

SCIENTIFIC REPORTS

OPEN

C-terminal fragments of the amyloid precursor protein in cerebrospinal fluid as potential biomarkers for Alzheimer disease

María-salud García-Ayllón^{1,2,3}, Inmaculada Lopez-Font^{1,2}, Claudia P. Boix^{1,2}, Juan Fortea^{2,4,5}, Raquel Sánchez-Valle⁶, Alberto Lleó^{2,4}, José-Luis Molinuevo⁶, Henrik Zetterberg^{7,8,9}, Kaj Blennow^{7,8} & Javier Sáez-Valero^{1,2}

This study assesses whether C-terminal fragments (CTF) of the amyloid precursor protein (APP) are present in cerebrospinal fluid (CSF) and their potential as biomarkers for Alzheimer's disease (AD). Immunoprecipitation and simultaneous assay by Western blotting using multiplex fluorescence imaging with specific antibodies against particular domains served to characterize CTFs of APP in human CSF. We demonstrate that APP-CTFs are detectable in human CSF, being the most abundant a 25-kDa fragment, probably resulting from proteolytic processing by η -secretase. The level of the 25-kDa APP-CTF was evaluated in three independent CSF sample sets of patients and controls. The CSF level of this 25-kDa CTF is higher in subjects with autosomal dominant AD linked to *PSEN1* mutations, in demented Down syndrome individuals and in sporadic AD subjects compared to age-matched controls. Our data suggest that APP-CTF could be a potential diagnostic biomarker for AD.

Accumulation of the β -amyloid peptide ($A\beta$) in the brain is an early and specific phenomenon associated with the pathogenesis of Alzheimer's disease (AD)¹. Many reports support that the determination of $A\beta_{42}$ in cerebrospinal fluid (CSF) is a core biomarker for AD². While the amount of the pathological species of $A\beta$ is increased in the AD brain, their levels in CSF are decreased, probably due to increased brain deposition. To enable monitoring early disturbance in amyloid precursor protein (APP) and $A\beta$ mis-metabolism additional biomarkers are needed.

Other plausible biomarkers for AD are additional fragments resulting from the processing of the amyloid precursor protein (APP). APP is a large type I transmembrane spanning protein consisting of a large N-terminal extracellular domain, a hydrophobic transmembrane domain, and a short intracellular C-terminal domain. APP is usually cleaved by α -secretase (ADAM10; leading to non-amyloidogenic pathway), or by β -secretase (BACE1; leading to amyloidogenic pathway), which causes the secretion of large sAPP α and sAPP β N-terminal fragments (NTFs). CSF levels of sAPP α and sAPP β show no change in AD³. The membrane remaining C-terminal fragments (CTFs) are always processed by γ -secretase generating shortest intracellular domain (AICD) peptides (for a review see Haass *et al.*⁴).

APP can also undergo alternative proteolytic processing pathways (for a review see Andrew *et al.*⁵). Thereby, concerted cleavage of β -secretase and α -secretase result in the secretion of sAPP β and shorter $A\beta$ peptides⁶. The presence in CSF of short NTF derivatives of APP, which generation does not involve α -secretase or BACE, has been also demonstrated⁷. More interestingly in the context of this report, a recently discovered alternative

¹Is tu de Neurociencias de Alicante, Unives dad Miguel Hernández-CSIC, 03550, Sa Joa d'Alacant, Alicante, españa. ²ce ntro de investigación Biomédica en Red sobre enfermedades ne urodegenerativas (ci BeRneD), Sant Joa d'Alacant, 03550, Alicante, s aña. ³Unidad de investigación, Hospital General Universitario de elche, fi SABiO, elche, Spain. ⁴Memory Unit, ne urology Department, Hospital de la Santa cre u i Sant Pau, Barcelona, Spain. ⁵Down Medical center, fundació catalana Síndrome de Down, Barcelona, Spain. ⁶Alzheimer's Dss O Dss Un Neurology Servic Hs Clinic 0803 Barcelon Spain. ⁷clinical neuroc hemistry Laboratory, Sahlgrenska University Hospital, Mölndal, Sweden. ⁸institute of ne uroscience and Physiology, University of Gothenburg, Mölndal ca mpus, Sweden. ⁹Department of Molecular ne uroscience, institute of ne urology, University College London, London, U. Correspondence and request materias s ld be address d J. .(ema: j.saez@umh.es)

