-II kit (Stratagene) with wt PS1 cDNA as a template (Okochi et al, 2002).

Cell culture and cell lines

SH-SY5Y neuroblastoma cells were grown in 1:1 DMEM/F12 media containing 10% fetal calf serum. HEK293 cells stably expressing either wt or mutant PS1, APLP1 and β APP sw mutant were generated using Lipofectamine 2000 (Invitrogen) and cultured as described previously (Okochi et al, 2000b).

Immunoblotting, combined IP-immunoblotting (IP-blot), and combined IP-autoradiography

For immunoblotting, cell lysates or brain FA-soluble fractions were prepared, diluted in SDS-sample buffer and separated by Tris-glycine or Tris-tricine (Invitrogen) SDS-PAGE as described previously (Okochi et al, 2000b). For analysis of proteins other than APL1 β /A β , the proteins were transferred to a polyvinylidene difluoride membrane, and for analysis of APL1 β /A β , the proteins were transferred to a nitrocellulose membrane and boiled for 10 min in phosphate buffered saline (PBS). Membranes were blocked in 5% skim milk and probed with 1:1,000 anti-APLP-1 C-terminal antibody, 1 μ g/ml antibody 4G8 or 28 μ g/ml biotinylated OA601 IgG, followed by probing with HRP-conjugated anti-rabbit IgG, anti-mouse IgG or neutravidin, respectively. Immunoreactive proteins were detected using ECL or ECL plus reagents (GE Healthcare), and chemiluminescence intensities were measured using a LAS3000 scanner, followed by analysis with Multi Gauge Ver3.0 software (Fuji Film). IP-blot analysis of cultured cell lysates expressing wt APLP1 or mutant PS1 was performed as described previously (Okochi et al, 1997). IP-autoradiography of

The paper explained

PROBLEM:

The 42 amino acid version of amyloid β -peptide (A β 42) is the major constituent of senile plaques, which is the pathological hallmark of AD and is generated by proteolytic processing of the β -amyloid precursor protein (β APP). Remarkably, in the CSF of AD patients A β 42 levels are low, whereas this peptide accumulates within the brain. It is currently believed that this discrepancy may be due to the fact that A β 42 is largely deposited in insoluble plaques within the brain and that clearance into the CSF is therefore reduced. Although the reverse relationship of A β 42 levels can be used as a biomarker to some extent after disease onset, better surrogate markers specifically for presymptomatic diagnosis are desperately required.

RESULTS:

In this study, we discovered APL1 β 28 as a novel and highly sensitive biomarker. This peptide is generated by the same

proteolytic mechanism as A β 42, except that it is derived from a divergent substrate, namely the β APP-like protein, APLP1. Non-amyloidogenic APL1 β 28 can be detected in the CSF and its levels correlate with A β 42 production. Remarkably, the ratio of APL1 β 28 to total APL1 β are significantly increased in familial and sporadic AD cases.

IMPACT:

We propose using the levels of APL1 β 28 as a surrogate marker for A β 42 production in the central nervous system. This has clinical importance for the diagnosis and early detection of sporadic AD.

cultured media was performed as described previously (Okochi et al, 2002). Conditioned media collected from radiolabelled SH-SY5Y cells were adjusted to 50 mM Tris (pH 7.4), 1:500 protease inhibitor mix (Sigma) and 5 mM EDTA (pH 8.0) and then immunoprecipitated with OA601.

Combined IP/MALDI-TOF MS (IP/MS) analysis

Combined IP-MALDI-TOF MS analysis was carried out as described previously (Okochi et al, 2002). Either human CSF or conditioned media from SH-SY5Y cells was used. CSF (300 μ l) was diluted with 700 μ l of Tris buffer (pH 7.6) containing 5 mM EDTA and 1:500 protease inhibitor mix (Sigma). The MS peak heights and molecular masses were normalized to those of angiotensin and bovine insulin β -chain.

Radiolabelled pulse-chase experiment

Following treatments with 1 μ M L685458, 10 μ M DAPT, or 1 μ M inhibitor IV for 16 h, SH-SY5Y cells were metabolically labelled for 8 h as described previously (Okochi et al, 2000a).

