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1 *Award Review*

2 *Running Title: Conformation-specific Antibodies of A β*

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4 **Conformation-specific Antibodies to Target Amyloid β Oligomers and Their**
5 **Application to Immunotherapy for Alzheimer's Disease**

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Abstract (123<150 words)

Amyloid β -protein ($A\beta$) oligomers, intermediates of $A\beta$ aggregation, cause cognitive impairment and synaptotoxicity in the pathogenesis of Alzheimer's disease (AD). Immunotherapy using anti- $A\beta$ antibody is one of the most promising approaches for AD treatment. However, most clinical trials using conventional sequence-specific antibodies have proceeded with difficulty. This is probably due to the unintended removal of the non-pathological monomer and fibrils of $A\beta$ as well as the pathological oligomers by these antibodies that recognize $A\beta$ sequence, which is not involved in synaptotoxicity. Several efforts have been made recently to develop conformation-specific antibodies that target the tertiary structure of $A\beta$ oligomers. Here we review the recent findings of $A\beta$ oligomers and anti- $A\beta$ antibodies including our own, and discuss their potential as therapeutic and diagnostic tools.

Key words:

amyloid β ; Alzheimer's disease; oligomer; antibody; conformation

Introduction

Accumulation of aggregated proteins is characteristic of many neurodegenerative diseases including Alzheimer's disease (AD), Parkinson's disease, and Huntington's disease. AD is generally characterized by the aggregation of extracellular amyloid β -protein ($A\beta$) in senile plaques. $A\beta$ mainly consists of 40- and 42-mer amyloid β peptides ($A\beta_{40}$, $A\beta_{42}$), which are predominantly secreted from $A\beta$ protein precursor (APP) by two proteases (β - and γ -secretases).^{1,2)} β -Secretase is identified as an aspartyl protease of the pepsin family, called β -site APP-cleaving enzyme (BACE-1).³⁾ It is noted in amyloid theory that $A\beta$ aggregates through β -sheet formation and shows neurotoxicity. On the other hand, neurofibrillary tangles (NFTs) are another feature of AD pathology and are composed of intracellular deposits of tau protein.^{4,5)} Abnormal aggregation of tau is related to its hyperphosphorylation. Recent clinical reports by the Alzheimer's Disease Neuroimaging Initiative (ADNI) support the amyloid theory; the accumulation of $A\beta$ occurs earliest during the process of AD as a molecular trigger, followed by neuronal injury, deposition of phosphorylated tau, and a shrunken hippocampus, respectively.⁶⁾ The pre-symptomatic and mild cognitive impairment (MCI) stages, prior to AD onset, are dependent on progression based on these biomarkers (Fig. 1).

The cleavage of APP by BACE-1 generates a secreted APP β (sAPP β) and a membrane-bound C-terminal fragment of APP (CTF β), which is a precursor of the following cleavage by γ -secretase (amyloidogenic pathway, Fig. 2). Two homologous presenilins, presenilin 1 (PS1) and presenilin 2 (PS2), play an important role in γ -secretase activity, which requires three other cofactors: nicastrin (Nct), anterior pharynx-defective phenotype (APH-1), and presenilin-enhancer (PEN-2).⁷⁾ The broad substrate specificity of γ -secretase at the C-terminal region of APP results in the multiple production of other lengths of $A\beta$ s (*e.g.* 37-, 38- or 43-mer).^{8,9)} Additional $A\beta$ heterogeneity is generated by an enzymatic reaction: isomerase (Asp7, Asp23),^{10,11)} glutaminylcyclase (Glu3, Glu11),^{11,12)} aminopeptidases ($A\beta_{3-42}$),¹¹⁾ and phosphorylation (Ser8).¹³⁾ Despite recent rediscovery of the potent amyloidogenicity and pathogenicity of $A\beta_{43}$ ¹⁴⁾ in the animal study, the aggregative ability and

neurotoxicity of A β 43 does not exceed those of A β 42.¹⁵⁾ These findings suggest that A β 42 or these modification products of A β 42 plays the most critical role in the pathogenesis of AD.¹⁶⁾

On the other hand, APP is cleaved by α -secretase between residues 16 and 17 to produce secreted APP α (sAPP α) and the C-terminal fragment (CTF α), resulting in no production of A β 40 and A β 42 from these cleaved precursors (non-amyloidogenic pathway, Fig. 2). Concurrently, smaller fragments, referred to as p3 (A β 17-40/42) and APP intracellular domain (AICD), are produced. The physiological role of these APP metabolites remains unclear in spite of their ubiquitous expression in almost all human organs. Furthermore, a proportion of A β is also modulated by degrading enzymes, such as insulin-degrading enzyme¹⁷⁾ and neprilysin.¹⁸⁾

Although most of the present clinical drugs in AD target glutamatergic and cholinergic neurotransmission, their benefits are limited in terms of symptomatic treatments. Disease-modifying drugs to prevent the aggregation of A β , to hinder the production of A β , and to enhance the degrading activity of A β are currently being developed. In particular, immunotherapy using anti-A β antibody for A β clearance and anti-aggregation has been intensively examined in clinical trials.¹⁹⁾ However, some conventional antibodies targeting A β sequence are struggling in trials. In recent years, conformation[§]-specific antibodies that target synaptotoxic A β oligomers (intermediate aggregates), rather than the physiological A β monomer and fibrils, have received a lot of attention. In the following chapters, this review focuses on the features of A β oligomers and unique attempts to develop antibodies against A β oligomers, and introduces our findings of a monoclonal antibody against a toxic conformer^{§§} of A β 42 together with its application to AD treatment.

