Available online at www.sciencedirect.com
ScienceDirect
Biochemical and Biophysical Research Communications 361 (2007) 43–48
BBRC
www.elsevier.com/locate/ybbrc

BACE1 modulates filopodia-like protrusions induced by sodium channel β4 subunit

Haruko Miyazaki [a,b], Fumitaka Oyama [a], Hon-Kit Wong [a], Kumi Kaneko [a], Takashi Sakurai [a], Akira Tamaoka [b], Nobuyuki Nukina [a,*]

[a] *Laboratory for Structural Neuropathology, RIKEN Brain Science Institute, 2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan*
[b] *Department of Neurology, Institute of Clinical Medicine, University of Tsukuba, Tennoudai 1-1-1, Tsukuba, Ibaraki 305-8575, Japan*

Received 21 June 2007
Available online 17 July 2007

Abstract

Processing of APP by BACE1 plays a crucial role in the pathogenesis of Alzheimer disease (AD). Recently, the voltage-gated sodium channel (Na_v) β4 subunit (β4), an auxiliary subunit of Na_v that is supposed to serve as a cell adhesion molecule, has been identified as a substrate for BACE1. However, the biological consequence of BACE1 processing of β4 remains illusive. Here, we report the biological effects of β4 processing by BACE1. Overexpression of β4 in Neuro2a cells promoted neurite extension and increased the number of F-actin rich filopodia-like protrusions. While coexpression of BACE1 together with β4 further accelerated neurite extension, the number of filopodia-like protrusions was reduced. Overexpression of C-terminal fragment of β4 that was generated by BACE1 (β4-CTF) partially recapitulated the results obtained with BACE1 overexpression. These results suggest that the processing of β4 by BACE1 regulates neurite length and filopodia-like protrusion density in neurons.

Keywords: BACE1; Filopodia-like protrusion; Neurite outgrowth; Sodium channel β4 subunit

The voltage-gated sodium channels (Na_v) consist of a complex of pore-forming α subunits and one or two β subunits [1]. There are five identified β subunits: β1, β1A, β2, β3, and β4. β subunits are auxiliary components of the voltage-gated sodium channel and have been known to modulate sodium channel activity [1–3] and cell surface expression of α subunits [4–6].

β4 is structurally related to β2 and binds to the α subunit by disulfide bond [3]. Coexpression of β4 with brain Na_v 1.2a or skeletal muscle Na_v 1.4 subunits in the human embryonic cell line tsA-201 resulted in negative shift in the voltage dependence of channel activity [3]. β4 has also been shown to be the endogenous open-channel blocker responsible for resurgent kinetics [7]. Furthermore, β4 expression is downregulated in Huntington disease (HD) transgenic mice [8].

Based on structural and amino acid homologies, β subunits belong to the immunoglobulin superfamily of cell adhesion molecules (IgCAMs) [9,10]. In the nervous system, IgCAMs play important roles in cell–cell interactions, such as axon guidance and migration [11]. Recent reports strongly suggest that β subunits play a functional role in neurite outgrowth as IgCAMs. β1 and β2 exhibit strong homophilic cell adhesion leading to ankyrin recruitment at sites of cell–cell contact [12]. β1 promotes neurite extension in cerebellar granule neurons [13]. Recently, we have reported that overexpression of β4 induces neurite extension and increases spine density in cultured cells, indicating that β4 modulates neurite outgrowth activity [8].

β-Site APP cleaving enzyme (BACE1) is a membrane-bound aspartyl protease that cleaves amyloid precursor

* Corresponding author. Fax: +81 48 462 4796.
E-mail address: nukina@brain.riken.jp (N. Nukina).

0006-291X/$ - see front matter © 2007 Elsevier Inc. All rights reserved.
doi:10.1016/j.bbrc.2007.06.170

protein (APP). Sequential processing of APP by BACE1 and γ-secretase leads to the release of amyloid-β peptide (Aβ) which accumulates in senile plaques in Alzheimer disease (AD) [14]. Although the role of BACE1 as APP processing enzymes is well established, the physiological consequence of other processing is not clear.

Recently, we and others have reported that voltage-gated sodium channel β subunits are new substrates for BACE1 and γ-secretase [15,16] but the physiological function of this sequential processing has not been determined. We report in this paper that BACE1 modulates β4-induced neurite morphology in neuroblastoma (Neuro2a) cells.