Preparation of FA-soluble fractions in human brains

Frozen brains were minced and suspended in two volumes of Tris buffered saline (TBS v/w) supplemented with protease inhibitor mix (Sigma). Suspensions were homogenized with a Teflon homogenizer and centrifuged at 100,000 $\times g$ for 15 min. The suspensions were extracted twice with 1% Triton X-100 and three times with 2% SDS in TBS, after which the 2% SDS-insoluble fractions were sonicated in FA and then centrifuged at 100,000 $\times g$ for 15 min. The resultant FA-soluble fractions were evaporated using a Speed-Vac, mixed with 2 \times SDS-sample buffer and heated for 5 min at 100°C.

Determination of amino acid sequences of APL1 β peptides in human CSF

APL1 β peptides immunoprecipitated from human CSF by OA601 were eluted with a 20% acetonitrile/0.1% FA solution. The eluates were passed through a 50-kDa filter unit (YM50 Microcon; Millipore), after which the filter was washed twice with the same solution. The resultant filtrates were applied to a C18 column (ODS-100V, TOSOH) using an auto-injection system (Agilent 1100 series). Subsequently, we performed LC/MS/MS analysis using a 50-min gradient (5 to 100% acetonitrile) at a flow rate of 200 μ l/min (3200QTRAP; Applied Biosystems). The brain APL1 β 25, APL1 β 27 and APL1 β 28 species were eluted at \sim 20.7, 21.5 and 22.0 min, respectively. Enhanced mass scan, enhanced resolution and enhanced product ion analyses were performed after elution. All spectra for all peptides in CSF matched those of the synthetic APL1 β 25, APL1 β 27 and APL1 β 28 peptides. Turbo spray was used as an ion source and for each analysis, the curtain gas pressure, collision gas pressure, ion spray voltage, temperature, ion source gas 1 pressure and ion source gas 2 pressure were 15 pounds per square inch (p.s.i.), 5 p.s.i., 5,500 V, 600°C, 50 and 50 p.s.i., respectively. The declustering potential, enhanced potential and collision cell exit potential were set at 70, 10 and 3 V, respectively. Analyst Version 1.4.1 software was used.

Quantitative LC/MS/MS analysis of APL1 β species

Human CSF samples were pretreated using the ProteoSeek™ Albumin/IgG removal kit (PIERCE) according to the manufacturer's instructions. CSF, Cibacron Blue/Protein A gel slurry, and binding/wash buffer were mixed at 2:1:2 (v/v/v) ratio. The pretreated CSF samples were directly applied to a C18 column (ODS-100V; TOSOH) using an auto-injection system (Agilent 1100 series). Conditioned medium was

immunoprecipitated with OA601, and the precipitates were eluted with a solution of 20% acetonitrile and 0.1% FA. The eluates were passed through a 50-kDa filter unit (YM50 Microcon; Millipore). The resultant filtrates were applied to the C18 column. The HPLC parameters were as follows: mobile phase A, 0.1% FA; mobile phase B, acetonitrile with 0.1% FA; mobile phase gradient, 95% A–100% B in 50 min; flow rate, 200 μ l/min. After LC/MS/MS analysis (3200QTRAP; Applied Biosystems), the peak areas of the daughter ions (b2, y20 and y21 for APL1 β 25/28; b2, y21 and y22 for APL1 β 27) were measured using the MultiQuant™ software. The average of three calculated concentrations was defined as the concentration for each APL1 β species in the CSF.

A β and total tau ELISA

A β 40 or A β 42 levels in human CSF or conditioned media were quantified using commercial sandwich ELISA kits (WAKO Pure Chemical Industries, Ltd.). Total tau levels in human CSF were quantified using commercial sandwich ELISA kits (Innogenetics, Belgium). After the addition of the protease inhibitor mixture, human CSF and conditioned media (Sigma) were appropriately diluted with the standard diluents provided in the kits.