I. Amyloid β Oligomer Hypothesis

1. A β oligomers

There is increasing evidence that soluble oligomeric assemblies of A β can induce cognitive decline and synaptic dysfunction in the pathology of AD,²⁰⁾ whereas mature plaques composed of insoluble fibrils are not always consistent with neuronal degeneration^{21,22)} and

serve as a store of the toxic assembly of A β .²³⁾ Accumulated studies on the etiology of A β assemblies; paranucleus (5-mer),²⁴⁾ A β *56 (56 kDa, 12-mer),²⁵⁾ protofibrils (24~700-mer),^{26,27)} globulomer (38/48 kDa, ~12-mer),²⁸⁾ A β O (~90 kDa, 15~20-mer),²⁹⁾ A β -derived diffusible ligands (ADDLs; ~90 kDa, ~24-mer),³⁰⁾ annulus (150~250 kDa, ~50-mer),³¹⁾ and amylospheroid (ASPD; 158~669 kDa, ~100-mer)³²⁾ have been appreciated (Fig. 3, Table 1). Paranucleus is supposed to be a unit of protofibrils. In particular, the synaptotoxic potentials of ADDLs are well studied, and they are extensively used as an oligomer model. These synaptotoxic high molecular-weight oligomers are composed of a dimer and/or trimer as a minimum unit of A β assemblies (2 x *n*-mer, 3 x *n*-mer).^{33,34)} More correctly, A β 40 preferably exists as dimer,³⁵⁾ while A β 42 likely form trimer or tetramer.³⁶⁾ Studies using synthetic dimers (S26C-A β 40)³⁷⁾ and *in vivo*-derived dimers³⁷⁾ and trimers³⁸⁾ support their significance to the synaptotoxicity.

2. Synaptotoxicity

Long-term potentiation (LTP) is a lasting enhancement in signal transmission among neurons, reflecting synaptic health.³⁹⁾ Synthetic A β oligomers (ADDLs),³⁰⁾ brain-derived oligomers (A β *56)²⁵⁾ from AD transgenic mice (Tg2576 line), and dimers³⁷⁾ from human AD patients inhibit LTP and induce dendritic spine shrinkage in rat neurons, resulting in synaptotoxicity in the CA1 region of the hippocampus. Because memory loss is closely related to synaptotoxicity, the removal of A β oligomers and prevention of oligomer formation would be a promising approach for AD therapeutics. Shankar *et al.* demonstrated that the inhibition of LTP was neutralized by the administration of anti-A β antibodies to a rat model of AD.³⁷⁾

3. Oxidative stress

Oxidative stress induced from reactive oxygen species (ROS; *e.g.* superoxide radical, hydroxyl radical) is an early event underlying synaptotoxicity and the subsequent neuronal death by A β oligomer. Reports using human brain materials show a strong correlation

1 between oxidative damage levels (total SOD, catalase, glutathione, protein carbonyls,
2 thiobarbituric acid reactive substances, 3-nitrotyrosine, 4-hydroxynonenal, and acrolein) and
3 the dementia status of subjects.⁴⁰⁾ Klein and colleagues proposed that ADDLs induce LTP
4 accompanied with oxidative damage *ex vivo*.⁴¹⁾ Barnham and colleagues proposed that A β
5 forms dityrosine cross-linked dimers *via* oxidation of the tyrosine residue at position 10
6 (Tyr10) under oxidative conditions,⁴²⁾ and that generic dityrosine levels were also elevated in
7 the AD brain.⁴³⁾

8 Superoxide dismutase (SOD) is one of the major antioxidant metallo-enzymes converting
9 toxic superoxide radicals to hydrogen peroxide. In AD brains, the amount of CuZn-SOD
10 (SOD1), which is found in the peroxisomes and nucleus as well as in the cytosol and
11 intermembrane space of mitochondria, was larger than in non-AD cases.⁴⁴⁾ On the other hand,
12 no such increase was found in Mn-SOD (SOD2) in the mitochondrial matrix or in
13 extracellular CuZn-SOD (SOD3) in specific cell types, such as vascular smooth muscular
14 cells, lungs, and plasma.⁴⁴⁾ Furthermore, to evaluate the contribution of SOD1 to AD
15 progression, our group previously bred *Sod1*-deficient mice (*Sod1*^{-/-}), which showed drusen
16 deposition,⁴⁵⁾ fatty liver,⁴⁶⁾ skin thinning,⁴⁷⁾ and osteoporosis,⁴⁸⁾ as a senescence model, with an
17 APP transgenic mouse model (Tg2576) as an AD model. In the resultant double transgenic
18 mice (*hAPP/Sod1*^{-/-}), A β oligomerization associated with memory loss and synaptic loss
19 worsened as compared with control AD mice.⁴⁴⁾ BACE1 amounts were also augmented in
20 *hAPP/Sod1*^{-/-}, implying stimulation of the amyloidogenic pathway by cytoplasmic superoxide
21 radicals.⁴⁹⁾ The relevance of oxidative stress to oligomer formation of A β in the etiology of
22 AD was described in the previous review.⁵⁰⁾