Materials and methods

Plasmids. Mouse sodium channel β4 subunit was subcloned as described previously [8]. C-terminal fragment of β4 (β4-CTF) (nucleotides 358–687 of full length β4 cDNA, GenBank™ Accession No. BK001031) was amplified by PCR using the oligonucleotide primers anchored with BamHI (5′-end) and NotI (3′-end) restriction sites. The forward primer was 5′-gactacggatccgacctggagttcagtgacac-3′ and the reverse primer was 5′-aaagacgcggccgctcacacttttgtgggtggct-3′. PCR was carried out for 35 cycles with each cycle consisting of 30 s at 94 °C, 30 s at 50 °C and 30 s at 68 °C using KOD plus (Toyobo, Osaka, Japan). The PCR products were then digested with BamHI and NotI and subcloned into the expression vector pSecTag2/HygroB (Invitrogen, Carlsbad, California). Human BACE1 cDNA (nucleotides 408–2034; GenBank™ Accession No. NM_012104) was amplified by PCR using the oligonucleotide primers anchored with BamHI (5′-end) and XhoI (3′-end) restriction sites. The forward primer was 5′-gactacggatccagggacggacgtgggccagt-3′ and the reverse primer was 5′-aaagacctcgagcttgtgaccaaagtgaacca-3′. PCR was carried out for 35 cycles with each cycle consisting of 30 s at 94 °C, 30 s at 50 °C and 2 min at 68 °C using KOD plus. The PCR products were then digested with BamHI and XhoI and subcloned into the expression vector pcDNA3 (Invitrogen). The sequences of all the constructs were verified by sequencing.

Antibodies. The antibodies used were as follows: rabbit polyclonal anti-β4 [8]; mouse monoclonal anti-GFP (Roche Diagnostics, Basel, Switzerland); rat monoclonal anti-tubulin (Chemicon, Temecula, CA); goat anti-mouse IgG (H+L)-Alexa Fluor 488 and goat anti-rabbit IgG (H+L)-Alexa Fluor 647 (Invitrogen) were utilized as secondary antibodies in indirect immunofluorescence.

Cell culture, transient transfection, and treatments. Mouse neuroblastoma (Neuro2a) cells were maintained as described previously [8]. Neuro2a cells were transfected using Lipofectamine 2000 (Invitrogen) according to the manufacturer's instruction. After transfection, cells were differentiated with 5 mM dbcAMP [*N*6,2′-*O*-dibutyryladenosine-3′:5′-cyclic monophosphate sodium salt (Nacalai Tesque, Kyoto, Japan)].

F-actin staining, immunocytochemistry, image analysis, and quantification. Cells were fixed and permeabilized as described previously [8]. Cells were incubated 1 h at room temperature with Alexa Fluor 546 Phalloidin (Invitrogen) which labeled filamentous actin (F-actin). Immunocytochemistry was carried out as described previously [8]. To identify the neurites and filopodia-like protrusions, Neuro2a cells were transfected with Venus and immunostained by anti-GFP. Image analysis was performed as previously described with slight modification [17–19]. Protrusions, longer than the soma diameter, were classified as neurite. About 150 cells from 10 random fields were selected and longest neurite was measured with the MacSCOPE program (Mitani, Tokyo, Japan). The number of filopodia-like protrusions was counted on any neurite for 30 μm from at least 20 randomly selected cells.

Statistics. Data were expressed as means ± standard error of the mean (SEM). Neurite length and the number of filopodia-like protrusions were compared by Student's *t*-test or ANOVA followed by Fisher's Protected Least Significant Difference (PLSD).

Results

Overexpression of β4 extends length of neurites and increases the number of filopodia-like protrusions

We previously reported that overexpression of β4-induced neurite extension and increased number of branch point [8]. To investigate other morphological changes in β4 expressing cells, Neuro2a cells were transiently transfected with β4 or mock and differentiated by 5 mM dbcAMP. To visualize neurites, cells were cotransfected with Venus, a variant of yellow fluorescent protein (YFP) [20]. Neuro2a cells were immunostained with anti-β4 antibodies 24 h after transfection. Because Venus signal is not enough to visualize small structures in neurite, Neuro2a cells were also stained by anti-GFP. Quantification of GFP-positive neurites by McSCOPE software showed that neurites were significantly longer in cells expressing β4, (63.9 ± 3.3 μm) compared with mock cells (42.1 ± 1.2 μm) (Fig. 1A–D and I) confirming our previous observation using ArrayScan™ [8]. In addition to the extension of neurites, overexpression of β4 also led to the increased number of small and thin protrusions (2.8 ± 0.2 per 10 μm of neurite) compared with mock cells (1.8 ± 0.2 per 10 μm) (Fig. 1E–H and J). The features of β4-induced protrusions are similar to the thin, small, and headless dendritic filopodia that have been previously reported [21].

