

Altered filamin A enables amyloid beta-induced tau hyperphosphorylation and neuroinflammation in Alzheimer's disease

Lindsay H. Burns¹, Hoau-Yan Wang^{2,3}

¹Pain Therapeutics Inc., Austin, TX 78731, USA.

²Department of Physiology, Pharmacology and Neuroscience, City University of New York School of Medicine, New York, NY 10031, USA.

³Department of Biology and Neuroscience, Graduate School of the City University of New York, New York, NY 10031, USA.

Correspondence to: Dr. Lindsay H. Burns, Pain Therapeutics Inc., 7801 N. Capital of Texas Hwy, Ste. 260, Austin, TX 78731, USA.
E-mail: lburns@paintrials.com

How to cite this article: Burns LH, Wang HY. Altered filamin A enables amyloid beta-induced tau hyperphosphorylation and neuroinflammation in Alzheimer's disease. *Neuroimmunol Neuroinflammation* 2017;4:263-71.

ABSTRACT

Article history:

Received: 25 Sep 2017

First Decision: 16 Oct 2017

Revised: 20 Oct 2017

Accepted: 8 Nov 2017

Published: 8 Dec 2017

Key words:

Proteopathy,
hyperphosphorylation,
 $\alpha 7$ nicotinic acetylcholine
receptor,
toll-like receptor 4,
neuroinflammation,
PTI-125

Alzheimer's disease (AD) is a neurodegenerative disease with proteopathy characterized by abnormalities in amyloid beta ($A\beta$) and tau proteins. Defective amyloid and tau propagate and aggregate, leading to eventual amyloid plaques and neurofibrillary tangles. New data show that a third proteopathy, an altered conformation of the scaffolding protein filamin A (FLNA), is critically linked to the amyloid and tau pathologies in AD. Altered FLNA is pervasive in AD brain and without apparent aggregation. In a striking interdependence, altered FLNA is both induced by $A\beta$ and required for two prominent pathogenic signaling pathways of $A\beta$. $A\beta$ monomers or small oligomers signal via the $\alpha 7$ nicotinic acetylcholine receptor ($\alpha 7nAChR$) to activate kinases that hyperphosphorylate tau to cause neurofibrillary lesions and formation of neurofibrillary tangles. Altered FLNA also enables a persistent activation of toll-like-receptor 4 (TLR4) by $A\beta$, leading to excessive inflammatory cytokine release and neuroinflammation. The novel AD therapeutic candidate PTI-125 binds and reverses the altered FLNA conformation to prevent $A\beta$'s signaling via $\alpha 7nAChR$ and aberrant activation of TLR4, thus reducing multiple AD-related neuropathologies. As a regulator of $A\beta$'s signaling via $\alpha 7nAChR$ and TLR4, altered FLNA represents a novel AD therapeutic target.

INTRODUCTION

Alzheimer's disease (AD) is a complex neurodegenerative disease characterized by a variety of synaptic and receptor dysfunctions, neuroinflammation, insulin resistance, degeneration

and atrophy. Although the pathogenesis of AD is debated, the disease itself can be considered a proteopathy, a disease of abnormal proteins, due to the misfolding and aggregation of amyloid beta ($A\beta$) and hyperphosphorylated tau in brain areas critical to cognition and memory. These abnormal proteins



This is an open access article licensed under the terms of Creative Commons Attribution 4.0 International License (<https://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, as long as the original author is credited and the new creations are licensed under the identical terms.

For reprints contact: service@oaepublish.com

Quick Response Code:



ultimately form the histopathological hallmarks of AD brain: amyloid plaques and tau-containing tangles. Misfolded dysfunctional proteins and their aggregation occurs in many other neurodegenerative diseases including Parkinson's disease, dementia with Lewy bodies, multiple systems atrophy, frontotemporal dementia, amyotrophic lateral sclerosis and Huntington's disease^[1-4]. Typically, misfolded proteins self-aggregate, creating intracellular inclusions that become extracellular deposits following cell death. In many cases, misfolded proteins propagate in a cell-to-cell "prion-like" manner^[1-3,5].