24 4. Target receptors

25 It is still unclear how A β oligomer interferes with signaling pathways to inhibit LTP
26 activity. Some candidates for oligomer-targeted receptors at the synaptic plasma membrane
27 have been reported. Snyder *et al.* suggested that the application of naturally secreted A β
28 oligomers to cortical slices promoted the endocytosis of *N*-methyl-D-aspartate (NMDA)

receptors by binding the oligomers to $\alpha 7$ -nicotinic receptors.⁵¹⁾ Subsequently, the disturbance of NMDA function affected calcium influx and the downstream cascades, such as AMPA (α -amino-3-hydroxy-5-methyl-4-isoxazole) receptors.⁵²⁾ A β oligomers also interacted with RAGE (receptor for advanced glycation endproducts) receptor⁵³⁾ and the insulin receptor⁵⁴⁾ to induce oxidative stress. Notably, the cellular prion protein (PrP^C) functions as a specific receptor for A β oligomers to inhibit LTP activity and to disrupt insulin activity.⁵⁵⁾ These interactions could be dependent on the size, polarity, and conformations of A β oligomers.

II. A β Immunotherapy

1. Active immunization

Solomon *et al.* reported that anti-A β antibody prevented the aggregation of A β ⁵⁶⁾ and disaggregated the pre-existed fibril of A β using thioflavin T,⁵⁷⁾ which is a reagent showing fluorescence by binding the β -sheet structure within amyloid aggregates.⁵⁸⁾ In 1999, Schenk *et al.* first demonstrated active immunization using an AD mouse model (PDAPP). In this study, the administration of synthetic A β 42 to animals led to a reduction of plaque area⁵⁹⁾, and recovery of cognitive impairment was also reported in later studies.^{60,61)} Subsequently, an experiment using 3xTg-AD mice showed that behavioral improvement by immunization was related to the reduction of A β oligomer levels,⁶²⁾ indicating A β oligomers as more optimal targets than plaques for AD treatment.

In a clinical trial (AN1792) in which Elan and Wyeth initiated active immunization in 2001, synthetic A β 42 combined with the surface-active saponin adjuvant QS-21 was vaccinated. Although phase I was safely conducted, phase II was halted because of severe adverse effects (aseptic meningoencephalitis) in ~6% of patients.⁶³⁾ The subsequent follow-up study indicated that A β plaques were reduced in AD patients but not progressive cognitive impairment.⁶⁴⁾ This was likely due to the unintended removal of both pathological and non-pathological A β 42; the role of the latter in physiological function is currently controversial. Soscia *et al.* reported one interesting study on the involvement of A β 42 in the

immune system as an antimicrobial protein.⁶⁵⁾ Alternatively, the involvement of the excessive induction of T-helper (T_H) 1 lymphocytes by QS-21 adjuvant has been noted, which causes the strong response of the cell-mediated immune system in order to enhance antibody responses in the elderly.

2. Passive immunization

Active A β immunization is cost-effective and long-lasting with only a few injections, although it is difficult to avoid the risk of undesirable immune responses because of the use of strong adjuvants to boost antibody generation. In contrast, passive immunization by the intravenous administration of antibodies is moderate even in the elderly, whose proinflammatory cytokine levels are normally higher,⁶⁶⁾ and it can be halted at any time if adverse events occur. Additionally, the usage of antibodies only directing the target agent of interest, such as toxic A β assemblies or conformations, is one of their advantages over active immunization.

So far, over 600 antibodies against A β have been deposited in Alzforum (<http://www.alzforum.org/>), and most of these were dependent on the A β sequence. The initial application of passive immunotherapy using AD mice (PDAPP) described that treatment with anti-A β N-terminus monoclonal (3D6) antibodies prevented plaque formation, but not anti-A β C-terminus monoclonal antibodies.⁶⁷⁾ In particular, the binding of antibody to amyloid plaque could induce the microglial phagocytosis of A β burden through Fc receptor.⁶⁷⁾ Also, the injection of anti-A β middle portion antibody (m266), whose epitope lies in A β 13-28, to young PDAPP mice prevented plaque formation and decreased the levels of soluble A β .⁶⁸⁾ The complex of A β with antibody in the blood was detected in this study, supporting the potent role of anti-A β antibody therapy in AD prevention. These therapeutic effects are suggested to be mediated by the following inhibitory mechanisms: (1) the complex formation of A β with antibodies could induce binding of the Fc portion to microglia, leading to the phagocytosis of these complexes.⁶⁷⁾ (2) The antibodies could directly prevent the aggregation (oligomerization) of A β .⁶⁹⁾ These mechanisms are based on the assumption that

antibodies can cross the blood–brain barrier (BBB) in order to bind A β within the brain. There is an alternative idea that antibodies in the blood might induce a shift in the concentration gradient of A β over BBB, followed by increased efflux of A β from the brain to the periphery (sink hypothesis).⁶⁸⁾