Dendritic filopodia are highly motile structures that may play important roles in early synaptogenesis, especially in the process of axon-dendrite contact, and they are believed to be a precursor of the spine [21]. During spine morphogenesis, F-actin is observed in dendritic filopodia and it forms cluster when filopodia-to-spines transition occurred [22]. Thus, it is widely accepted that actin cytoskeleton dynamics is involved in spine formation [21,22]. In addition to actin assembly, microtubules transport has also been reported to be one of the underlying molecular mechanisms of neurite formation [23,24]. To examine whether β4-induced neurites and protrusions contain F-actin or microtubules, Neuro2a cells were transfected with β4 and stained by phalloidin (a high-affinity probe for F-actin) and anti-tubulin antibody. Immunocytochemical analysis showed that β4-induced neurites were stained by anti-tubulin (Fig. 2A). In contrast, β4-induced protrusions were stained by phalloidin (Fig. 2B). These results indicate that β4-induced protrusions contain F-actin and are similar to dendritic filopodia. Thus, we called β4-induced protrusions "filopodia-like protrusions" in this paper.

Overexpression of BACE1 accelerates neurite extension and reduces the number of filopodia-like protrusions induced by β4

We have previously shown that β4 is a novel substrate of BACE1 but the physiological role of the cleavage is unknown [15]. BACE1 generates an N-terminal fragment (β4-NTF) and a C-terminal fragment (β4-CTF) as shown

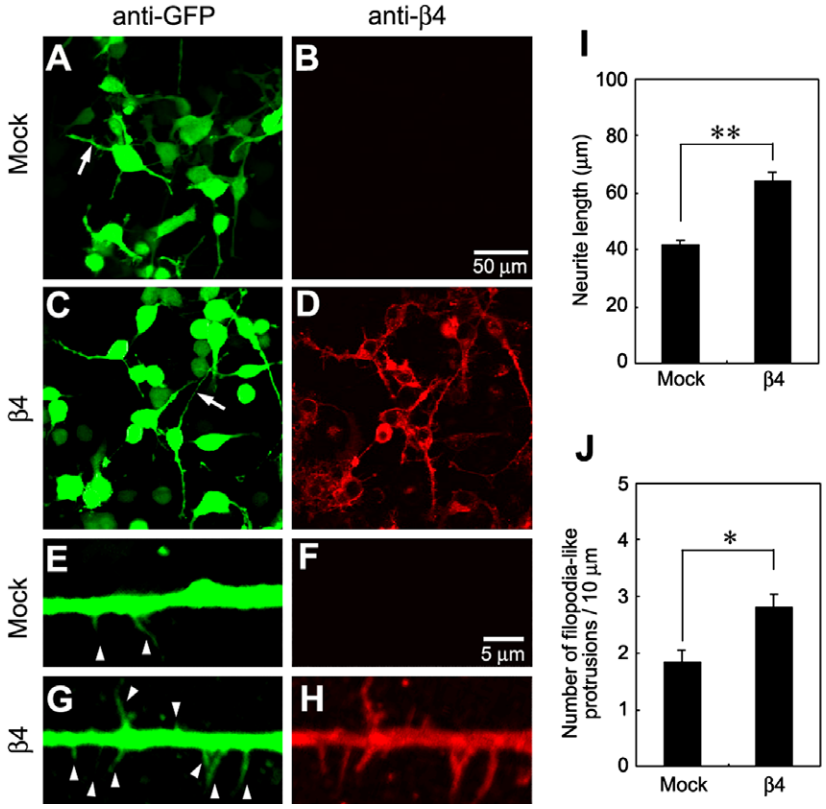

Fig. 1. Overexpression of β4 induces neurite extension and increases formation of filopodia-like protrusions in Neuro2a cells. (A–D) Low magnification images of mock (A,B) and β4 (C,D) overexpressing Neuro2a cells immunostained by anti-GFP (green) and anti-β4 (red). Arrows indicate neurite (A,C). Scale bar, 50 μm. (E–H) High magnification images of mock (E,F) and β4 (G,H) overexpressing Neuro2a cells. Arrowheads indicate protrusions (E,G). Scale bar, 5 μm. (I) Quantification of the neurite length. β4-Positive cells extended neurite length compared with mock cells. Mock: $n = 145$; β4: $n = 123$ ($^{**}p < 0.0001$, Student's t-test). (J) Quantification of the number of filopodia-like protrusions. β4 expressing cells significantly increased the number of filopodia-like protrusions. Mock: $n = 20$; β4: $n = 20$ ($^{*}p < 0.005$, Student's t-test). Error bars indicate SEM.