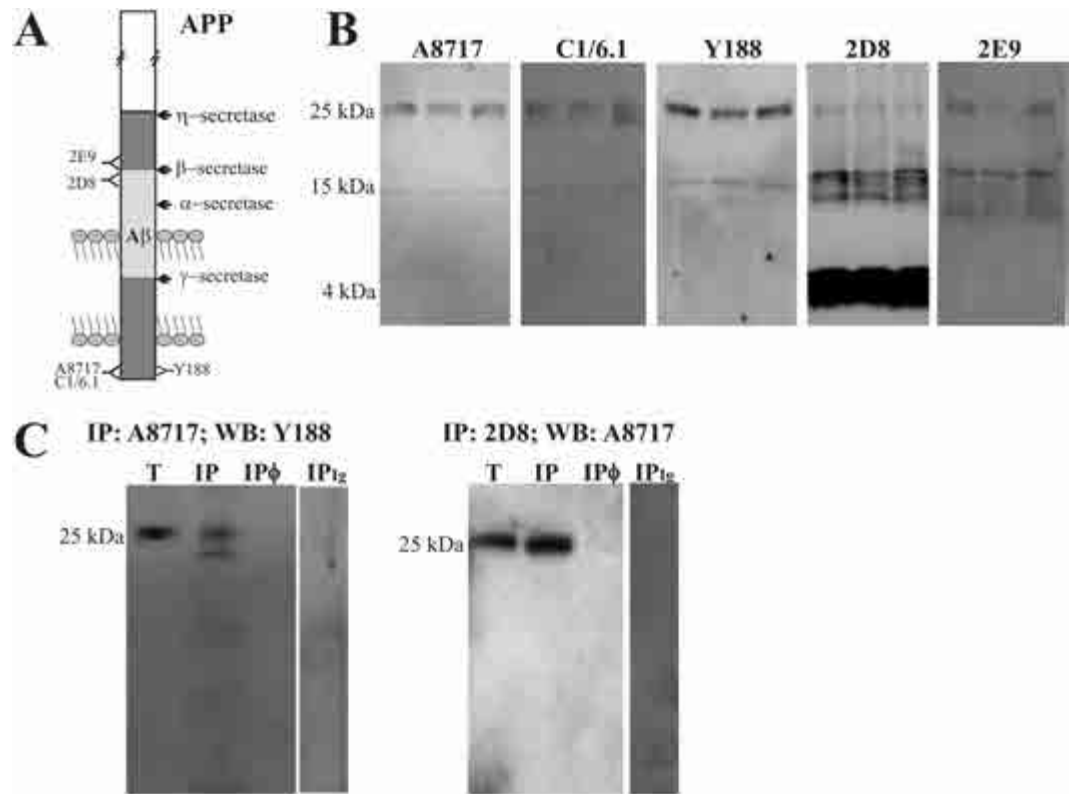


Figure 1. Soluble CTFs of APP are present in human CSF. **(A)** Schematic representation of full-length APP processing by secretases. The epitopes for the antibodies used in this study are indicated. **(B)** Western blotting of three human CSF samples from non-demented controls subjects, resolved with the indicated antibody (samples were the same between different blots). **(C)** CSF aliquots (Total, T) were immunoprecipitated with the indicated antibody, and precipitated proteins (bound fraction, IP) were immunoblotted with the indicated alternative antibody. CSF aliquots incubated with protein A-Sepharose in the absence of capture-antibody (IP \emptyset) or with an irrelevant IgG (IP_{Ig}; a rabbit IgG for A8717 IP and a rat IgG for 2D8 IP), were analyzed in parallel as negative controls.

physiological APP processing pathway driven by an asparagine endopeptidase (AEP) named δ -secretase⁸ or by a metalloproteinase named η -secretase⁹ will generate alternative proteolytic metabolites, including NTFs and CTFs, of different molecular mass.

In addition to the different species of A β , all the large extracellular APP-NTFs have been studied in human CSF^{9–11}; but the presence of APP-CTFs in CSF has not been reported to date. In this study we investigated if APP-CTFs are detectable in CSF, characterized the major APP-CTF immunoreactive band, and determined whether the levels of this peptide fragment are altered in autosomal dominant AD (ADAD), Down syndrome subjects with Alzheimer's type dementia (dDS), and sporadic AD subjects (sAD).