However, some animal experiments using other sequence-specific antibodies of A β led to the occurrence of microhemorrhages in the regions of cerebral amyloid angiopathy, despite the mitigation of senile plaques and neuritic dystrophy.^{70,71)} Recently, the humanized antibody (bapineuzumab) of 3D6 was tested in clinical trials. Although bapineuzumab reduced A β plaques examined by plaque-detective positron emission tomography (PET) imaging in AD patients in phase III, almost no clinical benefits were observed, thus resulting in the termination of this trial, according to the report by Lemere *et al.*⁷²⁾ These problems may have occurred because the treatment was too late to recover from neurodegenerative decline during the disease process.^{73,74)} It is therefore indispensable to develop highly sensitive oligomer-specific antibodies for the purpose of early diagnosis and passive immunization in AD therapeutics.

III. Conformation-specific Antibodies to Target A β Oligomers

Wirth *et al.* reported no association of A β plaques by [¹¹C] Pittsburgh compound B (PiB) PET and neuronal degeneration in older subjects with normal cognition.⁷⁵⁾ These findings imply the need for a novel detection tool for oligomeric A β in place of PiB, which is one of the most reliable techniques for amyloid detection in clinical practice. If the involvement of tau hyperphosphorylation and accumulation is considered in AD pathology, these may be stimulated by A β oligomers.⁷⁶⁾ However, well-established detection reagents of A β oligomers are presently lacking. Considering the difference of conformations between A β oligomers and fibrils based on previous NMR analysis,⁷⁷⁾ several endeavors have been made to develop conformation-specific antibodies to target A β oligomers (Table 1).

1. A11, OC, α APF antibody

Glabe and colleagues generated an oligomer-specific antibody (A11), which does not recognize A β fibrils and also reacts with other types of amyloid oligomers (α -synuclein in Parkinson's disease, polyglutamine in Huntington's disease, and prion peptide 106-126 in prion disease), using a molecular mimic of the presumed organization of A β oligomers.⁷⁸⁾ They used A β 40 octamer as a hapten, which was synthesized by conjugating the C-terminal thioester A β 40 to colloidal gold nanoparticles. The gold-coupled A β 40 octamer forms a typical β -sheet structure in the circular dichroism (CD) spectra.⁷⁹⁾ This octamer is also spherical in atomic force microscopy, but weak in thioflavin T fluorescence.⁷⁹⁾ This is the first antibody that binds intermediates of A β aggregation, but not fibrillar A β .⁸⁰⁾ In fact, immunohistochemistry using human AD brains showed that the localization of A11 staining was different from that of thioflavin staining.⁷⁸⁾

Subsequently, they produced OC antibody by immunizing with A β 42 fibrils, and OC recognized only amyloid fibrils, not prefibrillar oligomer detected by A11.⁸¹⁾ The mechanism of A11-positive prefibrillar oligomer formation is proposed to be distinct from that of OC-positive fibrillar oligomer formation. They also identified the annular protofibrillar oligomer (α APF), and made an antiserum selective for α APF as the second generation of A11.⁸²⁾

Regarding the application of these antibodies to the diagnosis, they performed dot blotting using human materials. The levels of soluble fibrillar oligomer detected by OC were larger in AD brain extracts than in age-matched individuals, and these increased levels were associated with cognitive decline. Surprisingly, levels of soluble prefibrillar oligomer by A11 and α APF were not associated.⁸³⁾ Similar results were obtained in the experiment using mouse brain extracts.⁸⁴⁾ These results raise another concern that there are at least two classes of oligomers: oligomers supposed to move into the fibrillar stage (on-pathway) or those supposed to remain as the intermediate (off-pathway) (Fig. 3). These also suggest that fibrillar deposition may not be necessarily as benign as previously considered. Recent research also showed that α APF levels in the cerebrospinal fluid (CSF) were elevated during the presymptomatic phase in a hereditary (familial) AD patient.⁸⁵⁾ α APF might be an optimized biomarker for the early

diagnosis of AD.