The proteopathy of A β in AD is an amyloidosis, meaning the protein converts from an α -helix-rich state to a β -sheet conformation. To enter an amyloid or β -sheet state, proteins must expose the backbone amide N-H and C=O groups to allow hydrogen bonding^[4]. Cleavage of amyloid precursor protein into A β_{42} by secretases can expose these amide N-H and C=O groups and promote a β -sheet conformation^[4]. Elevated concentrations from overproduction or insufficient clearance/processing may also contribute. The hydrogen bonding of the pleated, β -sheet conformation between parallel or anti-parallel β -sheets is much stronger than that in native α -helices, making reversal unlikely. Additionally, the β -sheet conformation allows hydrogen bonding between separate, stacked molecules, promoting oligomerization and eventual plaque formation^[4]. A β is proposed to form a toxic, small oligomer "seed" requiring 3 or 4 molecules used as a template to "infect" native molecules and propagate in a prion-like manner^[6].

The proteopathy of tau, or tauopathy, in AD is primarily caused by hyperphosphorylation. Hyperphosphorylated tau loses its function of stabilizing microtubules and dissociates from them^[7]. The increased pool of free tau after dissociation from microtubules is likely an important first step to aggregation in AD^[8]. Untethered from microtubules, hyperphosphorylated tau twists together to form the paired helical filaments (PHFs) found in neurofibrillary tangles. In a toxic gain of function, hyperphosphorylated tau also actively disrupts microtubules and inhibits their assembly^[7,9] and even sequesters functional tau and other microtubule associated proteins^[9]. Hyperphosphorylation also changes tau's localization from axon-predominant to include dendrites, neuronal cell bodies and presynaptic areas, leading to synaptic dysfunction^[10-12].

This mini-review focuses on a third, interconnected proteopathy in AD and its critical role in 2 toxic signaling pathways of soluble A β . The newly

described proteopathy is an altered conformation of the ubiquitous scaffolding protein filamin A (FLNA), induced by A β_{42} and without apparent aggregation^[13]. The 1st toxic cascade of A β enabled by altered FLNA is A β 's signaling via $\alpha 7$ nicotinic acetylcholine receptor ($\alpha 7$ nAChR) to hyperphosphorylate tau. The 2nd signaling pathway is A β 's aberrant activation of toll-like-receptor 4 (TLR4), by binding CD14^[14], to induce neuroinflammation. In both cases, altered FLNA associates with these receptors to allow their aberrant signaling by A β ^[13,15]. Native FLNA in control brains does not associate with either receptor. Whether the altered conformation precedes or is a consequence of these receptor linkages is discussed. The interdependence of altered FLNA with A β signaling to hyperphosphorylate tau and promote neuroinflammation has been elucidated via the reversal of the FLNA proteopathy by a small molecule therapeutic candidate, PTI-125.

A β SIGNALING VIA $\alpha 7$ NACHR TO HYPERPHOSPHORYLATE TAU

The most toxic form of A β is considered soluble A β oligomers rather than plaque deposits^[16,17]. Evidence that soluble A β induces tau pathology has grown, with hyperphosphorylation as the primary pathological modification^[18]. Extensive research has elucidated the role of the $\alpha 7$ nAChR in the toxicity of soluble A β_{42} and the consequent hyperphosphorylation of tau^[19-24]. Soluble A β_{42} in monomeric or oligomeric form binds and signals via $\alpha 7$ nAChR^[25-28], essentially hijacking this receptor to abnormally activate various kinases^[27,29-31] to heighten tau phosphorylation. Supportive data include co-localization of A β_{42} and $\alpha 7$ nAChR in AD pyramidal neurons and a complete blockade of A β_{42} -induced tau hyperphosphorylation *in vitro* by $\alpha 7$ nAChR antisense oligonucleotides^[32]. A β_{42} dose-dependently activates tau kinases to persistently phosphorylate tau at the three proline-directed sites, resulting in elevated hyperphosphorylated tau in neurofibrillary tangles. This A β -driven tau hyperphosphorylation can also be blocked by the $\alpha 7$ nAChR antagonist α -bungarotoxin or other $\alpha 7$ nAChR ligands if administered prophylactically^[32-35]. The hyperphosphorylation of tau renders it dysfunctional, alters its cellular distribution and disrupts axonal/dendritic transport, leading to neurofibrillary lesions, dendritic breakdown, and ultimately, neurofibrillary tangles^[27]. Importantly, soluble A β_{42} binds $\alpha 7$ nAChR with an extraordinarily high (high femtomolar) affinity, rendering the A β_{42} - $\alpha 7$ nAChR interaction nearly irreversible^[26,36].