Results

APP-CTFs are present in human CSF. To determine the presence of APP-CTFs in human CSF, we first examined human CSF samples by Western blotting using three different anti-CTF antibodies (a schematic representation of APP and epitopes for antibodies is represented in Fig. 1A). The three APP-CTF antibodies demonstrated specificity in assess the accumulation of C-terminal fragments of APP in cells transfected with a construct that encodes the C-terminal 99 amino acids of APP (amino acids 597–695; blots not shown). Immunoblotting revealed a similar pattern of immunoreactive bands, with a predominant band of ~25 kDa (Fig. 1B). This band was also observed with the 2D8 and 2E9 antibodies, both against an extracellular domain close to the transmembrane domain, thus recognizing a η -secretase-generated CTF-APP (CTF η)⁹. 2D8 and 2E9 also detected other soluble fragments around ~15 kDa, termed A η , generated after concerted cleavage by η -secretase and α/β -secretases⁹. 2D8 antibody also detected A β monomers. Multiplex fluorescence imaging with the A8717 and 2E9 antibodies indicated that the major 25 kDa band is compatible with the CTF η ; similar co-labelling was revealed with antibodies C1/6.1 and 2D8 (Supplemental Fig. 1). To further examine the identity of CTF bands in human CSF, we performed immunoprecipitation/Western blot analysis (Fig. 1C). Since in SDS-PAGE the immunoglobulin light chain migrates at similar molecular mass that the APP-CTF 25-kDa band, we used dimethyl pimelimidate dihydrochloride to covalently link primary antibodies to protein A Sepharose, and eluted with 0.1 M glycine buffer at pH 2.5, in order to prevent the co-elution of the antibody along with the target protein¹². CSF samples were immunoprecipitated using the A8717 antibody and blotted with the Y188 antibody, confirming the identity

Group	Age (years)	Gender	CSF A β 42 (pg/mL)	CSF T-tau (pg/mL)	CSF P-tau (pg/mL)
sAD	71 \pm 2 [55–86]	15F/5M	412 \pm 19**	665 \pm 52**	84 \pm 6**
NC	72 \pm 2 [57–88]	6F/14M	739 \pm 32	233 \pm 14	36 \pm 2
ADAD	43 \pm 2 [31–49]	5F/2M	266 \pm 49**	883 \pm 204**	168 \pm 69*
NC	39 \pm 3 [25–47]	5F/2M	809 \pm 94	245 \pm 29	46 \pm 4
dDS	53 \pm 2 [43–57]	4F/3M	422 \pm 17*	767 \pm 170*	108 \pm 19*
NC	48 \pm 2 [47–53]	5F/2M	751 \pm 84*	160 \pm 26	33 \pm 5

Table 1. Clinical, demographic data and classic CSF biomarker levels. The *PSEN1* mutations included in this study from ADAD cases (autosomal dominant AD subjects) corresponded to 3 carriers of L286P, and one S169P, L173F, L235R and L282R. The data represent the means \pm SEM, and for age the range of values is also indicated. All the pathological groups were compared with age-matched NC obtained from the same Hospital. Significantly different ** $p < 0.005$; * $p < 0.05$ from the NC group.

of the 25-kDa band as an APP-CTF. Immunoprecipitating with 2D8 antibody and blotting with A8717 antibody supported the identity of the 25-kDa band as a CTF η .

The 25-kDa APP-CTF is increased in AD CSF. To assess whether APP-CTF levels are altered in AD, we first analyzed CSF samples from autosomal dominant AD (ADAD), an early-onset form of genetically determined AD¹³. Clinical, demographic data and classic CSF biomarker levels are included in Table 1. Genetically determined AD offers unique opportunities to analyze diagnostic biomarkers particularly given that diagnosis is guaranteed. The 25-kDa band was detected with A8717 antibody in all CSF analyzed (Fig. 2A). The immunoreactivity of the 25-kDa APP-CTF band in the CSF from ADAD subjects increased (95 \pm 27%; $p = 0.01$) compared to those in age-matched NC composed by non-mutation carriers from the same families (Fig. 2A). Down syndrome subjects with Alzheimer's type dementia (dDS) can be also considered a form of genetically determined AD¹³. Once more, an increase (68 \pm 18%; $p = 0.01$) in the intensity of the 25-kDa APP-CTF band, resolved with A8717 antibody, was determined in CSF samples from dDS patients, comparing these to age-matched NC (Fig. 2B). Finally, we also have assessed potential differences in the level of the 25-kDa APP-CTF band in sporadic AD subjects (sAD) compared to aged-matched controls (see Table 1). We found that the total immunoreactivity for this band, detected with the A8717 antibody, increased (35 \pm 9%; $p = 0.01$) in sAD compared to age-matched NC subjects (Fig. 2C). CSF samples from sAD subjects also showed a similar increment for the 25-kDa band when they were analyzed with the 2D8 antibody (35 \pm 9%; $p = 0.01$), correlating tightly with the estimation of the levels calculated with the A8717 antibody ($R = 0.73$; $p < 0.001$; Supplemental Fig. 2). There were no clear correlations between the level of the 25-kDa APP-CTF band and the levels of classical biomarkers, A β 42, T-tau or P-tau, in either the control or sAD groups considered individually (Supplemental Fig. 3). Only when control and sAD subjects were pooled, a positive correlation emerged between immunoreactivity levels of the 25-kDa APP-CTF band with T-tau, and with P-tau levels (Supplemental Fig. 3).