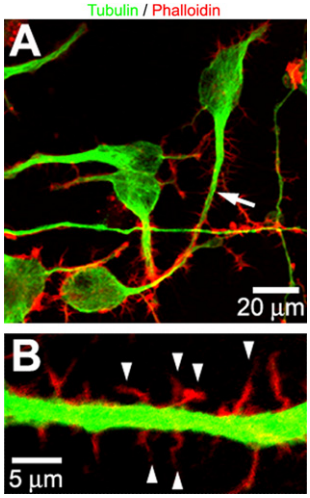

Fig. 2. β4-Induced neurite contains microtubules and protrusions are rich in F-actin. (A) Low magnification image (B) and high magnification image of β4 overexpressing Neuro2a cells were stained by anti-tubulin (green) and phalloidin (red). Neurites were mainly immunostained by anti-tubulin (arrow) (A). Scale bar, 20 μm. β4-Induced protrusions were stained by phalloidin (arrowheads) (B). Scale bar, 5 μm.

in Fig. 3A. And indeed, 15-kDa C-terminal fragment of β2 of Na_v (β2-CTF) inhibits β2-mediated cell migration [16]. As β4 is structurally similar to β2 [3] and can also be cleaved by BACE1, we wondered whether BACE1 cleavage of β4 would modulate neurite extension and filopodia-like protrusions.

To make this examination possible, Neuro2a cells were cotransfected with β4 and BACE1. β4 and mock cotransfected cells were used as control. Quantification of GFP-positive neurites revealed that overexpression of BACE1 accelerated neurite extension induced by β4 (70.9 ± 2.5 μm) compared with control (60.5 ± 3.0 μm) (Fig. 3B, C, and H). In contrast, no difference was observed in the neurite length between protease-inactive BACE1 (D93G) [25] expressing cells (60.4 ± 2.5 μm) and control (Fig. 3C, D, and H). On the other hand, overexpression of BACE1 markedly decreased the number of filopodia-like protrusions induced by β4 (0.9 ± 0.2 per 10 μm) when compared with control (3.0 ± 0.2 per 10 μm) (Fig. 3E, F, and I) and inactive BACE1 (D93 G) did not affect the number of filopodia-like protrusions (2.7 ± 0.2 per 10 μm) (Fig. 3F, G, and I). BACE1 transfection without β4 had no effect on neurite length and