2. *Anti-ADDLs antibody*

Klein and colleagues found that A β 42-derived ADDLs blocked LTP by binding to synaptic terminals.³⁰⁾ A β 40 failed to form ADDLs. Anti-ADDLs antibody (NU-1) was developed based on its ability to discriminate an AD brain from a control brain.⁸⁶⁾ Although these antibodies were generated by immunization with ADDLs, the epitope of NU-1 likely lay in the A β sequence (A β 1-28) or its assemblies. Neutralization by these antibodies significantly rescued A β 42-induced LTP inhibition as well as ROS.⁸⁶⁾ The amounts of ADDLs were enhanced in CSF and brain extracts of AD.^{87,88)}

Shughrue *et al.* also produced an antibody against ADDLs according to the method developed by Klein and colleagues, and one clone (ACU-954) significantly inhibited the loss of dendritic spines induced by ADDLs through its binding to hippocampal neurons.⁸⁹⁾ ACU-954 also detected naturally-occurring ADDLs in AD brains, which was localized in the hippocampal dendritic spines as well as in the cortex, but not within neuronal cells.⁸⁹⁾

3. *Anti-ASPD antibody*

Hoshi and colleagues generated monoclonal antibodies (rpASD1, mASD3) against amylospheroid (ASPD), which are considered to be an off-pathway product of A β intermediates because ASPD were not included in mature fibrils and were different from ADDLs in morphology and size.⁹⁰⁾ They isolated 10~15-nm spherical A β oligomer (named as native ASPD) by immunoisolation using anti-ASPD antibodies from AD brains. The amount of native ASPD correlated with the severity of AD. These antibodies also immunostained dense-core plaques in cryosections as well as paraffin sections of AD brains. Based on an experiment using the antibodies, they proposed that ASPD-mediated toxicity has a distinct mechanism from other oligomers, where ASPD binds a presynaptic target in an NMDA-receptor-independent manner.⁹⁰⁾

The subsequent study by the same group using a combination measurement of

fluorescence correlation spectroscopy and transmission electron microscopy showed that the formation of ASPD begins with a trimer, whereas the initial step of fibrillogenesis is dimerization.⁹¹⁾ The oligomeric size of most toxic ASPD was ~32-mer (~128 kDa). These findings raise a future concern how dimers and trimers show such different toxicity profiles.

4. Anti-globulomer antibody

Hillen and colleagues developed an antibody (A-887755) against synthetic oligomer (globulomer), whose conformation is different from that of A β monomer or fibril.⁹²⁾ In this study, A β 20-42 was used for preparation of globulomer. They originally found a globulomer made from A β 42, which is supposed to be a stable neurotoxin,²⁸⁾ and showed that A β 42 globulomer inhibited spontaneous synaptic function by modulation of the P/Q-type calcium current.⁹³⁾ They used a truncated peptide (A β 20-42) to avoid the reactivity of all A β species (monomers, oligomers, fibrils) because of the broad immunogenicity of N-terminal regions. Indeed, the antibody (6G1) against A β 42 globulomer did not discriminate among monomers, oligomers, and fibrils.²⁸⁾

In immunoprecipitation experiments, A-887755 did not recognize A β monomer in the CSF and plasma of AD patients. More importantly, A-887755 did not immunolabel senile plaque in AD brains (*e.g.* brain parenchyma and vessel),⁹²⁾ suggesting little cross-reactivity of oligomer-targeted A-887755 antibody with A β monomer and deposits. A β 20-42 globulomer-induced synaptotoxicity was also neutralized by A-887755. Regarding the therapeutic approach, active immunization with A β 20-42 globulomer improved the impaired novel object recognition. Furthermore, passive immunization with A-887755 rescued cognitive impairment as well as synaptic spine density in AD mice.⁹²⁾ Considering adverse effects with the removal of plaques, A-887755 might be a good candidate for an AD therapeutic agent.

5. Grafted amyloid-motif antibody (Gammabody)

Tessier and colleagues proposed a unique “grafting” approach to develop conformation-

1 and sequence-specific antibodies for A β .⁹⁴⁾ This approach is based on the concept, originated
2 by Williamson and colleagues,⁹⁵⁾ that selectivity against aggregated A β conformers can be
3 enhanced by grafting the A β sequence responsible for aggregation into the
4 complementarity-determining region (CDR) in the F_V domain of antibodies, which are
5 generally bound to antigens. They focused on the third CDR (CDR3) of an antibody domain
6 (V_H), whose structure has been identified (PDB: 3B9V). The folding of V_H, which is a stable
7 scaffold, is insensitive to point mutations in the CDR3 loop motif.⁹⁶⁾ Systematic grafting of
8 the A β sequence revealed that the antibody including the central region (Val18-Ala21) bound
9 to A β fibrils, and the antibody including the C-terminal region (Leu34-Ala21) reacted with
10 A β oligomers as well as fibrils. However, an oligomer-specific antibody was not obtained.
11 Such broad reactivity may be why the selected grafting sequence is shared between the
12 formation of oligomers and fibrils. Immunohistochemistry has not been performed.

13 In subsequent studies, these antibodies inhibited the aggregation of A β 42 by forming
14 A β -antibody complex, which was detected by size-exclusion chromatography.⁹⁷⁾ These
15 approaches were expanded to other amyloid proteins: islet amyloid polypeptide (type 2
16 diabetes) and α -synuclein (Parkinson's disease).

