

# Amyloid- $\beta$ Receptors: The Good, the Bad, and the Prion Protein<sup>\*[S]</sup>

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Several different receptor proteins have been identified that bind monomeric, oligomeric, or fibrillar forms of amyloid- $\beta$  (A $\beta$ ). “Good” receptors internalize A $\beta$  or promote its transcytosis out of the brain, whereas “bad” receptors bind oligomeric forms of A $\beta$  that are largely responsible for the synaptic loss, memory impairments, and neurotoxicity that underlie Alzheimer disease. The prion protein both removes A $\beta$  from the brain and transduces the toxic actions of A $\beta$ . The clustering of distinct receptors in cell surface signaling platforms likely underlies the actions of distinct oligomeric species of A $\beta$ . These A $\beta$  receptor-signaling platforms provide opportunities for therapeutic intervention in Alzheimer disease.

Alzheimer disease (AD)<sup>2</sup> is characterized pathologically by the deposition in the brain of the 40–42-amino acid amyloid- $\beta$  (A $\beta$ ) peptide in extracellular plaques and of the microtubule-binding protein tau in intracellular neurofibrillary tangles. The amyloid cascade hypothesis, formulated over 20 years ago, posits that A $\beta$ , derived from the proteolytic processing of the amyloid precursor protein, is the causative agent in AD pathology and that neurofibrillary tangles, cell loss, vascular damage, and dementia follow (1). A recent and critical interpretation of the existing data concluded that aggregated A $\beta$  acts primarily as a trigger of other downstream processes, particularly tau aggregation, which mediate neurodegeneration (2). Understanding the nature of the interaction of A $\beta$  with neurons and other cell types in the brain is key to a complete understanding of the pathogenesis of AD. Furthermore, identifying the proteins

involved in the binding of aggregated forms of A $\beta$  and the downstream cytotoxic signaling pathways that are subsequently activated may reveal sites for therapeutic intervention. In this minireview, we provide an overview of the “bad” receptors involved in the binding and cytotoxic action of A $\beta$ , as well as the “good” receptors involved in A $\beta$  metabolism and clearance from the brain (Fig. 1, Table 1). More detailed information on the A $\beta$  receptors and carriers, including the type of A $\beta$  they bind, the cell type they are expressed on, binding partners, and downstream targets, is provided in supplemental Table 1.

## The Ligand: Multiple Forms of A $\beta$

Any discussion of receptors has to take into account the properties of the ligand(s) that binds to that receptor. In the case of the ligand A $\beta$ , this is complicated by the fact that it exists in multiple forms from monomers, through dimers, trimers, and oligomers to protofibrils and fibrils that range in size from 4 kDa to assemblies of >100 kDa, and vary in morphology and conformation (3). A $\beta$  oligomers (A $\beta$ O) appear to be the most neurotoxic species, triggering various processes that underlie AD, including synaptic dysfunction, impairment of long-term potentiation (LTP), Ca<sup>2+</sup> dysregulation, mitochondrial dysfunction, endoplasmic reticulum stress, and the activation of pro-apoptotic pathways leading to cell death (4, 5). Various oligomeric forms of A $\beta$  have been isolated from human AD brain and from the brains of AD model mice, as well as from cell culture medium, in addition to being produced from preparations of recombinant or synthetic A $\beta$  peptides (6–10). Almost certainly, preparations of A $\beta$ O, whether isolated from natural sources or produced *in vitro*, are composed of a number of oligomeric species with diverse biophysical and biological properties existing in dynamic equilibrium (6, 11). This dynamic equilibrium complicates studies when attempting to isolate a particular population of oligomers, *e.g.* by size exclusion chromatography, as the resultant “purified” oligomer preparation will remodel to other species as the preparation resets its equilibrium. Therefore, it is not surprising that there is controversy over which is the toxic form of A $\beta$ O, and indeed whether there is a single toxic entity (6).

The conformation of A $\beta$ O aggregates has emerged as a useful classification method that is more biologically relevant than size, given that the structural motifs present on the surface of a protein will determine its binding partners and biological activities. Various conformation-specific antibodies that react with A $\beta$ O have been produced and characterized (reviewed in Ref. 6). Two of the more widely used conformation-specific antibodies are the A11 and OC antibodies (12, 13), which recognize mutually exclusive structural epitopes on a range of amyloid-forming proteins, not just A $\beta$ , independent of primary amino acid sequence. A11 antibodies recognize out-of-register anti-parallel  $\beta$  sheet structures, whereas OC antibodies detect in-register parallel  $\beta$  sheets (14–16).

A recent study (16) classified brain-derived A $\beta$ O into two types based in part on their reactivity to these conformation-specific antibodies. Type 1 A $\beta$ O were A11-immunoreactive

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[S] This article contains supplemental Table 1.

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<sup>2</sup> The abbreviations used are: AD, Alzheimer disease; A $\beta$ , amyloid- $\beta$ ; A $\beta$ O, amyloid- $\beta$  oligomer(s);  $\alpha$ 7-nAChR,  $\alpha$ 7-nicotinic acetylcholine receptor; ADDL, A $\beta$ -derived diffusible ligand; apo, apolipoprotein; ASPD, amylo-spheroid(s); BBB, blood-brain barrier; Eph, Ephrin; LDLR, low-density lipoprotein receptor; LMW, low molecular weight; LRP1, low-density lipoprotein receptor-related protein 1; LTP, long-term potentiation; NaK $\alpha$ 3, Na<sup>+</sup>/K<sup>+</sup>-ATPase neuron-specific  $\alpha$ 3 subunit; NMDAR, N-methyl-D-aspartate receptor; PrP<sup>C</sup>, cellular prion protein; RAGE, receptor for advanced glycation end products; mGluR, metabotropic glutamate receptor.

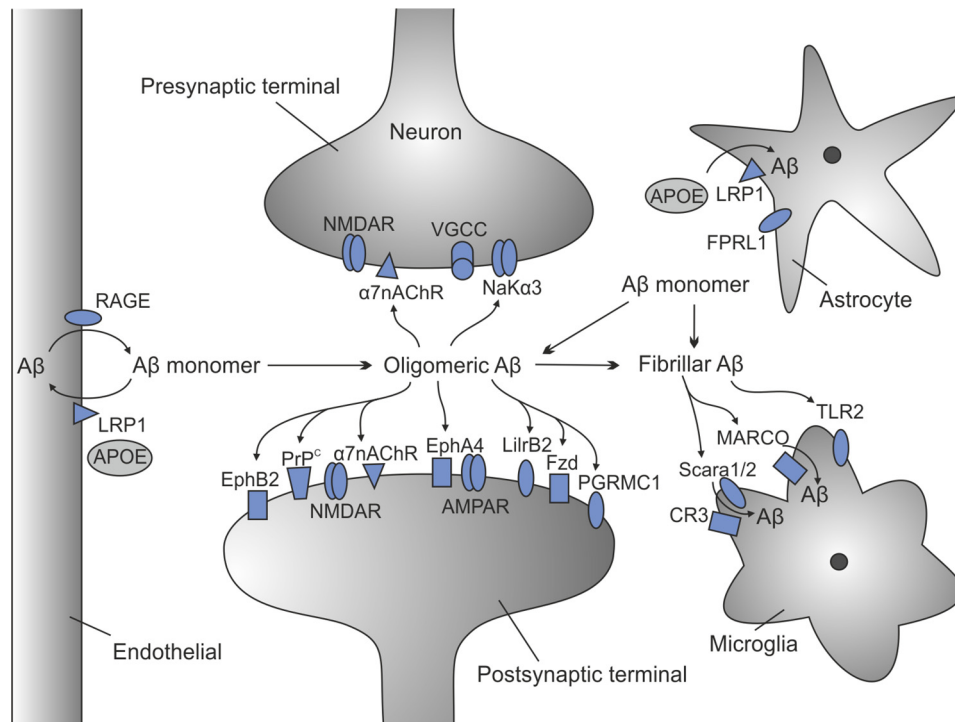


FIGURE 1.  **$A\beta$  receptors and their cellular locations.**  $A\beta$  monomers aggregate into oligomers and fibrils in the brain, interacting with a variety of receptors on the presynaptic and postsynaptic membranes of neurons, on endothelial cells, and on astrocytes and microglia. The endothelial receptors RAGE and LRP1 are involved in  $A\beta$  monomer clearance through the blood-brain barrier. LRP1 also mediates monomer efflux into astrocytes. The microglial receptors Scara1/2 and MARCO are linked to  $A\beta$  clearance by interaction with fibrillar  $A\beta$ . Oligomeric  $A\beta$  is widely viewed as the pathogenic species, triggering synaptic impairment and cell death following interaction with a range of postsynaptic neuronal receptors, including EphB2,  $PrP^C$ , and  $\alpha 7nAChR$ , which are linked to NMDAR dysfunction.  $A\beta$  also bind to EphA4, LillrB2, Frizzled (Fzd), and PGRMC1 receptors, triggering synaptic impairment. In addition,  $A\beta$  bind to the presynaptic receptors  $\alpha 7nAChR$  and  $NaK\alpha 3$ , which are linked to altering presynaptic calcium levels. See text and Table 1 for details.

(also referred to as  $A\beta^{*56}$ ) and had no temporal, spatial, or structural relationship to amyloid fibrils, whereas type 2  $A\beta$  recognized by OC antibodies were related to amyloid fibrils temporally, spatially, and structurally and represented the majority of oligomers generated *in vivo*. The authors concluded that although most of the soluble  $A\beta$  in brains with dense core plaques (e.g. AD brains) are type 2  $A\beta$ , the bulk of these oligomers are rendered functionally innocuous by their effective containment within plaques. In contrast, they suggested that type 1  $A\beta$  may be more directly pathogenic in certain brain regions as they are more finely dispersed than the type 2  $A\beta$  (16). Further work is required to reconcile these conclusions with the observations that OC reactivity, not A11 reactivity, correlated with the onset and severity of AD in human brain studies (17, 18) and that only OC-positive oligomers correlated with cognitive decline and promoted tau aggregation and phosphorylation in a different transgenic AD mouse model (18).