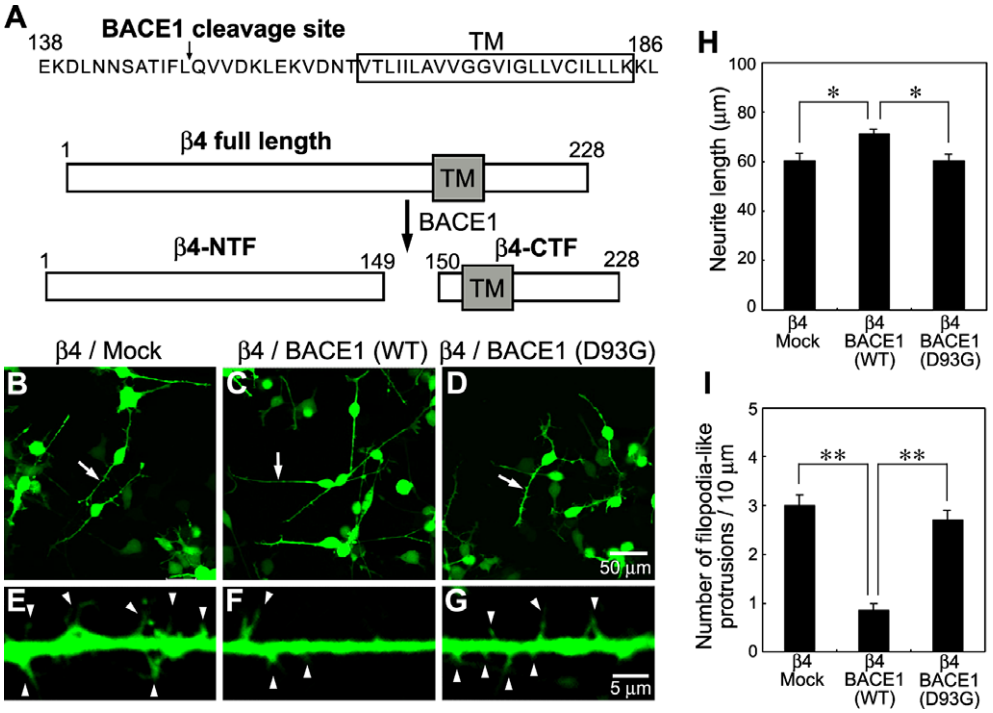

Fig. 3. Overexpression of BACE1 reduces the number of filopodia-like protrusions. (A) Proteolytic processing of β4 by BACE1. BACE1 cleavage generates β4-NTF and β4-CTF. NTF, N-terminal fragment; CTF, C-terminal fragment. The number indicates amino acid residue of full length β4. (B–D) Low magnification images of Neuro2a cells transfected with β4 together with mock (B), BACE1 (WT) (C) or protease-inactive BACE1 (D93G) (D). Neuro2a cells were immunostained by anti-GFP. Arrows indicate neurite (B–D). Scale bar, 50 μm. (E–G) High magnification images of Neuro2a cells transfected with β4 together with mock (E), BACE1 (WT) (F) or BACE1 (D93G) (G). β4 and mock transfected cells were used as control. Arrowheads indicate filopodia-like protrusions (E–G). Scale bar, 5 μm. (H) Quantification of the neurite length. Overexpression of BACE1 (WT) accelerated neurite extension in β4 expressing Neuro2a cells. In contrast, overexpression of BACE1 (D93G) did not accelerate neurite extension. β4/Mock: $n = 122$; β4/BACE1 (WT): $n = 125$; β4/BACE1 (D93G): $n = 118$ ($^{*}p < 0.003$, ANOVA followed by Fisher's PLSD). (I) Quantification of the number of filopodia-like protrusions. BACE1 (WT) markedly decreased the number of filopodia-like protrusions when compared with control. In contrast, there are no differences between BACE1 (D93G) expressing cells and control cells. β4/Mock: $n = 20$; β4/BACE1 (WT): $n = 20$; β4/BACE1 (D93G): $n = 20$ ($^{**}p < 0.0001$, ANOVA followed by Fisher's PLSD). Error bars indicate SEM.

the number of filopodia-like protrusions (data not shown). These results indicate that BACE1 regulates neurite extension and the number of filopodia-like protrusions induced by β4.

To further examine whether β4-NTF or β4-CTF was responsible for the modulation of neurite length and protrusions density, we transiently expressed β4-CTF in Neuro2a cells. β4-CTF localized in membrane and their distribution (Fig. 4C) was similar to that of β4 (Fig. 4B). Quantification of GFP-positive neurites showed that overexpression of β4-CTF promoted neurite extension (60.3 ± 3.0 μm) that was comparable to that of β4 (57.0 ± 3.0 μm) when compared with mock (36.8 ± 1.4 μm) (Fig. 4D, E, and H). These data indicate that it is likely that β4-CTF promotes neurite extension. In contrast, overexpression of β4-CTF did not increase the number of filopodia-like protrusions (1.6 ± 0.2 per 10 μm) that was comparable to that of mock (1.4 ± 0.2 per 10 μm) when compared with β4 (2.8 ± 0.2 per 10 μm) (Fig. 4F, G, and I), indicating that β4-CTF significantly attenuates the formation of filopodia-like protrusions. These results corresponded with the results of overexpression of β4 and BACE1. Taken together, our data suggest that the cleavage of β4 by BACE1 modulates the number of filopodia-like protrusions induced by β4.

Discussion

In this study, we report the biological role of BACE1 cleavage of β4. First, overexpression of β4 promoted neurite extension and increased the number of F-actin rich protrusions which were small, thin, and similar to dendritic filopodia in Neuro2a cells (Figs. 1 and 2). Second, overexpression of BACE1 caused further neurite extension and significantly decreased the density of filopodia-like protrusions induced by β4 (Fig. 3). Finally, overexpression of β4-CTF extended neurite but not induce increasing the number of filopodia-like protrusions (Fig. 4). These results suggest that BACE1 regulates neurite morphology induced by β4 in Neuro2a cells.

Overexpression of β4 caused neurite extension and increased the number of filopodia-like protrusions, suggesting that β4 can function as a cell adhesion molecule and may be involved in neurite morphological changes. Feature and structure of β4-induced protrusions were similar to dendritic filopodia, which are small, thin and F-actin rich