Discussion

Here, we demonstrate that APP-CTFs are detectable in human CSF. Particularly, the most abundant soluble APP-CTF, a 25-kDa fragment, is attributed to a CTF recently characterized as the result of proteolytic processing by η -secretase (CTF η)⁹. Canonical APP proteolysis occurs via α - and β -secretases, resulting in CTF α and CTF β with a molecular mass lower than 15 kDa; but novel APP-CTF that migrates \sim 25 kDa has also been described¹⁴. In addition to the described alternative pathways for APP^{7–9}, other cleavages for APP could occur since non-canonical N-terminal APP fragments have been also identified in human CSF¹⁵. The precise characterization of the APP-CTF 25-kDa fragment as a CTF η requires further confirmation. In this regard, the development of pan-specific antibodies against the predicted N-terminus of CTF η could be valuable. Similarly to the reported by others¹⁵, attempts to immunoprecipitate the 25-kDa APP-CTF for sequencing were not fruitful. Since soluble full-length APP protein is also present in CSF, forming heteromers that co-immunoprecipitate with more abundant sAPP β and sAPP α ¹⁶, an enrichment process based in available APP C-terminal antibodies could result of lower efficiency and specificity for APP-CTFs. Similar handicap will difficult development of a specific ELISA assay (discussed below).

As an intermediate of proteolytic process, the presence of any APP-CTF in CSF was unexpected. Anyhow, the presence in CSF of soluble forms of full-length membrane proteins containing the transmembrane and intracellular domains is not an unusual finding^{16,17}. Early studies failed to detect short C-terminal fragments of APP in the medium of cultured cells¹⁸; but others suggested the release of largest APP-CTF fragments from cultured neural cells¹⁹. Moreover, a series of APP-CTFs was found to be secreted within exosomes in cultured cells²⁰, as well AICD²¹. The mechanisms by which these membrane-bound proteins reached the CSF are unknown; but neuronal death may be also a major contributing factor. Regarding the cellular source of the soluble 25-kDa APP-CTF found in CSF, the presence of hitherto undocumented APP fragments, including a 25-kDa CTF, has been documented in hippocampal neurons⁹, but also across other multiple cell types, including bovine brain microvascular endothelial cells¹⁵. Since the δ -secretase enzyme AEP is a widely distributed²², we could not discard a non-neural source for the 25-kDa APP-CTF found in CSF. The cellular origin of the 25-kDa APP-CTF could be also relevant in order to define their potential as an AD biomarker.

Different APP C-terminal antibodies confirmed the 25 kDa as the predominant band in human CSF. As stated, these APP proteolytic fragments are derived from a constitutive processing step driven by a η -secretase that is