Another recent study (19) utilized several oligomer-directed quantitative assays, including a high specificity binding assay based on the affinity of certain  $A\beta$  for the cellular form of the prion protein ( $PrP^C$ ) (PrP-ELISA or PLISA) (20), to assay  $A\beta$  across brain tissue from multiple AD mouse models and human brain samples. The  $PrP^C$ -interacting  $A\beta$  represented a distinct population of high molecular weight  $A\beta$  assemblies that were as accurate as any other predictor of memory impairment in the AD mouse models and human AD patients. Oligomers interacting with  $PrP^C$  were preferentially recognized by the OC

antibody rather than the A11 antibody (21, 22) and thus would appear to correspond to the type 2  $A\beta$  (16). Critically, the fraction of  $PrP^C$ -interacting  $A\beta$  varied greatly between transgenic AD mouse models and likely determines the extent to which  $PrP^C$ -dependent molecular mechanisms contribute to the progression of AD (19). That different transgenic AD mouse models may produce predominantly one (or a few) of the many potential types of  $A\beta$  present in the human AD brain clearly complicates interpretation of data from the animal models. More work is required to clarify these discrepancies in  $A\beta$  type and function both between animal models and between the animal models and the human situation. However, the characterization of different  $A\beta$  species based on antibody or other conformational recognition (e.g.  $PrP^C$  interaction) is a useful criterion with which to help decipher the contribution of particular oligomeric species to AD pathogenesis. *In vivo* it is highly likely that more than one oligomeric species contributes to toxicity, and thus understanding the temporal and spatial distribution of all  $A\beta$  types in the brain during the initiation and development of AD, as well as knowing their receptors and mechanisms of toxicity, is essential to progress the field. Although  $A\beta$  have been proposed to cause neurotoxicity through a variety of mechanisms, including direct interaction with lipids resulting in damage to the membrane through, for example, pore formation, or through intracellular accumulation leading to cytotoxicity (23, 24), here we focus on the binding of  $A\beta$  to cell surface receptors.

**TABLE 1**
**A $\beta$  receptors and carriers**

The A $\beta$  receptors and soluble carrier proteins are classified into “good” receptors that promote the clearance or degradation of A $\beta$ , thereby lowering the amount available to form A $\beta$ O, and into “bad” receptors that mediate the neurotoxic actions of A $\beta$ O. See text and supplemental Table I for more details. AMPAR,  $\alpha$ -amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid receptor; VLDLR, very low-density-lipoprotein receptor.

A $\beta$ receptors and carriers	A $\beta$ type/conformation	Other interactors	Reference
<b>“Good” receptors</b>			
$\alpha$ 7-Nicotinic acetylcholine receptor ( $\alpha$ 7nAChR)	A $\beta$ 42 monomer/LMW oligomers (4–24 kDa)		79
Apolipoprotein E (apoE)	A $\beta$ 40/42 monomer	LRP1, LDLR	31
Clusterin (ApoJ)	A $\beta$ 40 monomer	LRP2	80
Complement receptor type 3 (CR3 or Mac1)	A $\beta$ 40/42 fibrillar	SR-A	81
Formyl peptide receptor (FPR1)/formyl-peptide receptor-like 1 (FPRL1)	A $\beta$ 42		81
Heparan sulfate proteoglycan (HSPG)	A $\beta$ 40/42 monomer	LRP1	82
Low-density lipoprotein receptor (LDLR)	A $\beta$ 40/42 monomer	apoE	83
Low-density lipoprotein receptor-related protein 1 (LRP1)	A $\beta$ 40/42 monomer	PICALM, apoE	25–28
Macrophage receptor with collagenous structure (MARCO)	A $\beta$ 42 monomer	FPRL1	33
Phosphatidylinositol-binding clathrin assembly (PICALM) protein	A $\beta$ 40/42 monomer	Clathrin/LRP1	28
Prion protein (PrP <sup>C</sup> )	A $\beta$ 40 monomer	LRP1	29
Scavenger receptors (SCARA1/2)	A $\beta$ 42 fibrillar		84
<b>“Bad” receptors</b>			
$\alpha$ 7nAChR	A $\beta$ 42 oligomers (4–56 kDa)		85
AMPA receptor	A $\beta$ 42 ADDLs (8–40 kDa) A11-negative		86
Amylin 3 receptor (AMY3)	A $\beta$ 42 ADDLs (4–96 kDa)		87
apoE	A $\beta$ 40/42 oligomers	VLDLR/LRP1	31, 88
$\beta$ 2 adrenergic receptor ( $\beta$ 2AR)	A $\beta$ 42 dimer	GluR1 (AMPA)	89
Clusterin (ApoJ)	A $\beta$ 42 oligomer (8–200 kDa)		90
Ephrin A4 (EphA4)	A $\beta$ 42 oligomers (4–100 kDa)		91
Ephrin B2 (EphB2)	A $\beta$ 42 ADDLs (LMW)	NMDAR, PSD95	55, 58
Fc $\gamma$ receptor IIb (Fc $\gamma$ RIIb)	A $\beta$ 42 ADDLs (LMW)		92
Frizzled (Fzd)	A $\beta$ 40/42 ADDLs (12–96 kDa)		93
Insulin receptor	A $\beta$ 42 ADDLs (50–100 kDa)		94
Leukocyte immunoglobulin-like receptor B2 (LilrB2)/PirB	A $\beta$ 42 ADDLs (50–150 kDa)		95
Na <sup>+</sup> /K <sup>+</sup> -ATPase neuron-specific $\alpha$ 3 subunit (NaK $\alpha$ 3)	ASPD (128 kDa spheres)		38
Neuroigin-1	A $\beta$ 42 A11-positive	PSD95	96
NMDA receptor	A $\beta$ 42 ADDLs (12–96 kDa)	PSD95	10, 55, 57
p75 neurotrophin receptor (p75NTR)	A $\beta$ 42 ADDLs (LMW)	DR6	97
P/Q-type calcium channels	A $\beta$ 42 globulomers		98
PrP <sup>C</sup>	A $\beta$ 42 ADDLs (70–250 kDa) OC-positive	mGluR5, LRP1	20, 21, 43, 48
Receptor for advanced glycation end products (RAGE)	A $\beta$ 40/42 monomer		99
SCARB2/ CD36	Fibrillar A $\beta$	TLR-4, TLR-6	100
Sigma-2/PGRMC1	A $\beta$ 42 oligomers (50–75 kDa)		74, 77
Toll-like receptor 2 (TLR2)	A $\beta$ 42 fibrillar		81

**The “Good” A $\beta$  Receptors**

Proteins that bind A $\beta$  (whether monomeric, oligomeric, or fibrillar forms) and reduce the amount available to aggregate into toxic oligomers can in many ways be considered “good” receptors. Such receptors may internalize A $\beta$  into neurons or other cells (e.g. microglia) and target it for lysosomal degradation or remove it from the brain by transcytosis across the blood-brain barrier (BBB) (Fig. 1). One such receptor is the low-density lipoprotein receptor-related protein 1 (LRP1), which binds multiple ligands including monomeric A $\beta$  and is abundantly expressed in various brain cell types. LRP1 has been implicated in mediating A $\beta$  transcytosis across the BBB (25), as well as in the uptake and local clearance of A $\beta$  in vascular smooth muscle cells and neurons (26, 27). Recently, the AD genetic risk factor *PICALM*, which encodes the phosphatidylinositol-binding clathrin assembly (PICALM) protein involved in the endocytosis of various cell surface receptors, was reported to influence A $\beta$  clearance across the BBB through regulating the function of LRP1 in brain endothelial cells (28). PrP<sup>C</sup> has also been linked to A $\beta$  transport across the BBB (29). PrP<sup>C</sup> on endothelial cells bound monomeric A $\beta$ 40, and genetic knock-out or the addition of a competing PrP<sup>C</sup> antibody blocked the transcytosis of A $\beta$ 40 in a process that also required LRP1 (29). The low-density lipoprotein receptor (LDLR) is also implicated in neuronal and astrocytic A $\beta$  uptake and BBB transcytosis of A $\beta$  (30). Although not cell surface receptors, the

carriers apolipoprotein (apo) E and clusterin (apoJ) bind soluble A $\beta$  and facilitate its uptake through receptors such as LRP1 or LRP2 and LDLR, thereby reducing the amount of A $\beta$  available to aggregate (31). Microglial cells surrounding A $\beta$  plaques express the scavenger receptors SCARA1 and SCARA2, which have a high affinity for soluble and fibrillar A $\beta$  and mediate phagocytosis and clearance of A $\beta$  from the brain (32). The macrophage receptor with collagenous structure (MARCO) binds A $\beta$  and activates the ERK1/2 signaling pathway, leading to reduced inflammation (33). Collectively, these and other receptors and carriers (Table 1) work together, alongside other mechanisms for degrading or inactivating A $\beta$  in the extracellular environment, such as the A $\beta$ -degrading enzymes neprilysin and insulin-degrading enzyme (34), to maintain A $\beta$  at low, manageable, non-toxic levels in the brain.

**The “Bad” A $\beta$  Receptors**

In contrast to the “good” receptors described above that promote the transcytosis of A $\beta$  out of the brain, one mechanism of action of the “bad” receptors is to mediate the uptake of A $\beta$  into the brain across the BBB. The receptor for advanced glycation end products (RAGE), present on endothelial cells, mediates the influx of circulating A $\beta$  (35). RAGE also internalizes A $\beta$  into neurons, promoting its intracellular aggregation and accumulation, leading to rapid activation of p38 MAPK and mitochondrial dysfunction (36). Contributing to the accumulation

of  $A\beta$  in the brain is apoE4, a well established genetic risk factor for the development of late-onset AD. As well as being involved in modulating the clearance and degradation of  $A\beta$  in the brain, apoE also slows the transport of  $A\beta$  across the BBB in an isoform-dependent manner, with apoE4 having the greatest effect (37). The detrimental effects of apoE4 are further exacerbated by its ability to bind to and stabilize  $A\beta O$ , slowing down their transition to fibrils (37).