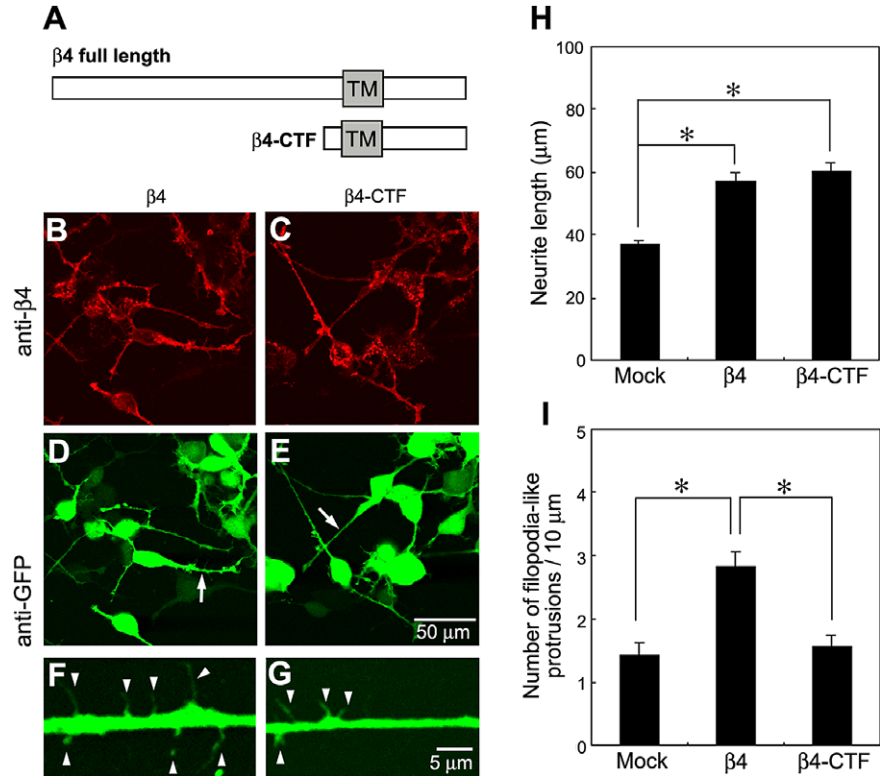

Fig. 4. Overexpression of β4-CTF extends neurite but not increase the number of filopodia-like protrusions. (A) A schematic diagram of construction of β4-CTF cloned into pSecTag2B. CTF, C-terminal fragment. (B,C) Subcellular localization of β4 (B) and β4-CTF (C) expressed in Neuro2a cells immunolabeled by anti-β4. (D,E) Low magnification images of β4 (D) and β4-CTF (E) overexpressing Neuro2a cells immunostained by anti-GFP. Arrows indicate neurite. Scale bar, 50 μm. (F, G) High magnification images of β4 (F) and β4-CTF (G) overexpressing Neuro2a cells. Arrowheads indicate filopodia-like protrusions. Scale bar, 5 μm. (H) Quantification of the neurite length. Overexpression of β4-CTF induced neurite extension almost same length as β4 expressing cells. Mock: $n = 109$; β4: $n = 120$; β4-CTF: $n = 120$ ($^*p < 0.0001$, ANOVA followed by Fisher's PLSD). (I) Quantification of the number of filopodia-like protrusions. The number of filopodia-like protrusions did not increase in β4-CTF expressing cells compared with β4 expressing cells. Mock: $n = 20$; β4: $n = 20$; β4-CTF: $n = 20$ ($^*p < 0.0001$, ANOVA followed by Fisher's PLSD). Error bars indicate SEM.

protrusions [21,22]. It has been proposed that filopodia play important roles in synaptogenesis [21]. Recently, we reported that overexpression of β4 increased spine density in hippocampal primary neuron [8]. Our results suggest that β4 may be involved in spine morphogenesis.

We found that BACE1 markedly decreased the number of filopodia-like protrusions induced by β4. We also found that β4-CTF did not increase the number of filopodia-like protrusions. The results suggest that extracellular domain of β4 may play important roles in the formation of filopodia-like protrusions. Voltage-gated sodium channel β subunits interact with other cell adhesion molecules and extracellular matrix through their extracellular region. For example, β1 interacts with neurofascin, *N*-cadherin, connexin and contactin [5,6,26]. Both β1 and β2 interact with tenascin-C and tenascin-R [27,28]. β4-NTF may interact with cell adhesion molecules or extracellular matrix and these interactions may be important for the formation of filopodia-like protrusions.

BACE1 are preferentially associated with lipid rafts and BACE1 cleavage occurs predominantly in lipid raft [29,30]. Recently, we reported that β4 is also associated with lipid raft [15]. These results indicate that lipid raft may play important roles in β4 processing by BACE1. Not only β4 but also other β subunits are cleaved by BACE1 [15]. It is possible that physiological functions of β1, β2, and β3 subunits are also regulated by BACE1 in lipid raft.

Overexpression of β4 in mouse hippocampal primary neurons increased the number of spines [8] and β4-induced F-actin rich protrusions in Neuro2a cells are similar to dendritic filopodia. These results suggest that β4 may be related to spine morphogenesis and maintenance. Synapse and dendritic spine loss are common pathological features in neurodegenerative disease [31]. During the course of AD and aging, increases of BACE1 protein and its activity levels have been reported [32,33]. These reports suggest that aberrant β4 and processing of other substrates by BACE1 may lead to neuritic degeneration. Our findings may provide new insight into both understanding the function of BACE1 and pathogenic mechanism of neurodegenerative disorders.

Acknowledgments

We thank Dr. A. Miyawaki (RIKEN Brain Science Institute) for providing Venus cDNA, M. Kumai (Research Resource Center, RIKEN Brain Science Institute) for antibody preparation. This work was supported in part

by Grants-in-Aid for Scientific Research 18500284, Grants-in-Aid for Scientific Research on Priority Areas 17025044 from the Ministry of Education, Culture, Sports, Science, and Technology, Japan and Grants-in-Aid from the Ministry of Health, Labor, and Welfare. HM was supported by the Junior Research Associate Program in RIKEN.