18 *6. Antibodies generated by phage display*

19 Phage display is a conventional and powerful technique for antibody selection from
20 libraries by inserting a gene encoding a protein of interest into a phage gene. In general, a
21 virus with the ability to infect and replicate within bacteria is used as a bacteriophage.
22 Fändrich and colleagues demonstrated a phage display using a recombinant library of the
23 camelid VHH domain, and selected the conformation-sensitive VHH-domain B10 by repeated
24 panning using A β 40 fibrils.⁹⁸⁾ The B10 antibody recognized only mature fibrils and prevented
25 fibrillization by stabilizing A β 40 protofibril.

26 Their next target was A β 40 oligomer. The reactivity of the obtained antibody (KW1) in a
27 similar approach was dependent on a hydrophobic and aromatic motif including A β fragment
28 (A β 18-20), which was in good agreement with the results from NMR analysis of the

interaction of A β 40 with KW1.⁹⁹⁾ KW1 bound to high molecular-weight oligomers rather than fibrils and detected brain-derived oligomers in AD patients.

Cattaneo and colleagues carried out advanced phage display selection using an anti-A β single chain F_V domain by targeting intracellular A β oligomers.¹⁰⁰⁾ They expressed a LexA-A β 42 fusion protein in yeast cells, and several antibodies were obtained against these intracellular antigens. The antibodies immunostained senile deposits in the AD brain, and the intracellular deposits were also confirmed in the cell-based experiment. These antibodies also inhibited ADDLs-induced toxicity in cell cultures by preventing the binding of ADDLs to the synapse. This will help us to understand the processing and trafficking of intracellular A β oligomers.

IV. Antibodies against toxic conformer of A β 42

Despite accumulated structural research using NMR, MS, and X-ray crystallography on A β 42¹⁰¹⁾ and A β 40,^{102,103)} studies focusing on the relationship between conformer and neurotoxicity are limited. We have previously proposed the toxic conformer of A β 42 with a turn at positions 22 and 23, and that this conformer could preferably form oligomeric conformation. Our strategy is to develop the oligomer-targeted antibodies based on the theory of the toxic conformer of A β 42.¹⁰⁴⁾

1. Toxic conformer of A β 42

Some investigations clarified that the *S*-oxidized radical cation in Met35 of A β 42 is closely related to its neurotoxicity. However, it remains fully unanswered how the radical is formed to induce toxic effects. Moreover, Met35 radical is generally too unstable to cause oxidative damage continuously.¹⁰⁵⁾ Our continued research, including systematic proline replacement and electron spin resonance (ESR), demonstrated that the turn structure at positions 22 and 23 could bring a phenoxy radical into Tyr10, which was generated through trace metals, close to Met35, resulting in the generation of the *S*-oxidized radical cation in Met35 (Fig. 4A). Another turn at Gly38 and Val39 as well as the turn at Glu22 and Asp23

was also involved in aggregation and neurotoxicity.¹⁰⁶⁾ Such an additional C-terminal turn could play a role in the stabilization of the *S*-oxidized radical cation by forming an *S-O* bonding with a carboxylate anion at Ala42 at the C-terminal core (Fig. 4A). Collectively, the resultant core facilitated by an intramolecular β -sheet (Met35~Ala42) would contribute to long-lasting oxidative stress, that is, the neurotoxicity,¹⁵⁾ and thus we have proposed the toxic conformer of A β 42 with a turn at positions 22 and 23. Further research using solid-state NMR clarified the existence of a non-toxic conformer with a turn at positions 25 and 26 in A β 42 aggregates as well as a toxic conformer with a turn at positions 22 and 23¹⁰⁷⁻¹⁰⁹⁾ (Fig. 4B). In the following study by Masuda *et al.*, the A β 42-lactam (E22K-D23E), in which the side chains of Lys22 and Glu23 in the toxic conformer are linked with an amide bond, enhanced oligomer (mainly trimer) formation and the radical-generating ability of A β 42 as well as the aggregative ability (oligomerization) and neurotoxicity. In contrast, the A β 42-lactam (G25K-S26E), in which the side chains of Lys25 and Glu26 in the non-toxic conformer are similarly linked, did not.¹⁰⁸⁾ A β 42 mutant (E22P-A β 42) with a high ability to form the toxic conformer induced the synaptotoxicity on the rat hippocampal slices.¹¹⁰⁾ These findings strongly suggest that the formation of toxic conformer could be required to facilitate the oligomeric conformation (termed as “toxic oligomer”).

2. 11A1 antibody

We next tried to develop a monoclonal antibody against the toxic conformer of A β 42. The truncated A β peptide (E22P-A β 10-35) including a toxic turn at positions 22 and 23, as a Pro-X corner (X: variable amino acid residue),¹¹¹⁾ based on the optimum length (A β 10-35) for neurotoxicity,¹⁵⁾ was utilized as a hapten (Fig. 4B). To address whether the obtained antibody (termed 11A1)¹⁰⁴⁾ can react with A β oligomers or not, a brain soluble fraction was prepared for western blotting. 11A1 bound a low-molecular-weight oligomer (predominantly trimer), whereas 4G8 against A β 17-24 and 82E1¹¹²⁾ against the N-terminus of A β , recognized mainly the monomer. These observation are consistent with the previous data that A β 42 mutants with a potent propensity to form a turn structure at positions 22 and 23 accelerated A β