When the first  $A\beta O$  were prepared from synthetic  $A\beta_{42}$  peptide, the now widely used  $A\beta$ -derived diffusible ligands (ADDLs), it was observed that their binding to hippocampal neurons was abolished by treating the cells with trypsin (7). This observation, coupled with the low oligomer concentration (5 nM) required for neurotoxicity, indicated that one or more high-affinity protein receptors are responsible for  $A\beta O$  binding and subsequent neurotoxicity. To date, several candidate "bad"  $A\beta$  receptors that bind  $A\beta O$  at the cell surface and then trigger a variety of downstream signaling pathways that negatively impact on neuronal function and survival have been described (Table 1; supplemental Table 1) (38–41). The role of several of these receptors in mediating  $A\beta O$  neurotoxicity is controversial or yet to be reproduced. The heterogeneity and dynamic nature of  $A\beta O$  preparations as discussed above undoubtedly have led to difficulties in first identifying a particular receptor and then in corroborating its involvement in different model systems and between different laboratories. The use of different and often poorly characterized preparations of  $A\beta O$ , different toxicity measurements on divergent target cell populations under different conditions, and the use of different transgenic AD mouse models at different stages of disease all confuse the picture. The recent report that the proportion of PrP<sup>C</sup>-interacting  $A\beta O$  varies between different mouse models of AD (19) may go some way to explain these discordant observations. Indeed this highlights a fundamental issue in the field; it is very unlikely that all receptors bind to the same oligomeric species of  $A\beta$ , and binding of different  $A\beta O$  to an individual receptor may be differentially influenced by other receptors or co-receptors in their vicinity (see below). Many of the signaling pathways initiated by these receptors converge into common downstream targets that are ultimately responsible for neurotoxicity and cell death.

### Dynamic Signaling Platforms Mediate $A\beta O$ Binding and Action

Various lines of evidence suggest that  $A\beta O$  binding to neurons may involve multi-protein cell surface receptor complex(es) whose assembly is initiated upon binding of oligomers to one or more of the receptor proteins listed in Table 1. These signaling platforms or signalosomes (5, 39, 42) will be formed from complexes of proteins and lipids in the plane of the plasma membrane, and will be transient in nature and likely involved in both physiological and pathological responses, contributing to both neuroprotection and neurotoxicity. The relative contribution to these two endpoints may depend on multiple factors, including the type and concentration of oligomer species, the compartmentalization of particular receptors and signaling effectors into different signaling platforms, the relative local interaction and concentration of particular recep-

tors, co-receptors, and lipids, the interplay between the various downstream signaling pathways, and the rate of receptor down-regulation/internalization.

One such signaling platform is based on PrP<sup>C</sup> (Fig. 2A). PrP<sup>C</sup> was identified to bind  $A\beta O$ , but not monomers or fibrils, with high affinity ( $K_d \sim 0.4$  nM) (43, 44) and to selectively interact with high molecular mass assemblies of  $A\beta O$  in AD but not control brains (45). PrP<sup>C</sup> was responsible for the  $A\beta O$ -mediated inhibition of LTP in hippocampal slices (43) and was also required for the manifestation of memory impairments in an AD mouse model (46).  $A\beta O$  binding to PrP<sup>C</sup> leads to activation of Fyn kinase, which in turn phosphorylates the GluN2B subunit of *N*-methyl-D-aspartate receptors (NMDARs), which was coupled to an initial increase and then a loss of surface NMDARs (20). In addition, the  $A\beta O$  activation of Fyn leads to tau phosphorylation (47). Both mGluR5 (48) and LRP1 (21) have been identified as co-receptors required for the PrP<sup>C</sup>-bound  $A\beta O$  to activate Fyn (Table 1).

PrP<sup>C</sup> localizes to cholesterol- and sphingolipid-rich, detergent-resistant lipid rafts due to the saturated acyl chains in its glycosylphosphatidylinositol anchor and to an N-terminal targeting signal interacting with the heparan sulfate proteoglycan, glypican-1 (49, 50). PrP<sup>C</sup> has been proposed as a key scaffolding protein for the dynamic assembly of cell surface signaling modules (51), and PrP<sup>C</sup>, along with the microdomain-forming flotillin or caveolin proteins, may lead to the local assembly of membrane protein complexes at sites involved in cellular communication, such as cell-cell contacts, focal adhesions, the T-cell cap, and synapses (52). The integrity of lipid rafts is critical for the cell surface binding of  $A\beta O$  and the subsequent activation of Fyn. Treatment of cells with methyl- $\beta$ -cyclodextrin, which depletes cellular cholesterol and thus disrupts the cholesterol-rich lipid rafts, caused the re-localization of PrP<sup>C</sup> and Fyn from detergent-resistant rafts to detergent-soluble, non-raft regions of the membrane (21). Surprisingly, disruption of the rafts with methyl- $\beta$ -cyclodextrin significantly reduced (by >80%) the cell surface binding of the  $A\beta O$ , although the cell surface expression of PrP<sup>C</sup> was unaffected, and prevented the  $A\beta O$  from activating Fyn (21). The addition of  $A\beta O$  to neurons caused a large increase of mGluR5 in the detergent-resistant fraction (53), and on binding oligomers, the co-localization of LRP1 and PrP<sup>C</sup> increased (21), suggesting that binding of  $A\beta O$  to PrP<sup>C</sup> causes these co-receptors to cluster together in rafts and activate the signaling complex. This cell-surface, raft-based signaling complex based on PrP<sup>C</sup> may be key in mediating the neurotoxic actions of type 2  $A\beta O$  (Fig. 2A). Another cholesterol-rich, raft-based platform may involve the presynaptic  $\alpha 7$ -nicotinic acetylcholine receptor ( $\alpha 7$ -nAChR) as its  $A\beta O$ -mediated activation was attenuated on disruption of the rafts by cholesterol depletion (54).

Another signaling platform(s) is likely based on NMDARs (Fig. 2B), which are necessary but not sufficient for  $A\beta O$  binding (reviewed in Ref. 5). NMDARs are anchored by PSD95, which acts as a scaffold to organize multiple membrane-associated proteins at synapses and which interacts with other  $A\beta O$  receptors including EphB2 (55). Binding of  $A\beta O$  to postsynaptic density complexes containing NMDARs promoted dendritic spine loss in an NMDAR-dependent manner and abol-

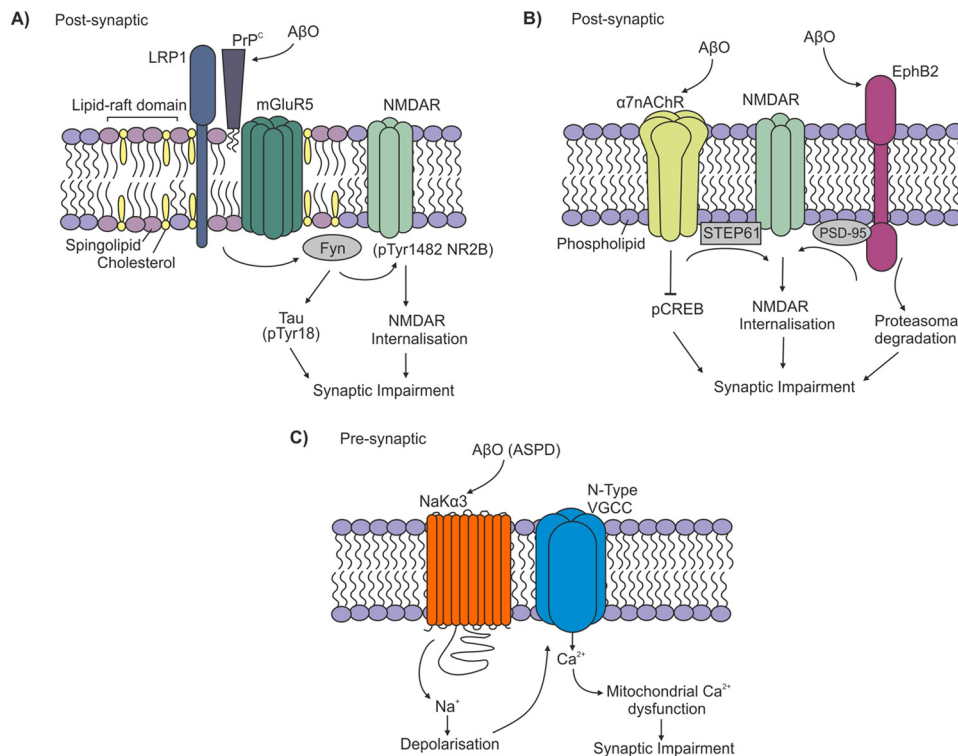


FIGURE 2. ***Aβ* oligomer receptor signaling platforms.** *Aβ*O induce synaptic impairment and neuronal cell death by interacting with multiple receptor signaling platforms. *A*, PrP<sup>C</sup>-based, cholesterol- and sphingolipid-rich lipid raft signaling platform. The co-receptors LRP1 and mGluR5 cluster with PrP<sup>C</sup> upon *Aβ*O binding and lead to activation of Fyn kinase, which phosphorylates NMDAR and tau. *pTyr18*, phospho-Tyr-18; *pTyr1482*, phospho-Tyr-1482. *B*, both  $\alpha 7$ nAChR and EphB2 bind *Aβ*O and induce NMDAR-mediated dysfunction and synaptic impairment. *pCREB*, phospho-cAMP-response element-binding protein. *C*, the presynaptic NaK $\alpha 3$  binds ASPD oligomers, inducing Ca<sup>2+</sup> influx via N-type VGCCs, resulting in mitochondrial dysfunction, tau phosphorylation, and synaptic impairment.