Though other targets have been demonstrated for

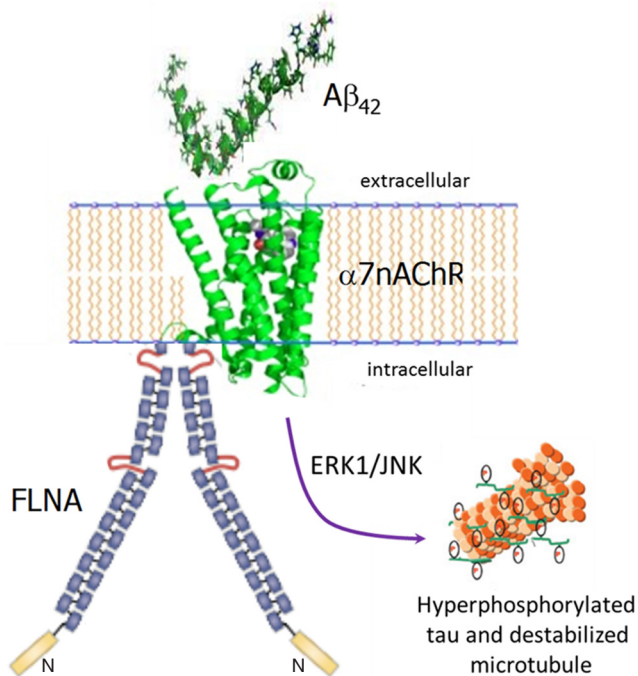


Figure 1: Altered FLNA linkage to $\alpha 7nAChR$ enables $A\beta_{42}$'s toxic signaling via $\alpha 7nAChR$ to hyperphosphorylate tau. Monomers or small oligomers of $A\beta_{42}$ bind $\alpha 7nAChR$, which recruits FLNA to link to $\alpha 7nAChR$. This recruitment likely alters FLNA's conformation, which in turn increases the affinity of the $A\beta_{42}$ - $\alpha 7nAChR$ interaction to a femtomolar affinity and enables the signaling. ERK1 and JNK kinases are activated to hyperphosphorylate tau. Hyperphosphorylated tau loses its function of stabilizing microtubules and dissociates from them, eventually creating PHFs and neurofibrillary tangles. FLNA: filamin A; $A\beta$: amyloid beta; $\alpha 7nAChR$: $\alpha 7$ nicotinic acetylcholine receptor; PHF: paired helical filament

soluble $A\beta_{42}$, their nanomolar or lower affinities suggest high off-rates and limited target engagement, in contrast to $A\beta_{42}$'s nearly irreversible sub-picomolar interaction with $\alpha 7nAChR$. Other targets of soluble $A\beta$ include PrP^C, a prion receptor, which $A\beta$ binds at 50-100 nmol/L to suppress LTP in slice cultures^[37]. Acting as a co-receptor for the $A\beta$ -PrP^C complex, mGluR5 also plays a role in the impaired LTP^[38]. Soluble $A\beta$ has also been shown to bind neuroligin-1, a post-synaptic cell adhesion protein, in the nanomolar range, and this interaction has been proposed to promote $A\beta$ oligomer formation^[39].

Evidence that phosphorylation can alter tau's conformation comes from a study showing that a particular AD-specific phosphorylated tau species is only formed when specific phosphoepitopes in a proline-rich region are sequentially phosphorylated by GSK-3 β (at Thr212) and then by PKA (at Ser214)^[40]. Whether tau's hyperphosphorylation contributes to protein misfolding prior to formation of PHFs is speculative, particularly as its pathological structure

has not been elucidated. The tau proteopathy in AD, therefore, involves hyperphosphorylation, but may or may not include misfolding. The formation of PHFs requires hyperphosphorylated tau, and tau protein in neurofibrillary tangles is hyperphosphorylated, most notably at Ser²⁰², Thr²³¹ and Thr¹⁸¹^[41]. Interestingly, the alpha-synuclein that forms fibrils and is abundant in Lewy bodies in Parkinson's disease is also hyperphosphorylated, at a single serine site^[42].