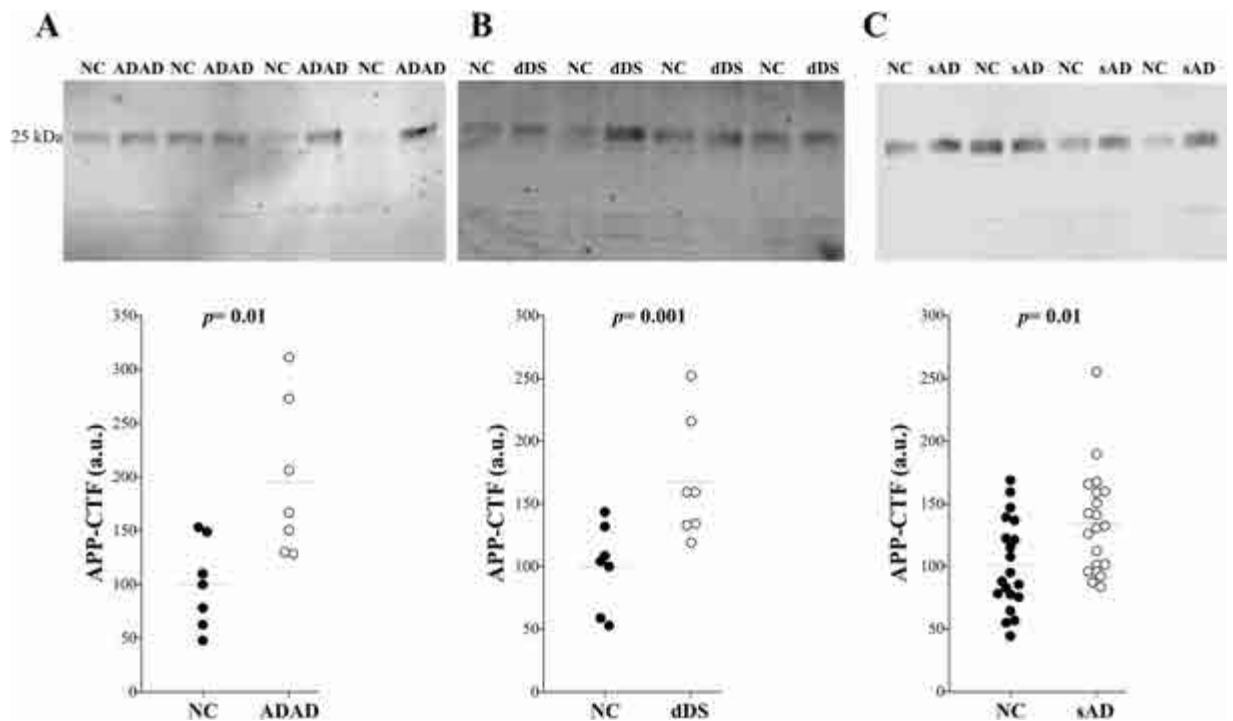


Figure 2. Higher levels of the 25-kDa APP-CTF band in the CSF of AD subjects. (A) Representative blot of the 25-kDa APP-CTF in the CSF samples from 7 symptomatic ADAD and 7 age-matched NC, which were from the same families that ADAD subjects but that did not carry mutations (black symbol; see also Table 1). Densitometric quantification of the immunoreactivity from the 25-kDa band is also shown. (B) Representative blot and densitometric quantification in CSF from 7 DS subjects with dementia of the Alzheimer's type (dDS) and 7 age-matched NC. (C) Representative blot and densitometric quantification of the immunoreactivity from the 25-kDa APP-CTF in CSF samples from 20 sAD and 20 age-matched NC subjects. Immunodetections for (A, B, C) were performed with the A8717 antibody. p values are displayed.

partially in dynamic equilibrium with α - and β -secretase-mediated proteolysis^{9,23,24}. The current canonical views about APP-related cleavage events are likely a partial understanding of the overall process. How secretases compete for the APP substrate and whether subcellular compartmentalization of APP and secretases is responsible of the dynamic equilibrium between secretases is under discussion²⁵. Thus, one may speculate that the particular abundance of the 25-kDa CTF η in CSF is related with compartmentalization of secretases, resulting in prolonged time of residence of these CTF η in comparison with canonical CTF α and CTF β . Anyhow, the other fragments derived of the further processing of CTF η by α - and β -secretases, the A η - α and A η - β fragments, have been also identified in human CSF with levels similar than those for A β ⁹.

Our determination of the 25-kDa APP-CTF levels by Western blotting displayed overlapping values between sAD and controls, whereas superior discrimination was obtained for ADAD and dDS subjects, compared to their respective controls. Interestingly, APP CTF β levels are also elevated in frontal cortex brain homogenates obtained from ADAD patients²⁶. Further studies will indicate if distinct pattern of APP processing in ADAD and sAD affect the generation of different APP-CTFs. Given that this is the first report that address the levels of APP-CTF in CSF, in order to prevent influence of pre-analytical confounding factors, in our study each pathological group was compared with age-matched controls obtained from the same center, with same volume of CSF taken, stored in aliquot of same volume and for similar period of time; and avoiding freeze/thaw cycles. Further studies are required to determine whether limiting pre-analytical confounding factors (discussed in del Campo *et al.*²⁷), have a significant impact on the measured levels of APP-CTF by Western blotting. The possibility that APP-CTF levels varies with age should also be considered and deserve a specific study with a larger number of samples.

In our statistical analysis high levels of the 25-kDa APP-CTF in CSF correlated with increased concentration of T-tau and P-tau, but failed to correlate with A β 42 levels. Increased concentration of T-tau in CSF is believed to reflect neurodegeneration whereas P-tau is supposed to reflect tangle pathology. Otherwise, the overall decrease in A β 42 concentration in the CSF patients is not illustrative of imbalances in the brain APP processing, since in parallel with the increase in the generation of A β 42, there will be an increment in A β aggregation with subsequent deposition. Thus, the positive correlations of the 25-kDa APP-CTF with T-tau and P-tau suggest a correlation with AD pathological process, but it is not possible to interpret links with altered APP processing. Anyhow, the mentioned correlations resulted positive only when all samples were considered, and not in control or sAD groups considered separately. Thus, these correlations obtained by pooling controls and demented subject, could be artefactual, driven by the anchoring effect of the control values. Further analysis with a large number of samples is required.