ished NMDAR-dependent LTP (55, 56). Antibodies against the subunits of NMDAR blocked the binding of *Aβ*O to neurons, and the NMDAR antagonist Memantine completely protected against *Aβ*O-induced reactive oxygen species formation (57), indicating that the receptors are required for binding and downstream action of *Aβ*O. However, no direct binding of *Aβ*O to NMDAR subunits has been reported. The EphB2 receptor modulates NMDAR by tyrosine phosphorylation and recruits active NMDAR to excitatory synapses. *Aβ*O interacted directly with the extracellular fibronectin repeats of EphB2, which led to depletion of surface EphB2 by enhancing its proteasomal degradation and to the internalization of GluN1 subunit-containing NMDARs (58). The  $\alpha 7$ -nAChR also induces *Aβ*O-mediated NMDAR dysfunction and synaptic impairment.  $\alpha 7$ -nAChR binds *Aβ*O with high affinity, and binding leads to activation of the channel, increased cytosolic Ca<sup>2+</sup>, and subsequent activation of protein phosphatase 2B (PP2B). De-phosphorylation of the tyrosine phosphatase striatal-enriched protein tyrosine phosphatase (STEP) via PP2B promotes STEP to dephosphorylate Tyr-1472 on the NMDAR subunit GluN2B, thereby disrupting its binding to PSD95, ultimately leading to the internalization of the receptor (59). Thus, binding of *Aβ*O (possibly distinct species) to multiple receptors promotes neurotoxicity via NMDAR. Although both EphB2 and  $\alpha 7$ -nAChR mediate *Aβ*O action via NMDARs, whether they are located in the same signaling platform awaits to be determined. Although binding of *Aβ*O to PrP<sup>C</sup> also results in altered NMDAR function, EphB2 does not link *Aβ*O-PrP<sup>C</sup>

complexes to Fyn activation (48), providing clear evidence for the existence of distinct *Aβ*O-binding signaling platforms.

A further signaling platform is based on the Na<sup>+</sup>/K<sup>+</sup>-ATPase (Fig. 2C), whose neuron-specific  $\alpha 3$  subunit (NaK $\alpha 3$ ) was recently identified to bind amylospheroids (ASPD) (38). ASPD are 15-nm spherical *Aβ*O that are distinct from ADDLs, that are not recognized by the A11 conformation-dependent antibody, and that caused selective degeneration of mature human neurons (60). The direct binding of ASPD to NaK $\alpha 3$  impaired its activity, resulting in an increase in cytoplasmic Na<sup>+</sup> and depolarization of the neuron. This in turn activated N-type voltage-gated Ca<sup>2+</sup> channels (N-type VGCC), leading to Ca<sup>2+</sup> overload in the cytoplasm and mitochondria, ultimately leading to tau phosphorylation and degeneration of neurons. This signaling platform is localized on the presynaptic membrane (Fig. 1).

Further signaling platforms, based on other groupings of the receptors in Table 1, possibly in association with distinct combinations of membrane lipids, may be involved in binding the same and/or other oligomeric forms of *Aβ* and transducing neurotoxic signals. It should also be noted that although we have described these different signaling platforms as distinct entities (Fig. 2), it is possible that they are not structurally or functionally isolated and that “super” platforms exist which contain multiple receptors interacting with multiple oligomeric forms of *Aβ*. Furthermore, the protein and lipid composition of these dynamic signaling platforms may alter as a result of electrophysiological activity, oxidative damage, changes in lipids

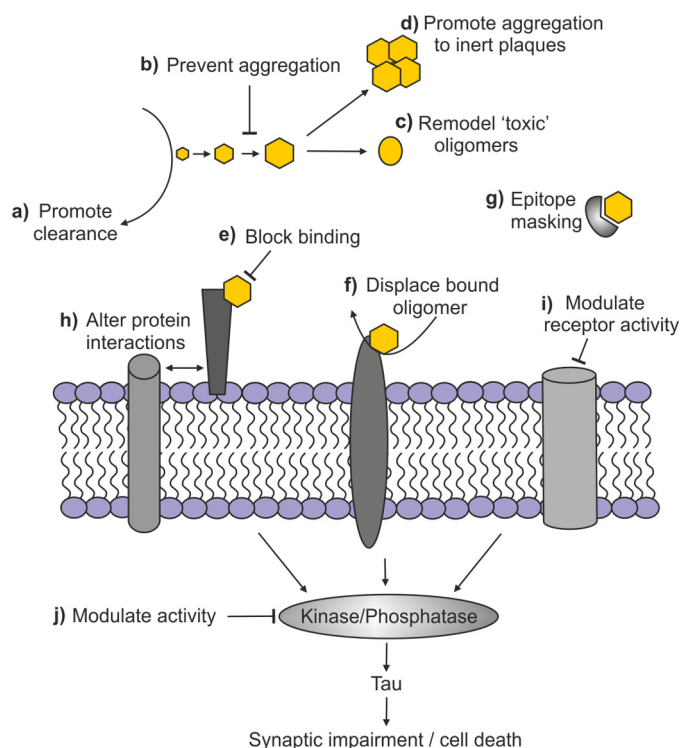
such as reduced cholesterol, hypoxia, and other cellular activities, and insults that are known to influence the initiation and/or progression of AD, thus influencing  $A\beta$  binding and the downstream signaling pathways that are activated.

Does the  $A\beta$ -promoted clustering of receptors lead to the induction of aberrant neurotoxic signaling (53) or over-stimulation of a physiological pathway (for example, due to prolonged stabilization of an otherwise transient complex involved in normal signaling processes), *i.e.* gain of toxic function? Or is it the hijacking of the signaling platform by  $A\beta$  that disrupts normal physiological signaling, *i.e.* loss of function? Or a combination of these that leads to the neurotoxicity apparent in AD? The amount and/or activity of, and interactions between, individual signaling platform components are likely finely balanced. Either an increase or a decrease in a particular component or an alteration in the interaction between components may be sufficient for  $A\beta$  to trigger neurotoxicity. It is possible that it is the binding of different  $A\beta$  to multiple signaling platforms that initiates the complex series of events underlying AD. Following on from this, in the transgenic mouse models that predominantly produce only one type of  $A\beta$  (19), not all of these signaling platforms will be engaged, resulting in activation of only some of the downstream signaling pathways and thus not recapitulating the complete array of molecular, cellular, and pathological responses seen in the human disease.

### Therapeutic Approaches to Blocking $A\beta$ Action

$A\beta$  and their cell surface receptors provide a multitude of potential therapeutic targets (Fig. 3). For example, the accumulation of the “toxic”  $A\beta$  could be prevented by blocking their formation, promoting their aggregation into larger order “inert” fibrils or plaques, altering their conformation, or inducing their clearance or degradation (Fig. 3, *a–d*). Immunotherapy is being actively explored as a potential means to reduce  $A\beta$  levels in the brain, although results from several clinical trials have been disappointing (61). Whether natural antibodies or other antibody preparations that bind to conformational epitopes on  $A\beta$  and are therefore selective for  $A\beta$  over other forms of  $A\beta$  will be more effective than antibodies that recognize peptide epitopes and thus bind both monomeric and oligomeric forms of  $A\beta$  awaits to be seen (62–64). The polyphenols, resveratrol and (–)epigallocatechin-gallate (EGCG) convert soluble  $A\beta$  into non-toxic aggregates (65, 66) whose binding to PrP<sup>C</sup> is severely impaired and which no longer activate Fyn (21). Another natural compound, brazilin, has recently been identified to potently remodel mature fibrils, preventing the formation of toxic oligomers by secondary nucleation (67). As clearance of  $A\beta$  across the BBB may be impaired in AD (68), approaches to increase transcytosis of  $A\beta$  out of the brain may hold potential. In this respect, a soluble form of LRP1 promoted  $A\beta$  clearance in a transgenic AD mouse model (69).

Another approach is to prevent the initial interaction of  $A\beta$  with its receptor or to displace  $A\beta$  that are already bound (Fig. 3, *e* and *f*). Following identification of PrP<sup>C</sup> as a high affinity receptor for  $A\beta$  (43), immuno-targeting of PrP<sup>C</sup> was shown to block completely the LTP impairments caused by  $A\beta$  derived from human AD brain extracts (70, 71), and intra-cerebral infusion of an anti-PrP<sup>C</sup> monoclonal antibody reversed the memory



**FIGURE 3. Potential targets for therapeutic intervention in  $A\beta$  oligomer receptor signaling platforms.** The toxic actions of  $A\beta$  can be prevented by multiple approaches. Their accumulation can be prevented by promoting the clearance/degradation of  $A\beta$  monomers (*a*), preventing aggregation (*b*), remodeling “toxic” conformations (*c*), or promoting aggregation to inert fibrils or plaques (*d*).  $A\beta$  action at the cell surface can be targeted by blocking their binding to receptors (*e*), displacing bound  $A\beta$  (*f*), or masking the epitope on the oligomers to prevent binding to their receptor (*g*). The receptors themselves can be targeted either by preventing aberrant clustering of receptors mediated by  $A\beta$  (*h*) or by allosterically modulating receptor activity (*i*). Downstream signaling of  $A\beta$  can be targeted by modulating kinase/phosphatase activity (*j*) in the downstream signal transduction pathways. See text for specific examples of each.

impairments in a transgenic AD mouse model (72). Recently, the small molecule Chicago Sky Blue 6B was identified in a high-throughput screen to bind to PrP<sup>C</sup> and inhibit  $A\beta$  binding (73). Sigma-2/PGRMC1 was identified as a receptor mediating the binding and toxicity of both brain-derived and synthetically prepared  $A\beta$  following the screening of a library of CNS drug-like small molecules that blocked  $A\beta$ -induced deficits (74). The compounds identified were ligands for Sigma-2/PGRMC1 and prevented  $A\beta$  from binding to primary hippocampal neurons and also displaced bound oligomeric species. The small molecule rhynchophylline was identified as a novel inhibitor of EphA4, which blocked the ligand-binding domain of EphA4 and rescued  $A\beta$ -induced deficits (75). Surface epitope masking peptides have recently been shown to prevent ASPD interacting with NaK $\alpha$ 3 (38) (Fig. 3g). Tetrapeptides mimicking the binding region of this receptor bound to the surface of ASPD, subsequently blocking their interaction with the receptor and preventing ASPD-induced impairments but without affecting the normal function of the Na<sup>+</sup>/K<sup>+</sup>ATPase (38).