oligomerization.¹⁰⁸⁾

MTT assay is one of the evaluation methods for A β -mediated neurotoxicity. The neurotoxicity of A β 42 on PC12 cells was recovered by 11A1, but not by 4G8.¹⁰⁴⁾ 11A1 also inhibited the cytotoxicity of E22P-A β 42, which can more readily form the toxic conformer of A β 42. Similar results were obtained in the test using rat primary neurons.¹¹³⁾ The following dot blotting study of A β 42 demonstrated the gradual increase of 11A1 reactivity in a time-dependent manner, which preceded neurotoxicity.¹¹⁴⁾ On the other hand, the immunoreactivity of A β 42 by other sequence-specific antibodies remained constant. Moreover, 11A1 potently detected the toxic conformer in A β 42 mutants related to familial A β mutations, such as Italian (E22K) and Arctic (E22G),¹¹⁴⁾ which augmented neurotoxicity as well as the aggregative ability of A β 42.¹¹⁵⁾ The neurotoxic effects of these mutants were in good agreement with the levels of reactive oxidative stress tested by the 2',7'-dichlorodihydrofluorescein (DCF) assay,¹¹⁴⁾ supporting the critical role of oligomerization induced from toxic A β 42 conformers in oxidative stress.

3. Intracellular A β

Although the accumulation of oligomeric A β within neuronal cells has been considered to be one of the early events during AD progression, there is little information on the conformation of intraneuronal A β aggregates.¹¹⁶⁾ It has been reported that the intracellular A β oligomer accumulates in the endoplasmic reticulum (ER), endosomes, lysosomes, and mitochondria.¹¹⁷⁾ Intracellular A β deposition precedes the accumulation of extracellular A β .¹¹⁸⁾ Mitochondrial toxicity, proteasome impairment, and synaptic damage due to intracellular A β have been identified.¹¹⁹⁾ Our immunohistochemical studies using the frontal lobe and hippocampus of AD patients (provided by Dr. Shigeo Murayama of the Brain Bank for Aging Research, Tokyo Metropolitan Institute of Gerontology) showed that 11A1 recognized not only typical amyloid plaques but also potent intracellular staining (Fig. 4B). On the other hand, only extracellular amyloid plaques were stained by other sequence-dependent antibodies.¹⁰⁴⁾ Interestingly, mild intracellular staining of 11A1 was

found even in non-AD individuals, suggesting that 11A1 can detect toxic species of A β within cells before the onset of AD. These do not contradict the previous results¹¹⁸⁾ of the potent immunoreactivity of intracellular A β in a patient with MCI.

Similar results using 11A1 have been followed by other researchers. Ohyagi and colleagues showed that intraneuronal staining by 11A1 was more closely related to the onset of memory impairment in 3xTg-AD mice than that by 4G8.¹²⁰⁾ They also found the co-localization of 11A1-positive deposits with GRP78, an ER stress marker, in AD brain sections, whose expression was associated with cognitive impairment and dysfunction of endosomes and Golgi-ER trafficking.¹²⁰⁾ Kulic *et al.* developed APP transgenic mice with double mutations of Swedish (K670N/M671L in APP) and Osaka (E693 Δ in APP), and observed the early depositions of intracellular fibrillar oligomers (11A1-positive) coupled with early memory decline.¹²¹⁾ Osaka mutation (E22 Δ in A β) favoring oligomerization induced the potent synaptotoxicity of A β 42,¹²²⁾ but not A β 40.¹¹⁰⁾ Inoue and colleagues using 11A1 demonstrated intracellular accumulation of A β oligomers with toxic conformer in neuronal cells derived from induced pluripotent stem cells (iPSCs), which were obtained from sporadic patients and a familial AD patient with Osaka mutation.¹²³⁾ Interestingly, anti-ADDLs antibody (NU-1) also immunostained intracellular A β similarly to 11A1. 11A1 is thus a unique antibody that preferably recognizes intracellular amyloid in the human brain along with senile plaques. These findings highlight that the toxic conformer of A β 42 could accumulate within neurons at the early stage during AD progression.

Regarding the intracellular accumulation of A β in AD pathology, key questions of how intracellular A β accumulates remain unanswered, that is, whether A β is partially secreted into the extracellular space but remains intracellular, or whether secreted A β is transported into the intracellular space. Indeed, some transporters involved in the internalization of A β have been reported; the scavenger receptor for advanced glycation end products (RAGE)⁵³⁾ and the formyl peptide receptor-like 1 (FPRL1).^{53,124)} Notably, extracellular plaques increase, while intracellular depositions of A β decrease.¹²⁵⁾ Considering the involvement of tau pathology, intraneuronal A β co-existed with NFT inside the neurons.^{4,126)} Intracellular A β may trigger

tau hyperphosphorylation and mitochondrial dysfunction to induce synaptotoxicity. Because the deposition of tau protein starts about 10 years later than A β accumulation (Fig. 1), a mediator regulating the cross-talk of A β with tau may exist. Quite recently, the synergistical interaction between the accumulation of 11A1-positive intracellular A β and human tau could accelerate each other's aggregation.¹²⁷⁾ These indicate the mediation role of toxic conformer of A β 42 in AD pathology.