In order to define the true potential of the 25-kDa APP-CTF as a CSF biomarker, it will be valuable to replicate our present findings using techniques such as ELISA. However, this desirable outcome will be challenging. As advanced above, we have described that the soluble full-length APP, containing the C-terminal domain, also exists in CSF as heteromeric complexes compromising other sAPP species¹⁶, and transmembrane domain, as well intracellular C-terminal domain could participate in APP dimerization (discussed in Isbertet *et al.*²⁸). Indeed, intracellular CTF aggregates have been described with the participation of A β ²⁹ and heparan sulfate degradation products³⁰, suggesting that other APP fragments and other proteolytic sub-products could interact with APP-CTFs. Thus, future studies should develop custom pan-specific antibodies targeting the predicted N-terminal sequence of the APP-CTFs present in CSF, maybe including pretreatment methods designed to disaggregate peptides³¹, for preventing co-precipitation of other APP fragments. Anyhow, even the disadvantages of Western blotting for quantitative analysis, we considered demonstrated that accumulation of APP-CTFs in CSF constitute a potential new biomarker of AD.

In resume, to our knowledge, the possibility that APP-CTFs can be assessed in the CSF has thus far not been considered. In this study, we demonstrate noticeable amounts of APP-CTFs in human CSF. Particularly, a 25-kDa APP-CTF appears increased in genetically determined AD, as well as in sAD. Our present findings provide sufficient evidence to justify further studies on the determination of APP-CTFs as a potential new diagnostic biomarker of AD.

Material and Methods

Patients. Lumbar CSF samples were obtained from autosomal dominant AD (ADAD) subjects that were all carriers of *PSEN1* mutations and who were part of the Genetic Counseling Program for familiar dementia (PICOGEN) at the Hospital Clínic (Barcelona, Spain). This group included 7 subjects carrying *PSEN1* mutations, and 7 age-matched non-mutation carriers from the same families (non-disease controls: NC). We also included lumbar CSF samples from 7 Down syndrome subjects with Alzheimer's type dementia (dDS), along with 7 age-matched NC obtained from the Hospital Sant Pau (Barcelona, Spain). In addition, 20 subjects with sporadic AD (sAD) defined as patients with cognitive symptoms and a CSF biomarker profile indicating AD (high total tau and phosphorylated tau together with low A β ₄₂ levels; see Table 1) and 20 age-matched controls defined as patients with non-specific symptoms without neurochemical evidence of AD were also obtained from the Clinical Neurochemistry Laboratory (Mölndal, Sweden). All AD patients fulfilled the 2011 NIA-AA criteria for dementia³². This study was approved by the ethic committee at the Miguel Hernandez University and it was carried out in accordance with the Declaration of Helsinki. All patients (or their nearest relatives) and controls gave informed consent to participate in the study.

Western blotting and immunoprecipitation. Samples of CSF (30 μ L) were denatured at 98 °C for 5 min and were resolved by electrophoresis on 16.5% Tris-Tricine gels. Following electrophoresis, proteins were blotted onto nitrocellulose membranes (Schleicher & Schuell Bioscience, GmbH, Dassel, Germany). CTFs of APP were detected using the following anti-APP C-terminal antibodies: C1/6.1 (mouse monoclonal; Covance Inc, Princeton, USA), A8717 (rabbit polyclonal; Sigma Aldrich Co, St. Louis, MO), and Y188 (rabbit monoclonal; Abcam, Cambridge, UK), as well as with the rat antibodies 2D8 and 2E9⁹. Multiplex fluorescence with two of the independent antibodies served to assess the specificity of the bands. Blots were then probed with the appropriate conjugated secondary antibodies (IRDye 680RD goat anti-rabbit; IRDye 680RD goat anti-mouse; and IRDye 800CW goat anti-rat from LI-COR Biosciences Lincoln) and imaged on an Odyssey Clx Infrared Imaging System (LI-COR Biosciences). Band intensities were analyzed using LI-COR software (Image Studio Lite). A control CSF sample was used to normalize the immunoreactive signal between blots.

For immunoprecipitation, samples were precleared for 2 h at 4 °C by incubation with protein A-Sepharose (Sigma Aldrich Co). Immunoprecipitations were performed overnight at 4 °C by incubating 150 μ L of CSF with the indicated anti-APP antibody. The antibody was previously coupled to protein A-Sepharose using dimethyl pimelimidate dihydrochloride (Sigma Aldrich Co). A rabbit IgG and a rat IgG (Vector) were used as control antibodies for immunoprecipitations. Precipitated proteins were washed with PBS and eluted with 0.1 M glycine buffer at pH 2.5. After pH neutralization, supernatants were denatured in Laemmli sample buffer at 98 °C for 5 min and subjected to SDS-PAGE. The membranes were then probed with an alternative anti-APP antibody.