Complete blocking of receptors may have deleterious effects on neuronal function; however, modulating receptor activity is another potential approach to abrogate  $A\beta$  action (76) (Fig.

3*h*). Antagonism of the mGluR5 receptor using negative allosteric modulators prevented AβO-induced spine loss and cognitive deficits in transgenic mice (48). The Sigma-2/PGRMC1 ligands also acted as allosteric antagonists for the receptor, preventing aberrant signaling, as well as the subsequent spine loss and cognitive impairments in AD transgenic mice (77). Another approach is to target the downstream signal transduction pathways activated upon AβO binding to its receptors (Fig. 3*i*). For example, given that AβO binding to PrP<sup>C</sup> activates Fyn, a Phase 1b trial of a potent small molecule inhibitor of Src and Fyn for the treatment of AD is underway (78). Ultimately, a combined therapeutic approach, targeting more than one AβO species, its receptor(s), and/or its downstream signaling pathway, will likely be required to alleviate all the neurotoxic effects of the multiple oligomeric forms of Aβ.

### Concluding Remarks

Although much progress has been made in identifying Aβ receptors, several questions remain unanswered. How many distinct AβO receptors and signaling platforms are there? What is the contribution of each receptor and signaling platform to AβO-mediated toxicity? What are the individual components in each signaling platform, and how do their compositions, as well as the interactions between them, differ between AD and healthy individuals? Are different AβO signaling platforms involved depending on the initial trigger of disease, and what is their spatial and temporal contribution to disease pathogenesis? Given that there are multiple species of AβO, and that some transgenic mouse models appear to have predominantly one type of AβO, each interacting with a distinct set of receptors, what is the most appropriate animal model? How can we target specific signaling platforms for therapeutic intervention in AD without disrupting the normal physiological roles of these signaling complexes? Answers to these questions will come only from further experimental work comparing the binding of defined AβO preparations (characterized on the basis of biophysical and conformational properties) with each of the identified receptors *in situ* on cells and *in vivo* in appropriate animal models. However, the recognition that there are multiple Aβ receptors, binding different forms of Aβ, possibly preferentially in different stages in the development of AD, provides several opportunities for therapeutic intervention as highlighted here. What must also be recognized is that not only are there “bad” Aβ receptors binding oligomeric forms of Aβ and triggering cytotoxicity, but there are also “good” receptors involved in Aβ clearance and metabolism, as well as some like PrP<sup>C</sup> that may play dual roles.

### References

1. Hardy, J. A., and Higgins, G. A. (1992) Alzheimer's disease: the amyloid cascade hypothesis. *Science* **256**, 184–185
2. Musiek, E. S., and Holtzman, D. M. (2015) Three dimensions of the amyloid hypothesis: time, space and 'wingmen'. *Nat. Neurosci.* **18**, 800–806
3. Rushworth, J. V., and Hooper, N. M. (2010) Lipid rafts: linking Alzheimer's amyloid-β production, aggregation, and toxicity at neuronal membranes. *Int. J. Alzheimers Dis.* **2011**, 603052
4. Walsh, D. M., and Selkoe, D. J. (2007) Aβ oligomers: a decade of discovery. *J. Neurochem.* **101**, 1172–1184
5. Ferreira, S. T., and Klein, W. L. (2011) The Aβ oligomer hypothesis for

synapse failure and memory loss in Alzheimer's disease. *Neurobiol. Learn. Mem.* **96**, 529–543

6. Benilova, I., Karran, E., and De Strooper, B. (2012) The toxic Aβ oligomer and Alzheimer's disease: an emperor in need of clothes. *Nat. Neurosci.* **15**, 349–357
7. Lambert, M. P., Barlow, A. K., Chromy, B. A., Edwards, C., Freed, R., Liosatos, M., Morgan, T. E., Rozovsky, I., Trommer, B., Viola, K. L., Wals, P., Zhang, C., Finch, C. E., Krafft, G. A., and Klein, W. L. (1998) Diffusible, nonfibrillar ligands derived from Aβ1–42 are potent central nervous system neurotoxins. *Proc. Natl. Acad. Sci. U.S.A.* **95**, 6448–6453
8. Li, S., Jin, M., Koeglsperger, T., Shepardson, N. E., Shankar, G. M., and Selkoe, D. J. (2011) Soluble Aβ oligomers inhibit long-term potentiation through a mechanism involving excessive activation of extrasynaptic NR2B-containing NMDA receptors. *J. Neurosci.* **31**, 6627–6638
9. Lesné, S., Koh, M. T., Kotilinek, L., Kaye, R., Glabe, C. G., Yang, A., Gallagher, M., and Ashe, K. H. (2006) A specific amyloid-β protein assembly in the brain impairs memory. *Nature* **440**, 352–357
10. Shankar, G. M., Li, S., Mehta, T. H., Garcia-Munoz, A., Shepardson, N. E., Smith, I., Brett, F. M., Farrell, M. A., Rowan, M. J., Lemere, C. A., Regan, C. M., Walsh, D. M., Sabatini, B. L., and Selkoe, D. J. (2008) Amyloid-β protein dimers isolated directly from Alzheimer's brains impair synaptic plasticity and memory. *Nat. Med.* **14**, 837–842
11. Hepler, R. W., Grimm, K. M., Nahas, D. D., Breese, R., Dodson, E. C., Acton, P., Keller, P. M., Yeager, M., Wang, H., Shughrue, P., Kinney, G., and Joyce, J. G. (2006) Solution state characterization of amyloid β-derived diffusible ligands. *Biochemistry* **45**, 15157–15167
12. Glabe, C. G. (2008) Structural classification of toxic amyloid oligomers. *J. Biol. Chem.* **283**, 29639–29643
13. Kaye, R., Head, E., Sarsoza, F., Saing, T., Cotman, C. W., Necula, M., Margol, L., Wu, J., Breydo, L., Thompson, J. L., Rasool, S., Gurlo, T., Butler, P., and Glabe, C. G. (2007) Fibril specific, conformation dependent antibodies recognize a generic epitope common to amyloid fibrils and fibrillar oligomers that is absent in prefibrillar oligomers. *Mol. Neurodegener.* **2**, 18
14. Laganowsky, A., Liu, C., Sawaya, M. R., Whitelegge, J. P., Park, J., Zhao, M., Pensalfini, A., Soriaga, A. B., Landau, M., Teng, P. K., Cascio, D., Glabe, C., and Eisenberg, D. (2012) Atomic view of a toxic amyloid small oligomer. *Science* **335**, 1228–1231
15. Liu, C., Zhao, M., Jiang, L., Cheng, P. N., Park, J., Sawaya, M. R., Pensalfini, A., Gou, D., Berk, A. J., Glabe, C. G., Nowick, J., and Eisenberg, D. (2012) Out-of-register β-sheets suggest a pathway to toxic amyloid aggregates. *Proc. Natl. Acad. Sci. U.S.A.* **109**, 20913–20918
16. Liu, P., Reed, M. N., Kotilinek, L. A., Grant, M. K., Forster, C. L., Qiang, W., Shapiro, S. L., Reichl, J. H., Chiang, A. C., Jankowsky, J. L., Wilmot, C. M., Cleary, J. P., Zaks, K. R., and Ashe, K. H. (2015) Quaternary structure defines a large class of amyloid-β oligomers neutralized by sequestration. *Cell Rep.* **11**, 1760–1771
17. Tomic, J. L., Pensalfini, A., Head, E., and Glabe, C. G. (2009) Soluble fibrillar oligomer levels are elevated in Alzheimer's disease brain and correlate with cognitive dysfunction. *Neurobiol. Dis.* **35**, 352–358
18. Chabrier, M. A., Blurton-Jones, M., Agazaryan, A. A., Nerhus, J. L., Martinez-Coria, H., and LaFerla, F. M. (2012) Soluble Aβ promotes wild-type tau pathology *in vivo*. *J. Neurosci.* **32**, 17345–17350
19. Kostylev, M. A., Kaufman, A. C., Nygaard, H. B., Patel, P., Haas, L. T., Gunther, E. C., Vortmeyer, A., and Strittmatter, S. M. (2015) Prion-protein-interacting amyloid-β oligomers of high molecular weight are tightly correlated with memory impairment in multiple Alzheimer mouse models. *J. Biol. Chem.* **290**, 17415–17438
20. Um, J. W., Nygaard, H. B., Heiss, J. K., Kostylev, M. A., Stagi, M., Vortmeyer, A., Wisniewski, T., Gunther, E. C., and Strittmatter, S. M. (2012) Alzheimer amyloid-β oligomer bound to postsynaptic prion protein activates Fyn to impair neurons. *Nat. Neurosci.* **15**, 1227–1235
21. Rushworth, J. V., Griffiths, H. H., Watt, N. T., and Hooper, N. M. (2013) Prion protein-mediated toxicity of amyloid-β oligomers requires lipid rafts and the transmembrane LRP1. *J. Biol. Chem.* **288**, 8935–8951
22. Nicoll, A. J., Panico, S., Freir, D. B., Wright, D., Terry, C., Risse, E., Heron, C. E., O'Malley, T., Wadsworth, J. D., Farrow, M. A., Walsh, D. M., Saibil, H. R., and Collinge, J. (2013) Amyloid-β nanotubes are associated