In vitro BACE cleavage assay

Recombinant ectodomain BACE1/2 was obtained from R&D Systems, and the synthetic fluorescent peptides wt APP (Nma-EVKM-DAEFK(Dnp)-RR-NH₂) and APLP1 (Nma-EIQR-DELA(KDnp)-RR-NH₂) were obtained from Peptide Institute Co. Ltd. Recombinant BACE1 or BACE2 (7.4 nM) was mixed with the substrate (1 μ M) in the reaction buffer (50 mM sodium acetate, pH 5.0, 0.008% Triton X-100) in a 96-well microtiter plate. The level of fluorescence in each well was determined using a fluorometer (Spectra Max GeminiXS), and the data were analysed using SOFTmax PRO (Molecular Devices).

Fibril formation by APL1 β

Fibril formation of A β peptide and SEC were previously described (Hartley et al, 1999). Briefly, A β 1-40, APL1 β 25, APL1 β 27 and APL1 β 28 peptides were dissolved in 1,1,1,3,3,3-hexafluoro-2-propanol to a concentration of 1 mg/ml. Before use, the peptides were dried using a Speed-Vac and dissolved in 1 mM NaOH to a concentration of 1 mM. Solutions were immediately adjusted to pH 7.0 with 10 mM NaOH and diluted to a final concentration of 500 μ M in 1:1 water/PBS. Peptides were then incubated at 37°C for 0–48 h and 5- μ l aliquots were collected every 4 h. Peptides were diluted with 15 μ l of PBS and then centrifuged for 10 min at 16,000 $\times g$. Supernatants were fractionated by SEC, and precipitated fibrils were analysed by a transmission electron microscopy (TEM).

SEC

Ten μ l of diluted supernatants (protofibrils and low molecular weight peptides) were separated by a Superdex 75 size exclusion column (Hartley et al, 1999) using an AKTA explorer 10S system (GE Healthcare). Peptides were eluted with 50 mM Tris pH 7.6 containing 150 mM NaCl. Elution was monitored by measuring the absorbance at 215 and 280 nm.

TEM

Precipitated fibrils were suspended in 10 μ l of PBS. Samples (3 μ l) were applied to carbon-coated Maxtaform HF36400 mesh grids

(Ohkeshoji) and incubated for 3 min. Excess samples were absorbed with filter paper, after which an equal volume of uranyl acetate solution was added. After incubation for 2 min, the solution was removed and the grid was air-dried. Samples were examined using a Hitachi H-7650 transmission electron microscope.

Immunohistochemistry

Formalin-fixed, paraffin-embedded brain blocks were obtained for immunohistochemistry. Sections (10 μ m) cut from these were deparaffinized and pretreated with 0.5% H₂O₂ in PBS for 30 min. The primary antibody was diluted in PBS containing 0.1% Triton X-100 (PBST) and 1% normal serum from the species in which the secondary antibody was raised. After incubation with a specific primary antibody for 48 h at 4°C, the sections were treated with the appropriate biotinylated secondary antibody at 1:1,000 concentration (Vector Laboratories) for 2 h at room temperature. The sections were then washed in PBST and incubated for 2 h at room temperature with avidin-biotinylated HRP complex (ABC Elite; Vector Laboratories). Peroxidase labelling was detected by incubation with a solution containing 0.01% 3,3'-diaminobenzidine (Sigma), 0.6% nickel ammonium sulfate, 0.05 M imidazole and 0.00015% H₂O₂. Negative control experiments were performed as described previously but in the absence of a primary antibody.

Author contributions

KY and MO detected APL1 β species in CSF; TSK determined amino acid sequence of APL1 β species by LC/MS/MS; ST, TN and TSK measured APL1 β by LC/MS/MS; KN, MO and KY performed pulse-chase experiments; MO, JJ and KY performed *in vitro* fibril/protofibril formation assay; KY and ST performed *in vitro* BACE cleavage assay; KY, KN and KM performed A β ELISA assay; ST and KY generated PS1 FAD mutant expressing cells; TA performed immunohistochemical study; TI, KK, TT, MK, MI, KD, HK, TT, TM, RH, KT, HA, RK, KT, MT, ST and MO collected CSF samples; HS and CH provided analytical tools and reagents; MO conceived and designed the study, and analysed the data; MO wrote the paper with contributions from HS, CH and ST.

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