Measurement of T-tau, P-tau and A β ₄₂ by ELISA. Total tau (T-tau), phosphorylated tau (P-tau) and A β _{1–42} (A β ₄₂) concentrations in CSF were measured using INNOTEST ELISA methods (Fujirebio Europe, Gent, Belgium).

Statistical analysis. All data were analyzed using SigmaStat (Version 3.5; Systac Software Inc.) by Student's *t* test (two-tailed) for determination of exact *p* values. Correlation was assessed by linear regression. Results are presented as means \pm SEM.

References

- Scheltens, P. *et al.* Alzheimer's disease. *Lancet* **388**, 505–517 (2016).
- Blennow, K., Mattsson, N., Schöll, M., Hansson, O. & Zetterberg, H. Amyloid biomarkers in Alzheimer's disease. *Trends Pharmacol Sci* **36**, 297–309 (2015).
- Olsson, B. *et al.* CSF and blood biomarkers for Alzheimer's disease: a systematic review and meta-analysis. *Lancet Neurol* **15**, 673–684 (2016).
- Haass, C., Kaether, C., Thiakaran, G. & Sisodia, S. Trafficking and proteolytic processing of APP. *Cold Spring Harb Perspect Med* **2**, a006270 (2012).
- Andrew, R. J., Kellett, K. A., Thiakaran, G. & Hooper, N. M. A Greek Tragedy: the Growing Complexity of Alzheimer Amyloid Precursor Protein Proteolysis. *J Biol Chem*. **291**, 19235–19244 (2016).
- Portelius, E. *et al.* A novel pathway for amyloid precursor protein processing. *Neurobiol Aging* **32**, 1090–1098 (2011).

7. Portelius, E. *et al.* Identification of novel N-terminal fragments of amyloid precursor protein in cerebrospinal fluid. *Exp Neurol* **223**, 351–358 (2010).
8. Zhang, Z. *et al.* Delta-secretase cleaves amyloid precursor protein and regulates the pathogenesis in Alzheimer's disease. *Nat Commun* **6**, 8762 (2015).
9. Willem, M. *et al.* η -Secretase processing of APP inhibits neuronal activity in the hippocampus. *Nature* **526**, 443–447 (2015).
10. Palmert, M. R. *et al.* The beta-amyloid protein precursor of Alzheimer disease has soluble derivatives found in human brain and cerebrospinal fluid. *Proc Natl Acad Sci USA* **86**, 6338–6342 (1989).
11. Ghiso, J., Tagliavini, F., Timmers, W. F. & Frangione, B. Alzheimer's disease amyloid precursor protein is present in senile plaques and cerebrospinal fluid: immunohistochemical and biochemical characterization. *Biochem Biophys Res Commun* **163**, 430–437 (1989).
12. Moser, J. J., Chan, E. K. & Fritzlter, M. J. Optimization of immunoprecipitation-western blot analysis in detecting GW182-associated components of GW/P bodies. *Nat Protoc* **4**, 674–685 (2009).
13. Dubois, B. *et al.* Advancing research diagnostic criteria for Alzheimer's disease: the IWG-2 criteria. *Lancet Neurol* **13**, 614–629 (2014).
14. Wang, H. *et al.* Cathepsin L Mediates the Degradation of Novel APP C-Terminal Fragments. *Biochemistry*. **54**, 2806–2816 (2015).
15. Vella, L. J. & Cappai, R. Identification of a novel amyloid precursor protein processing pathway that generates secreted N-terminal fragments. *FASEB J* **26**, 2930–2940 (2012).
16. Cuchillo-Ibañez, I. *et al.* Heteromers of amyloid precursor protein in cerebrospinal fluid. *Mol Neurodegener* **10**, 2 (2015).
17. García-Ayllón, M. S. *et al.* CSF Presenilin-1 complexes are increased in Alzheimer's disease. *Acta Neuropathol Commun* **1**, 46 (2013).
18. Haass, C. *et al.* Amyloid beta-peptide is produced by cultured cells during normal metabolism. *Nature* **359**, 322–325 (1992).
19. Baskin, F., Rosenberg, R. N. & Greenberg, B. D. Increased release of an amyloidogenic C-terminal Alzheimer amyloid precursor protein fragment from stressed PC-12 cells. *J Neurosci Res* **29**, 127–132 (1991).
20. Sharples, R. A. *et al.* Inhibition of gamma-secretase causes increased secretion of amyloid precursor protein C-terminal fragments in association with exosomes. *FASEB J* **22**, 1469–1478 (2008).
21. Vingtxdeux, V. *et al.* Alkalinizing drugs induce accumulation of amyloid precursor protein by-products in luminal vesicles of multivesicular bodies. *J Biol Chem* **282**, 18197–18205 (2007).
22. Chen, J. M., Dando, P. M., Stevens, R. A., Fortunato, M. & Barrett, A. J. Cloning and expression of mouse legumain, a lysosomal endopeptidase. *Biochem J* **335**, 111–117 (1998).
23. Haass, C., Koo, E. H., Mellon, A., Hung, A. Y. & Selkoe, D. J. Targeting of cell-surface beta-amyloid precursor protein to lysosomes: alternative processing into amyloid-bearing fragments. *Nature* **357**, 500–503 (1992).
24. Lauritzen, I. *et al.* Intraneuronal aggregation of the β -CTF fragment of APP (C99) induces A β -independent lysosomal-autophagic pathology. *Acta Neuropathol* **132**, 257–276 (2016).
25. Gandhi, S., Refolo, L. M. & Sambamurti, K. Amyloid precursor protein compartmentalization restricts beta-amyloid production: therapeutic targets based on BACE compartmentalization. *J Mol Neurosci* **24**, 137–143 (2004).
26. Pera, M. *et al.* Distinct patterns of APP processing in the CNS in autosomal-dominant and sporadic Alzheimer disease. *Acta Neuropathol* **125**, 201–213 (2013).
27. del Campo, M. *et al.* Recommendations to standardize preanalytical confounding factors in Alzheimer's and Parkinson's disease cerebrospinal fluid biomarkers: an update. *Biomark Med* **6**, 419–430 (2012).
28. Isbert, S. *et al.* APP dimer formation is initiated in the endoplasmic reticulum and differs between APP isoforms. *Cell Mol Life Sci* **69**, 1353–1375 (2012).
29. Woltjer, R. L. *et al.* Role of glutathione in intracellular amyloid-alpha precursor protein/carboxy-terminal fragment aggregation and associated cytotoxicity. *J Neurochem* **93**, 1047–1056 (2005).
30. Cheng, F. *et al.* Suppression of amyloid beta A11 antibody immunoreactivity by vitamin C: possible role of heparan sulfate oligosaccharides derived from glypican-1 by ascorbate-induced, nitric oxide (NO)-catalyzed degradation. *J Biol Chem* **286**, 27559–27572 (2011).
31. Janssen, L., Sobott, F., De Deyn, P. P. & Van Dam, D. Signal loss due to oligomerization in ELISA analysis of amyloid-beta can be recovered by a novel sample pre-treatment method. *MethodsX* **2**, 112–123 (2015).
32. McKhann, G. M. *et al.* The diagnosis of dementia due to Alzheimer's disease: recommendations from the National Institute on Aging-Alzheimer's Association workgroups on diagnostic guidelines for Alzheimer's disease. *Alzheimers Dement* **7**, 263–269 (2011).