- with prion protein-dependent synaptotoxicity. *Nat. Commun.* **4**, 2416
23. Inoue, S. (2008) *In situ* A $\beta$  pores in AD brain are cylindrical assembly of A $\beta$  protofilaments. *Amyloid* **15**, 223–233
  24. Demuro, A., Smith, M., and Parker, I. (2011) Single-channel Ca<sup>2+</sup> imaging implicates A $\beta$ 1–42 amyloid pores in Alzheimer's disease pathology. *J. Cell Biol.* **195**, 515–524
  25. Shibata, M., Yamada, S., Kumar, S. R., Calero, M., Bading, J., Frangione, B., Holtzman, D. M., Miller, C. A., Strickland, D. K., Ghiso, J., and Zlokovic, B. V. (2000) Clearance of Alzheimer's amyloid- $\beta$ 1–40 peptide from brain by LDL receptor-related protein-1 at the blood-brain barrier. *J. Clin. Invest.* **106**, 1489–1499
  26. Kanekiyo, T., Liu, C. C., Shinohara, M., Li, J., and Bu, G. (2012) LRP1 in brain vascular smooth muscle cells mediates local clearance of Alzheimer's amyloid- $\beta$ . *J. Neurosci.* **32**, 16458–16465
  27. Kanekiyo, T., Cirrito, J. R., Liu, C.-C., Shinohara, M., Li, J., Schuler, D. R., Shinohara, M., Holtzman, D. M., and Bu, G. (2013) Neuronal clearance of amyloid- $\beta$  by endocytic receptor LRP1. *J. Neurosci.* **33**, 19276–19283
  28. Zhao, Z., Sagare, A. P., Ma, Q., Halliday, M. R., Kong, P., Kisler, K., Winkler, E. A., Ramanathan, A., Kanekiyo, T., Bu, G., Owens, N. C., Rege, S. V., Si, G., Ahuja, A., Zhu, D., Miller, C. A., Schneider, J. A., Maeda, M., Maeda, T., Sugawara, T., Ichida, J. K., and Zlokovic, B. V. (2015) Central role for PICALM in amyloid- $\beta$  blood-brain barrier transcytosis and clearance. *Nat. Neurosci.* **18**, 978–987
  29. Pflanzner, T., Petsch, B., André-Dohmen, B., Müller-Schiffmann, A., Tschickardt, S., Weggen, S., Stitz, L., Korth, C., and Pietrzik, C. U. (2012) Cellular prion protein participates in amyloid- $\beta$  transcytosis across the blood-brain barrier. *J. Cereb. Blood Flow. Metab.* **32**, 628–632
  30. Castellano, J. M., Deane, R., Gottesdiener, A. J., Verghese, P. B., Stewart, F. R., West, T., Paoletti, A. C., Kasper, T. R., DeMattos, R. B., Zlokovic, B. V., and Holtzman, D. M. (2012) Low-density lipoprotein receptor overexpression enhances the rate of brain-to-blood A $\beta$  clearance in a mouse model of  $\beta$ -amyloidosis. *Proc. Natl. Acad. Sci. U.S.A.* **109**, 15502–15507
  31. Liu, C. C., Kanekiyo, T., Xu, H., and Bu, G. (2013) Apolipoprotein E and Alzheimer disease: risk, mechanisms and therapy. *Nat. Rev. Neurol.* **9**, 106–118
  32. Wilkinson, K., and El Khoury, J. (2012) Microglial scavenger receptors and their roles in the pathogenesis of Alzheimer's disease. *Int. J. Alzheimers Dis.* **2012**, 489456
  33. Brandenburg, L. O., Konrad, M., Wruck, C. J., Koch, T., Lucius, R., and Pufe, T. (2010) Functional and physical interactions between formyl-peptide-receptors and scavenger receptor MARCO and their involvement in amyloid  $\beta$ 1–42-induced signal transduction in glial cells. *J. Neurochem.* **113**, 749–760
  34. Nalivaeva, N. N., Belyaev, N. D., Kerridge, C., and Turner, A. J. (2014) Amyloid-clearing proteins and their epigenetic regulation as a therapeutic target in Alzheimer's disease. *Front. Aging Neurosci.* **6**, 235
  35. Deane, R., Du Yan, S., Subramanian, R. K., LaRue, B., Jovanovic, S., Hogg, E., Welch, D., Manness, L., Lin, C., Yu, J., Zhu, H., Ghiso, J., Frangione, B., Stern, A., Schmidt, A. M., Armstrong, D. L., Arnold, B., Lilien-siek, B., Nawroth, P., Hofman, F., Kindy, M., Stern, D., and Zlokovic, B. (2003) RAGE mediates amyloid- $\beta$  peptide transport across the blood-brain barrier and accumulation in brain. *Nat. Med.* **9**, 907–913
  36. Takuma, K., Fang, F., Zhang, W., Yan, S., Fukuzaki, E., Du, H., Sosunov, A., McKhann, G., Funatsu, Y., Nakamichi, N., Nagai, T., Mizoguchi, H., Ibi, D., Hori, O., Ogawa, S., Stern, D. M., Yamada, K., and Yan, S. S. (2009) RAGE-mediated signaling contributes to intraneuronal transport of amyloid- $\beta$  and neuronal dysfunction. *Proc. Natl. Acad. Sci. U.S.A.* **106**, 20021–20026
  37. Huang, Y., and Mahley, R. W. (2014) Apolipoprotein E: structure and function in lipid metabolism, neurobiology, and Alzheimer's diseases. *Neurobiol. Dis.* **72**, 3–12
  38. Ohnishi, T., Yanazawa, M., Sasahara, T., Kitamura, Y., Hiroaki, H., Fukazawa, Y., Kii, I., Nishiyama, T., Kakita, A., Takeda, H., Takeuchi, A., Arai, Y., Ito, A., Komura, H., Hirao, H., Satomura, K., Inoue, M., Muramatsu, S., Matsui, K., Tada, M., Sato, M., Saijo, E., Shigemitsu, Y., Sakai, S., Umetsu, Y., Goda, N., Takino, N., Takahashi, H., Hagiwara, M., Sawasaki, T., Iwasaki, G., Nakamura, Y., Nabeshima, Y., Teplow, D. B., and Hoshi, M. (2015) Na,K-ATPase  $\alpha$ 3 is a death target of Alzheimer patient amyloid- $\beta$  assembly. *Proc. Natl. Acad. Sci. U.S.A.* **112**, E4465–E4474
  39. Overk, C. R., and Masliah, E. (2014) Toward a unified therapeutics approach targeting putative amyloid- $\beta$  oligomer receptors. *Proc. Natl. Acad. Sci. U.S.A.* **111**, 13680–13681
  40. Benilova, I., and De Strooper, B. (2013) Promiscuous Alzheimer's amyloid: yet another partner. *Science* **341**, 1354–1355
  41. Viola, K. L., and Klein, W. L. (2015) Amyloid  $\beta$  oligomers in Alzheimer's disease pathogenesis, treatment, and diagnosis. *Acta Neuropathol.* **129**, 183–206
  42. Marin, R. (2011) Signalosomes in the brain: relevance in the development of certain neuropathologies such as Alzheimer's disease. *Front. Physiol.* **2**, 23
  43. Laurén, J., Gimbel, D. A., Nygaard, H. B., Gilbert, J. W., and Strittmatter, S. M. (2009) Cellular prion protein mediates impairment of synaptic plasticity by amyloid- $\beta$  oligomers. *Nature* **457**, 1128–1132
  44. Chen, S., Yadav, S. P., and Surewicz, W. K. (2010) Interaction between human prion protein and amyloid- $\beta$  (A $\beta$ ) oligomers. *J. Biol. Chem.* **285**, 26377–26383
  45. Dohler, F., Sepulveda-Falla, D., Krasemann, S., Altmepfen, H., Schlüter, H., Hildebrand, D., Zerr, I., Matschke, J., and Glatzel, M. (2014) High molecular mass assemblies of amyloid- $\beta$  oligomers bind prion protein in patients with Alzheimer's disease. *Brain* **137**, 873–886
  46. Gimbel, D. A., Nygaard, H. B., Coffey, E. E., Gunther, E. C., Laurén, J., Gimbel, Z. A., and Strittmatter, S. M. (2010) Memory impairment in transgenic Alzheimer mice requires cellular prion protein. *J. Neurosci.* **30**, 6367–6374
  47. Larson, M., Sherman, M. A., Amar, F., Nuvolone, M., Schneider, J. A., Bennett, D. A., Aguzzi, A., and Lesné, S. E. (2012) The complex PrP<sup>C</sup>-Fyn couples human oligomeric A $\beta$  with pathological Tau changes in Alzheimer's disease. *J. Neurosci.* **32**, 16857–16871
  48. Um, J. W., Kaufman, A. C., Kostylev, M., Heiss, J. K., Stagi, M., Takahashi, H., Kerrisk, M. E., Vortmeyer, A., Wisniewski, T., Koleske, A. J., Gunther, E. C., Nygaard, H. B., and Strittmatter, S. M. (2013) Metabotropic glutamate receptor 5 is a coreceptor for Alzheimer A $\beta$  oligomer bound to cellular prion protein. *Neuron* **79**, 887–902
  49. Walmsley, A. R., Zeng, F., and Hooper, N. M. (2003) The N-terminal region of the prion protein ectodomain contains a lipid raft targeting determinant. *J. Biol. Chem.* **278**, 37241–37248
  50. Taylor, D. R., Whitehouse, I. J., and Hooper, N. M. (2009) Glypican-1 mediates both prion protein lipid raft association and disease isoform formation. *PLoS Pathog.* **5**, e1000666
  51. Linden, R., Martins, V. R., Prado, M. A., Cammarota, M., Izquierdo, I., and Brentani, R. R. (2008) Physiology of the prion protein. *Physiol. Rev.* **88**, 673–728
  52. Solis, G. P., Malaga-Trillo, E., Plattner, H., and Stuermer, C. A. (2010) Cellular roles of the prion protein in association with reggie/flotillin microdomains. *Front. Biosci. (Landmark Ed.)* **15**, 1075–1085
  53. Renner, M., Lacor, P. N., Velasco, P. T., Xu, J., Contractor, A., Klein, W. L., and Triller, A. (2010) Deleterious effects of amyloid  $\beta$  oligomers acting as an extracellular scaffold for mGluR5. *Neuron* **66**, 739–754
  54. Khan, G. M., Tong, M., Jhun, M., Arora, K., and Nichols, R. A. (2010)  $\beta$ -Amyloid activates presynaptic  $\alpha$ 7 nicotinic acetylcholine receptors reconstituted into a model nerve cell system: involvement of lipid rafts. *Eur. J. Neurosci.* **31**, 788–796
  55. Lacor, P. N., Buniel, M. C., Furlow, P. W., Clemente, A. S., Velasco, P. T., Wood, M., Viola, K. L., and Klein, W. L. (2007) A $\beta$  oligomer-induced aberrations in synapse composition, shape, and density provide a molecular basis for loss of connectivity in Alzheimer's disease. *J. Neurosci.* **27**, 796–807
  56. Shankar, G. M., Bloodgood, B. L., Townsend, M., Walsh, D. M., Selkoe, D. J., and Sabatini, B. L. (2007) Natural oligomers of the Alzheimer amyloid- $\beta$  protein induce reversible synapse loss by modulating an NMDA-type glutamate receptor-dependent signaling pathway. *J. Neurosci.* **27**, 2866–2875
  57. De Felice, F. G., Velasco, P. T., Lambert, M. P., Viola, K., Fernandez, S. J., Ferreira, S. T., and Klein, W. L. (2007) A $\beta$  oligomers induce neuronal oxidative stress through an N-methyl-D-aspartate receptor-dependent