References

[1] W.A. Catterall, From ionic currents to molecular mechanisms: the structure and function of voltage-gated sodium channels, Neuron 26 (2000) 13–25.
[2] K. Morgan, E.B. Stevens, B. Shah, P.J. Cox, A.K. Dixon, K. Lee, R.D. Pinnock, J. Hughes, P.J. Richardson, K. Mizuguchi, A.P. Jackson, beta 3: an additional auxiliary subunit of the voltage-sensitive sodium channel that modulates channel gating with distinct kinetics, Proc. Natl. Acad. Sci. USA 97 (2000) 2308–2313.
[3] F.H. Yu, R.E. Westenbroek, I. Silos-Santiago, K.A. McCormick, D. Lawson, P. Ge, H. Ferriera, J. Lilly, P.S. DiStefano, W.A. Catterall, T. Scheuer, R. Curtis, Sodium channel beta4, a new disulfide-linked auxiliary subunit with similarity to beta2, J. Neurosci. 23 (2003) 7577–7585.
[4] C. Chen, V. Bharucha, Y. Chen, R.E. Westenbroek, A. Brown, J.D. Malhotra, D. Jones, C. Avery, P.J. Gillespie 3rd, K.A. Kazen-Gillespie, K. Kazarinova-Noyes, P. Shrager, T.L. Saunders, R.L. Macdonald, B.R. Ransom, T. Scheuer, W.A. Catterall, L.L. Isom, Reduced sodium channel density, altered voltage dependence of inactivation, and increased susceptibility to seizures in mice lacking sodium channel beta 2-subunits, Proc. Natl. Acad. Sci. USA 99 (2002) 17072–17077.
[5] D.P. McEwen, L.S. Meadows, C. Chen, V. Thyagarajan, L.L. Isom, Sodium channel beta1 subunit-mediated modulation of Nav1.2 currents and cell surface density is dependent on interactions with contactin and ankyrin, J. Biol. Chem. 279 (2004) 16044–16049.
[6] C.F. Ratcliffe, R.E. Westenbroek, R. Curtis, W.A. Catterall, Sodium channel beta1 and beta3 subunits associate with neurofascin through their extracellular immunoglobulin-like domain, J. Cell Biol. 154 (2001) 427–434.
[7] T.M. Grieco, J.D. Malhotra, C. Chen, L.L. Isom, I.M. Raman, Open-channel block by the cytoplasmic tail of sodium channel beta4 as a mechanism for resurgent sodium current, Neuron 45 (2005) 233–244.
[8] F. Oyama, H. Miyazaki, N. Sakamoto, C. Becquet, Y. Machida, K. Kaneko, C. Uchikawa, T. Suzuki, M. Kurosawa, T. Ikeda, A. Tamaoka, T. Sakurai, N. Nukina, Sodium channel beta4 subunit: down-regulation and possible involvement in neuritic degeneration in Huntington's disease transgenic mice, J. Neurochem. 98 (2006) 518–529.
[9] D.E. Vaughn, P.J. Bjorkman, The (Greek) key to structures of neural adhesion molecules, Neuron 16 (1996) 261–273.
[10] L.K. Kaczmarek, Non-conducting functions of voltage-gated ion channels, Nat. Rev. Neurosci. 7 (2006) 761–771.
[11] P.F. Maness, M. Schachner, Neural recognition molecules of the immunoglobulin superfamily: signaling transducers of axon guidance and neuronal migration, Nat. Neurosci. 10 (2007) 19–26.
[12] J.D. Malhotra, K. Kazen-Gillespie, M. Hortsch, L.L. Isom, Sodium channel beta subunits mediate homophilic cell adhesion and recruit ankyrin to points of cell–cell contact, J. Biol. Chem. 275 (2000) 11383–11388.
[13] T.H. Davis, C. Chen, L.L. Isom, Sodium channel beta1 subunits promote neurite outgrowth in cerebellar granule neurons, J. Biol. Chem. 279 (2004) 51424–51432.
[14] W. Annaert, B. De Strooper, A cell biological perspective on Alzheimer's disease, Annu. Rev. Cell Dev. Biol. 18 (2002) 25–51.
[15] H.K. Wong, T. Sakurai, F. Oyama, K. Kaneko, K. Wada, H. Miyazaki, M. Kurosawa, B. De Strooper, P. Saftig, N. Nukina, beta Subunits of voltage-gated sodium channels are novel substrates of beta-site amyloid precursor protein-cleaving enzyme (BACE1) and gamma-secretase, J. Biol. Chem. 280 (2005) 23009–23017.