Acknowledgements

We thank Drs C. Haass and M. Willem (Biomedical Center, Ludwig-Maximilians-University Munich, Munich, Germany) for the generous gift of the 2D8 and 2E9 antibodies. This study was funded in part by the EU BIOMARKAPD-Joint Programming on Neurodegenerative Diseases (JPND) project, by the Instituto de Salud Carlos III (ISCIII grants PI11/03026 and PI15/00665 to JSV, PI11/02425 and PI14/01126 to JF, PI11/03035 and PI14/1561 to AL, PI08/0036 and PI12/00013 to RSV, and PI11/03023 to JLM), co-financed by the Fondo Europeo de Desarrollo Regional, under the aegis of JPND, and through CIBERNED, ISCIII. This work was also supported by the Fundació Catalana de Síndrome de Down, by a “Marató TV3” grant (20141210) and a grant from the Griffols Foundation, Spain (to JF); and the Torsten Söderberg Foundation, Sweden (to KB). JSV also acknowledges financial support from the Spanish Ministerio de Economía y Competitividad, through the “Severo Ochoa” Programme for Centres of Excellence in R&D (SEV- 2013-0317).

Author Contributions

J.S.V., M.S.G.A., A.L., K.B., H.Z. and J.L.M. were involved with the conception, design, and interpretation of data. M.S.G.A., I.L.F. and C.P.B. performed the experiments. J.S.V., I.L.F. and M.S.G.A. were involved with data analysis. K.B., H.Z., J.L.M., A.L., R.S.V. and J.F. collected the clinical material. J.S.V., J.L.M., A.L., R.S.V., K.B. and J.F. provided general overall supervision of the study, and acquired funding. All authors contributed to the drafting and critical revision of the manuscript and have given final approval of the version to be published.

Additional Information

Supplementary information accompanies this paper at doi:10.1038/s41598-017-02841-7

Competing Interests: The authors declare no competing interests.

Publisher's note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2017