- mechanism that is blocked by the Alzheimer drug Memantine. *J. Biol. Chem.* **282**, 11590–11601
58. Cissé, M., Halabisky, B., Harris, J., Davidze, N., Dubal, D. B., Sun, B., Orr, A., Lotz, G., Kim, D. H., Hamto, P., Ho, K., Yu, G.-Q., and Mucke, L. (2011) Reversing EphB2 depletion rescues cognitive functions in Alzheimer model. *Nature* **469**, 47–52
  59. Snyder, E. M., Nong, Y., Almeida, C. G., Paul, S., Moran, T., Choi, E. Y., Nairn, A. C., Salter, M. W., Lombroso, P. J., Gouras, G. K., and Greengard, P. (2005) Regulation of NMDA receptor trafficking by amyloid- $\beta$ . *Nat. Neurosci.* **8**, 1051–1058
  60. Noguchi, A., Matsumura, S., Dezawa, M., Tada, M., Yanazawa, M., Ito, A., Akioka, M., Kikuchi, S., Sato, M., Ideno, S., Noda, M., Fukunari, A., Muramatsu, S.-i., Itokazu, Y., Sato, K., Takahashi, H., Teplow, D. B., Nabeshima, Y.-i., Kakita, A., Imahori, K., and Hoshi, M. (2009) Isolation and characterization of patient-derived, toxic, high mass amyloid  $\beta$ -protein ( $A\beta$ ) assembly from Alzheimer disease brains. *J. Biol. Chem.* **284**, 32895–32905
  61. Siemers, E. R., Sundell, K. L., Carlson, C., Case, M., Sethuraman, G., Liu-Seifert, H., Dowsett, S. A., Pontecorvo, M. J., Dean, R. A., and Demattos, R. (2015) Phase 3 solanezumab trials: secondary outcomes in mild Alzheimer's disease patients. *Alzheimers Dement.* 10.1016/j.jalz.2015.06.1893
  62. Britschgi, M., Olin, C. E., Johns, H. T., Takeda-Uchimura, Y., LeMieux, M. C., Rufibach, K., Rajadas, J., Zhang, H., Tomooka, B., Robinson, W. H., Clark, C. M., Fagan, A. M., Galasko, D. R., Holtzman, D. M., Jutel, M., Kaye, J. A., Lemere, C. A., Leszek, J., Li, G., Peskind, E. R., Quinn, J. F., Yesavage, J. A., Ghiso, J. A., and Wyss-Coray, T. (2009) Neuroprotective natural antibodies to assemblies of amyloidogenic peptides decrease with normal aging and advancing Alzheimer's disease. *Proc. Natl. Acad. Sci. U.S.A.* **106**, 12145–12150
  63. Goure, W. F., Krafft, G. A., Jerecic, J., and Hefti, F. (2014) Targeting the proper amyloid- $\beta$  neuronal toxins: a path forward for Alzheimer's disease immunotherapeutics. *Alzheimers Res. Ther.* **6**, 42
  64. Bodani, R. U., Sengupta, U., Castillo-Carranza, D. L., Guerrero-Muñoz, M. J., Gerson, J. E., Rudra, J., and Kaye, R. (2015) Antibody against small aggregated peptide specifically recognizes toxic  $A\beta$ -42 oligomers in Alzheimer's disease. *ACS Chem. Neurosci.* **6**, 1981–1989
  65. Ladiwala, A. R. A., Lin, J. C., Bale, S. S., Marcelino-Cruz, A. M., Bhat-tacharya, M., Dordick, J. S., and Tessier, P. M. (2010) Resveratrol selectively remodels soluble oligomers and fibrils of amyloid  $A\beta$  into off-pathway conformers. *J. Biol. Chem.* **285**, 24228–24237
  66. Bieschke, J., Russ, J., Friedrich, R. P., Ehrnhoefer, D. E., Wobst, H., Neugebauer, K., and Wanker, E. E. (2010) EGCG remodels mature  $\alpha$ -synuclein and amyloid- $\beta$  fibrils and reduces cellular toxicity. *Proc. Natl. Acad. Sci. U.S.A.* **107**, 7710–7715
  67. Du, W. J., Guo, J. J., Gao, M. T., Hu, S. Q., Dong, X. Y., Han, Y. F., Liu, F. F., Jiang, S., and Sun, Y. (2015) Brazilin inhibits amyloid  $\beta$ -protein fibrillogenesis, remodels amyloid fibrils and reduces amyloid cytotoxicity. *Sci. Rep.* **5**, 7992
  68. Tarasoff-Conway, J. M., Carare, R. O., Osorio, R. S., Glodzik, L., Butler, T., Fieremans, E., Axel, L., Rusinek, H., Nicholson, C., Zlokovic, B. V., Frangione, B., Blennow, K., Ménard, J., Zetterberg, H., Wisniewski, T., and de Leon, M. J. (2015) Clearance systems in the brain: implications for Alzheimer disease. *Nat. Rev. Neurol.* **11**, 457–470
  69. Sagare, A. P., Bell, R. D., Srivastava, A., Sengillo, J. D., Singh, I., Nishida, Y., Chow, N., and Zlokovic, B. V. (2013) A lipoprotein receptor cluster IV mutant preferentially binds amyloid- $\beta$  and regulates its clearance from the mouse brain. *J. Biol. Chem.* **288**, 15154–15166
  70. Barry, A. E., Klyubin, I., Mc Donald, J. M., Mably, A. J., Farrell, M. A., Scott, M., Walsh, D. M., and Rowan, M. J. (2011) Alzheimer's disease brain-derived amyloid- $\beta$ -mediated inhibition of LTP *in vivo* is prevented by immunotargeting cellular prion protein. *J. Neurosci.* **31**, 7259–7263
  71. Freir, D. B., Nicoll, A. J., Klyubin, I., Panico, S., Mc Donald, J. M., Risse, E., Asante, E. A., Farrow, M. A., Sessions, R. B., Saibil, H. R., Clarke, A. R., Rowan, M. J., Walsh, D. M., and Collinge, J. (2011) Interaction between prion protein and toxic amyloid  $\beta$  assemblies can be therapeutically targeted at multiple sites. *Nat. Commun.* **2**, 336
  72. Chung, E., Ji, Y., Sun, Y., Kasczak, R. J., Kasczak, R. B., Mehta, P. D., Strittmatter, S. M., and Wisniewski, T. (2010) Anti-PrP<sup>C</sup> monoclonal antibody infusion as a novel treatment for cognitive deficits in an Alzheimer's disease model mouse. *BMC Neurosci.* **11**, 130
  73. Risse, E., Nicoll, A. J., Taylor, W. A., Wright, D., Badoni, M., Yang, X., Farrow, M. A., and Collinge, J. (2015) Identification of a compound that disrupts binding of amyloid- $\beta$  to the prion protein using a novel fluorescence-based assay. *J. Biol. Chem.* **290**, 17020–17028
  74. Izzo, N. J., Xu, J., Zeng, C., Kirk, M. J., Mozzoni, K., Silky, C., Rehak, C., Yurko, R., Look, G., Rishton, G., Safferstein, H., Cruchaga, C., Goate, A., Cahill, M. A., Arancio, O., Mach, R. H., Craven, R., Head, E., LeVine, H., 3rd, Spires-Jones, T. L., and Catalano, S. M. (2014) Alzheimer's therapeutics targeting amyloid  $\beta$ 1–42 oligomers II: Sigma-2/PGRMC1 receptors mediate  $A\beta$ 42 oligomer binding and synaptotoxicity. *PLoS ONE* **9**, e111899
  75. Fu, A. K., Hung, K. W., Huang, H., Gu, S., Shen, Y., Cheng, E. Y., Ip, F. C., Huang, X., Fu, W. Y., and Ip, N. Y. (2014) Blockade of EphA4 signaling ameliorates hippocampal synaptic dysfunctions in mouse models of Alzheimer's disease. *Proc. Natl. Acad. Sci. U.S.A.* **111**, 9959–9964
  76. Rammes, G., Hasenjäger, A., Sroka-Saidi, K., Deussing, J. M., and Parsons, C. G. (2011) Therapeutic significance of NR2B-containing NMDA receptors and mGluR5 metabotropic glutamate receptors in mediating the synaptotoxic effects of  $\beta$ -amyloid oligomers on long-term potentiation (LTP) in murine hippocampal slices. *Neuropharmacology* **60**, 982–990
  77. Izzo, N. J., Staniszewski, A., To, L., Fa, M., Teich, A. F., Saeed, F., Wostein, H., Walko, T., 3rd, Vaswani, A., Wardius, M., Syed, Z., Ravenscroft, J., Mozzoni, K., Silky, C., Rehak, C., Yurko, R., Finn, P., Look, G., Rishton, G., Safferstein, H., Miller, M., Johanson, C., Stopa, E., Windisch, M., Hutter-Paier, B., Shamloo, M., Arancio, O., LeVine, H., 3rd, and Catalano, S. M. (2014) Alzheimer's therapeutics targeting amyloid  $\beta$ 1–42 oligomers I:  $A\beta$ 42 oligomer binding to specific neuronal receptors is displaced by drug candidates that improve cognitive deficits. *PLoS ONE* **9**, e111898
  78. Nygaard, H. B., van Dyck, C. H., and Strittmatter, S. M. (2014) Fyn kinase inhibition as a novel therapy for Alzheimer's disease. *Alzheimers Res. Ther.* **6**, 8
  79. Puzzo, D., Privitera, L., Leznik, E., Fà, M., Staniszewski, A., Palmeri, A., and Arancio, O. (2008) Picomolar amyloid- $\beta$  positively modulates synaptic plasticity and memory in hippocampus. *J. Neurosci.* **28**, 14537–14545
  80. Narayan, P., Meehan, S., Carver, J. A., Wilson, M. R., Dobson, C. M., and Klenerman, D. (2012) Amyloid- $\beta$  oligomers are sequestered by both intracellular and extracellular chaperones. *Biochemistry* **51**, 9270–9276
  81. Doens, D., and Fernández, P. L. (2014) Microglia receptors and their implications in the response to amyloid  $\beta$  for Alzheimer's disease pathogenesis. *J. Neuroinflammation* **11**, 48
  82. Kanekiyo, T., Zhang, J., Liu, Q., Liu, C.-C., Zhang, L., and Bu, G. (2011) Heparan sulphate proteoglycan and the low-density lipoprotein receptor-related protein 1 constitute major pathways for neuronal amyloid- $\beta$  uptake. *J. Neurosci.* **31**, 1644–1651
  83. Basak, J. M., Verghese, P. B., Yoon, H., Kim, J., and Holtzman, D. M. (2012) Low-density lipoprotein receptor represents an apolipoprotein E-independent pathway of  $A\beta$  uptake and degradation by astrocytes. *J. Biol. Chem.* **287**, 13959–13971
  84. Husemann, J., Loike, J. D., Kodama, T., and Silverstein, S. C. (2001) Scavenger receptor class B type I (SR-BI) mediates adhesion of neonatal murine microglia to fibrillar  $\beta$ -amyloid. *J. Neuroimmunol.* **114**, 142–150
  85. Parri, H. R., Hernandez, C. M., and Dineley, K. T. (2011) Research update:  $\alpha$ 7 nicotinic acetylcholine receptor mechanisms in Alzheimer's disease. *Biochem. Pharmacol.* **82**, 931–942
  86. Zhao, W. Q., Santini, F., Breese, R., Ross, D., Zhang, X. D., Stone, D. J., Ferrer, M., Townsend, M., Wolfe, A. L., Seager, M. A., Kinney, G. G., Shughrae, P. J., and Ray, W. J. (2010) Inhibition of calcineurin-mediated endocytosis and  $\alpha$ -amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid (AMPA) receptors prevents amyloid  $\beta$  oligomer-induced synaptic disruption. *J. Biol. Chem.* **285**, 7619–7632
  87. Fu, W., Ruangkittisakul, A., MacTavish, D., Shi, J. Y., Ballanyi, K., and Jhamandas, J. H. (2012) Amyloid  $\beta$  ( $A\beta$ ) peptide directly activates amylin-3 receptor subtype by triggering multiple intracellular signaling path-