[16] D.Y. Kim, L.A. Ingano, B.W. Carey, W.H. Pettingell, D.M. Kovacs, Presenilin/gamma-secretase-mediated cleavage of the voltage-gated sodium channel beta2-subunit regulates cell adhesion and migration, J. Biol. Chem. 280 (2005) 23251–23261.
[17] R.J. Crowder, H. Enomoto, M. Yang, E.M. Johnson Jr., J. Milbrandt, Dok-6, a Novel p62 Dok family member, promotes Ret-mediated neurite outgrowth, J. Biol. Chem. 279 (2004) 42072–42081.
[18] M. Domeniconi, N. Zampieri, T. Spencer, M. Hilaire, W. Mellado, M.V. Chao, M.T. Filbin, MAG induces regulated intramembrane proteolysis of the p75 neurotrophin receptor to inhibit neurite outgrowth, Neuron 46 (2005) 849–855.
[19] B. Kolb, G. Gorny, Y. Li, A.N. Samaha, T.E. Robinson, Amphetamine or cocaine limits the ability of later experience to promote structural plasticity in the neocortex and nucleus accumbens, Proc. Natl. Acad. Sci. USA 100 (2003) 10523–10528.
[20] T. Nagai, K. Ibata, E.S. Park, M. Kubota, K. Mikoshiba, A. Miyawaki, A variant of yellow fluorescent protein with fast and efficient maturation for cell-biological applications, Nat. Biotechnol. 20 (2002) 87–90.
[21] R. Yuste, T. Bonhoeffer, Genesis of dendritic spines: insights from ultrastructural and imaging studies, Nat. Rev. Neurosci. 5 (2004) 24–34.
[22] H. Takahashi, Y. Sekino, S. Tanaka, T. Mizui, S. Kishi, T. Shirao, Drebrin-dependent actin clustering in dendritic filopodia governs synaptic targeting of postsynaptic density-95 and dendritic spine morphogenesis, J. Neurosci. 23 (2003) 6586–6595.
[23] A.H. Futerman, G.A. Banker, The economics of neurite outgrowth—the addition of new membrane to growing axons, Trends Neurosci. 19 (1996) 144–149.
[24] M. Shirane, K.I. Nakayama, Protrudin induces neurite formation by directional membrane trafficking, Science 314 (2006) 818–821.
[25] W. He, Y. Lu, I. Qahwash, X.Y. Hu, A. Chang, R. Yan, Reticulon family members modulate BACE1 activity and amyloid-beta peptide generation, Nat. Med. 10 (2004) 959–965.
[26] J.D. Malhotra, V. Thyagarajan, C. Chen, L.L. Isom, Tyrosine-phosphorylated and nonphosphorylated sodium channel beta1 subunits are differentially localized in cardiac myocytes, J. Biol. Chem. 279 (2004) 40748–40754.
[27] J. Srinivasan, M. Schachner, W.A. Catterall, Interaction of voltage-gated sodium channels with the extracellular matrix molecules tenascin-C and tenascin-R, Proc. Natl. Acad. Sci. USA 95 (1998) 15753–15757.
[28] Z.C. Xiao, D.S. Ragsdale, J.D. Malhotra, L.N. Mattei, P.E. Braun, M. Schachner, L.L. Isom, Tenascin-R is a functional modulator of sodium channel beta subunits, J. Biol. Chem. 274 (1999) 26511–26517.
[29] J.M. Cordy, I. Hussain, C. Dingwall, N.M. Hooper, A.J. Turner, Exclusively targeting beta-secretase to lipid rafts by GPI-anchor addition up-regulates beta-site processing of the amyloid precursor protein, Proc. Natl. Acad. Sci. USA 100 (2003) 11735–11740.
[30] D.R. Riddell, G. Christie, I. Hussain, C. Dingwall, Compartmentalization of beta-secretase (Asp2) into low-buoyant density, noncaveolar lipid rafts, Curr. Biol. 11 (2001) 1288–1293.
[31] J.C. Fiala, J. Spacek, K.M. Harris, Dendritic spine pathology: cause or consequence of neurological disorders? Brain Res. Brain Res. Rev. 39 (2002) 29–54.
[32] H. Fukumoto, B.S. Cheung, B.T. Hyman, M.C. Irizarry, Beta-secretase protein and activity are increased in the neocortex in Alzheimer disease, Arch. Neurol. 59 (2002) 1381–1389.
[33] R.M. Holsinger, C.A. McLean, K. Beyreuther, C.L. Masters, G. Evin, Increased expression of the amyloid precursor beta-secretase in Alzheimer's disease, Ann. Neurol. 51 (2002) 783–786.