V. Conclusions and Future Directions

Given the growing medical and social burden, the necessity of the early resolution of AD is stronger than ever. To date, anti-A β drugs have been developed;¹²⁸⁾ these are mainly divided into three strategies: (1) anti-aggregation and clearance, (2) secretase inhibitors, (3) A β degradation activator. Since symptomatic drugs (denopetil, memantine, rivastigmine, and galantamine) have been established, these combination strategies based on an early diagnosis will be more effective. Several structure-based designs of aggregation inhibitors have been also recently reported.¹²⁹⁻¹³¹⁾ Conformation-specific antibodies to target the characteristic structure of A β oligomers will shed new light on the accurate diagnosis by ELISA development and vaccination therapy. Eventually, it may be possible to extend the diagnosis and intervention to asymptomatic people.

In the application of antibodies to ELISA development, the approach of two-site ELISA has received attention, in which the same sequence-specific antibody (82E1¹³²⁾ or Ban50¹³³⁾ against A β 1-16) for capture and detection is used. These approaches revealed a clear correlation of the oligomer levels in the plasma and brain extracts¹³²⁾ and CSF¹³³⁾ in various cognitive levels of AD patients. A recent study using brain lysates showed that two-site ELISA of the antibody (HJ3.4) against the N-terminal A β discriminated A β dimer from monomer, but the result that HJ3.4 did not discriminate oligomers from plaques caused confusion.¹³⁴⁾ Such a strategy aiming at ELISA specificity is questioned. Because 2 x *n*-mer oligomers with high molecular weight as well as the dimer can be theoretically detected in these strategies, oligomer levels in healthy individuals may be overestimated.¹³⁵⁾ Two-site

ELISA recently generated by the same group to target ADDLs using a modified ACU-954 conjugated with a bead-based fluorescent platform was improved in this aspect.¹³⁶⁾ Prospectively, the application of conformation-specific antibodies such as 11A1 into ELISA is promising.

Indeed, only a few antibodies can cross the BBB (0.1–0.2%).¹³⁷⁾ Even if unprecedented antibodies are developed, this concern may limit their therapeutic application, such as in vaccination. Quite recently, protein manipulation by binding anti-A β antibody to transferrin receptor, which is involved in receptor-mediated transcytosis, produced a monovalent “Brain Shuttle” module, leading to increased brain penetration.¹³⁸⁾ Consequently, continuous investigations to develop oligomer-specific antibodies with high affinity will be required to move closer to the realization of a world without AD.

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Footnotes

§“Conformation” in this context refers to tertiary structure of proteins including oligomers.

§§“Conformer” in this context refers to isomers which are exclusively interconvertible by the single bond rotation without breaking the chemical bonds.

Figure and Table legends

Fig. 1. A β -related and -unrelated Biomarkers Associated with Clinical Disease Stages during AD. The Figure 1 in the reference⁶⁾ was modified.

CSF, cerebrospinal fluid; MCI, mild cognitive impairment.

Fig. 2. APP Processing with α -, β -, γ -Secretases to Generate A β (Amyloidogenic Pathway) or Truncated A β (non-Amyloidogenic Pathway).

sAPP $\alpha(\beta)$, secreted APP $\alpha(\beta)$; CTF $\alpha(\beta)$, C-terminal fragment $\alpha(\beta)$ of APP; AICD, APP intracellular domain.

Fig. 3. Schematic Aggregation Pathway of A β Based on the Dimer and Trimer as a Minimum Unit for Oligomerization.

A β forms synaptotoxic oligomers to move into fibrillization (on-pathway), while to remain unchanged (off-pathway).

Fig. 4. Development of Antibody against Toxic Conformer of A β 42.

(A) A proposed mechanism of the formation of S-oxidized radical at Met35 and its stabilization within a C-terminal core to induce long-lasting oxidative stress by a partially cleaved carboxyl radical at Ala42 in A β 42. (B) Toxic conformation with a “toxic” turn at positions 22 and 23 and non-toxic conformation with a turn at positions 25 and 26 have been identified from solid-state NMR and systematic proline replacement studies. Immunohistochemical studies of anti-toxic turn antibody (11A1) using human AD brain sections. Arrows indicate extracellular A β depositions (senile plaques), and arrowheads

1 indicate the accumulation of intracellular A β within the cells, respectively. Scale bar
2 represent 100 μ m.

3

4 **Table legend**

5 **Table 1.** Synaptotoxic A β Oligomers of and Their Biological Activities Together with
6 Antibody Development against These Oligomers.

7 The three formers refer to the intermediates on the on-pathway into fibrillization, while
8 the four latters refer to the assemblies on the off-pathway.

9

Figure 1 K. Murakami

Figure 2 K. Murakami

Figure 3 K. Murakami

Figure 4 K. Murakami