- ways. *J. Biol. Chem.* **287**, 18820–18830
88. Garai, K., Verghese, P. B., Baban, B., Holtzman, D. M., and Frieden, C. (2014) The binding of apolipoprotein E to oligomers and fibrils of amyloid- $\beta$  alters the kinetics of amyloid aggregation. *Biochemistry* **53**, 6323–6331
  89. Wang, D., Govindaiah, G., Liu, R., De Arcangelis, V., Cox, C. L., and Xiang, Y. K. (2010) Binding of amyloid  $\beta$  peptide to  $\beta$ 2 adrenergic receptor induces PKA-dependent AMPA receptor hyperactivity. *FASEB J.* **24**, 3511–3521
  90. Killick, R., Ribe, E. M., Al-Shawi, R., Malik, B., Hooper, C., Fernandes, C., Dobson, R., Nolan, P. M., Lourdasamy, A., Furney, S., Lin, K., Breen, G., Wroe, R., To, A. W., Leroy, K., Causevic, M., Usardi, A., Robinson, M., Noble, W., Williamson, R., Lunnon, K., Kellie, S., Reynolds, C. H., Bazenot, C., Hodges, A., Brion, J. P., Stephenson, J., Simons, J. P., and Lovestone, S. (2014) Clusterin regulates  $\beta$ -amyloid toxicity via Dickkopf-1-driven induction of the wnt-PCP-JNK pathway. *Mol. Psychiatry* **19**, 88–98
  91. Vargas, L. M., Leal, N., Estrada, L. D., González, A., Serrano, F., Araya, K., Gysling, K., Inestrosa, N. C., Pasquale, E. B., and Alvarez, A. R. (2014) EphA4 activation of c-Abl mediates synaptic loss and LTP blockade caused by amyloid- $\beta$  oligomers. *PLoS ONE* **9**, e92309
  92. Kam, T. I., Song, S., Gwon, Y., Park, H., Yan, J. J., Im, I., Choi, J. W., Choi, T. Y., Kim, J., Song, D. K., Takai, T., Kim, Y. C., Kim, K. S., Choi, S. Y., Choi, S., Klein, W. L., Yuan, J., and Jung, Y. K. (2013) Fc $\gamma$ RIIb mediates amyloid- $\beta$  neurotoxicity and memory impairment in Alzheimer's disease. *J. Clin. Invest.* **123**, 2791–2802
  93. Magdesian, M. H., Carvalho, M. M., Mendes, F. A., Saraiva, L. M., Juliano, M. A., Juliano, L., Garcia-Abreu, J., and Ferreira, S. T. (2008) Amyloid- $\beta$  binds to the extracellular cysteine-rich domain of Frizzled and inhibits Wnt/ $\beta$ -catenin signaling. *J. Biol. Chem.* **283**, 9359–9368
  94. De Felice, F. G., Vieira, M. N. N., Bomfim, T. R., Decker, H., Velasco, P. T., Lambert, M. P., Viola, K. L., Zhao, W.-Q., Ferreira, S. T., and Klein, W. L. (2009) Protection of synapses against Alzheimer's-linked toxins: insulin signaling prevents the pathogenic binding of  $A\beta$  oligomers. *Proc. Natl. Acad. Sci. U.S.A.* **106**, 1971–1976
  95. Kim, T., Vidal, G. S., Djuricic, M., William, C. M., Birnbaum, M. E., Garcia, K. C., Hyman, B. T., and Shatz, C. J. (2013) Human LILRB2 is a  $\beta$ -amyloid receptor and its murine homolog PirB regulates synaptic plasticity in an Alzheimer's model. *Science* **341**, 1399–1404
  96. Dinamarca, M. C., Weinstein, D., Monasterio, O., and Inestrosa, N. C. (2011) The synaptic protein neuroligin-1 interacts with the amyloid  $\beta$ -peptide. Is there a role in Alzheimer's disease? *Biochemistry* **50**, 8127–8137
  97. Hashimoto, Y., Kaneko, Y., Tsukamoto, E., Frankowski, H., Kouyama, K., Kita, Y., Niikura, T., Aiso, S., Bredesen, D. E., Matsuoka, M., and Nishimoto, I. (2004) Molecular characterization of neurohybrid cell death induced by Alzheimer's amyloid- $\beta$  peptides via p75NTR/PLAIDD. *J. Neurochem.* **90**, 549–558
  98. Nimmrich, V., Grimm, C., Draguhn, A., Barghorn, S., Lehmann, A., Schoemaker, H., Hillen, H., Gross, G., Ebert, U., and Bruehl, C. (2008) Amyloid  $\beta$  oligomers ( $A\beta$ 1–42 globulomer) suppress spontaneous synaptic activity by inhibition of P/Q-type calcium currents. *J. Neurosci.* **28**, 788–797
  99. Origlia, N., Bonadonna, C., Rosellini, A., Leznik, E., Arancio, O., Yan, S. S., and Domenici, L. (2010) Microglial receptor for advanced glycation end product-dependent signal pathway drives  $\beta$ -amyloid-induced synaptic depression and long-term depression impairment in entorhinal cortex. *J. Neurosci.* **30**, 11414–11425
  100. Stewart, C. R., Stuart, L. M., Wilkinson, K., van Gils, J. M., Deng, J., Halle, A., Rayner, K. J., Boyer, L., Zhong, R., Frazier, W. A., Lacy-Hulbert, A., El Khoury, J., Golenbock, D. T., and Moore, K. J. (2010) CD36 ligands promote sterile inflammation through assembly of a Toll-like receptor 4 and 6 heterodimer. *Nat. Immunol.* **11**, 155–161