ALTERED FLNA LINKS A β AND TAU PROTEOPATHIES

We recently described a third, atypical proteopathy in AD that is critically interconnected with the toxicities of both $A\beta_{42}$ and tau. This third proteopathy is an altered conformation of the scaffolding protein FLNA. It is induced by $A\beta_{42}$, and in reciprocal action, enables $A\beta_{42}$'s toxic signaling via $\alpha 7nAChR$ to activate kinases that hyperphosphorylate tau^[13]. Altered FLNA enables $A\beta_{42}$'s signaling via $\alpha 7nAChR$ by associating with this receptor^[13,15]. Although FLNA constitutively associates with other receptors including the mu opioid receptor and insulin receptors^[43], FLNA does not normally link to $\alpha 7nAChR$. We hypothesize that upon $A\beta_{42}$ binding to $\alpha 7nAChR$, FLNA is recruited to this receptor and its conformation altered to enable $A\beta_{42}$'s aberrant signaling [Figure 1]. FLNA in control brains can be induced to link to $\alpha 7nAChR$ by incubation with $A\beta_{42}$ *in vitro* or by ICV $A\beta_{42}$ infusion *in vivo*^[13,15]. The altered conformation of FLNA is also illustrated by the 100-fold difference in binding affinities of the novel drug candidate PTI-125 to FLNA immunopurified from human postmortem AD vs. control brain^[13]. One distinct difference between altered FLNA and other proteopathies is that the altered conformation of FLNA does not appear to promote self-aggregation.

Best known for cross-linking actin to enable cell structure, flexibility and motility, FLNA is a prominent regulator of the actin cytoskeletal assembly and dynamics^[44-46]. The actin cytoskeleton, a vital component in synapses and the dendritic network, is impaired in AD^[47]. Hence, the FLNA proteopathy might also disrupt synaptic and dendritic function in AD by disrupting actin dynamics. FLNA exists as an intracellular homodimer and dimerizes in a membrane-bound, C-terminal domain. It is a large (280-kDa) protein with 24 immunoglobulin repeats that are natively β -sheet pleated, forming two rod-like domains separated by two hinge regions. The nature of the conformational change of FLNA in AD is not yet known, though it is interesting that native FLNA is predominantly β -sheeted. Demonstrating induction by

A β , the altered FLNA conformation exists not only in postmortem human AD brain and in triple transgenic (3xTg) AD mice, but also in ICV A β_{42} -infused wildtype mice and in A β_{42} -treated postmortem human control brain^[13].

This altered form of FLNA was evidenced by a shift in isoelectric focusing point (pI) from 5.9 in the native state to 5.3 in postmortem human AD brain or brains of mouse models^[13]. An altered pI can indicate an altered conformation, reflecting changes in hydrogen bonding, charge-charge interactions or accessibility of ionizable residues within the molecule^[48-50]. In this case, the shifted pI is resistant to complete dephosphorylation by alkaline phosphatase. Hence, unlike the proteopathies of tau and alpha-synuclein, the altered conformation of FLNA is not due to changes in phosphorylation state. Further studies are needed to reveal the details of FLNA's conformational change and whether altered FLNA is unique to AD.

The induction of the altered conformation by A β_{42} may suggest a direct interaction or some sort of cross-protein templating by A β_{42} . However, A β_{42} and FLNA do not directly interact because neither protein can be co-immunoprecipitated with the other (our unpublished observations). Although it is tempting to presume that FLNA must be in its altered conformation to associate with α 7nAChR, we hypothesize that it is FLNA's transmembrane recruitment to this receptor, induced by A β_{42} 's extracellular binding, that changes FLNA's conformation. A β_{42} binds α 7nAChR with high femtomolar affinity, the highest known binding affinity of A β_{42} . Interestingly, prevention of the FLNA linkage to α 7nAChR by FLNA-binding compound PTI-125 decreases A β_{42} 's affinity for this receptor 1,000-10,000-fold, illustrating that FLNA enables not only A β_{42} 's toxic signaling but also its high-affinity binding for α 7nAChR^[15]. Although this observation appears to suggest that altered FLNA is responsible for A β_{42} 's binding, we propose a dynamic, sequential process: (1) A β_{42} binds α 7nAChR to induce FLNA recruitment; (2) recruitment alters FLNA's conformation; and (3) FLNA's altered form secures (locks in) an ultra-high affinity A β_{42} - α 7nAChR interaction. The reasoning behind this hypothesis is that A β_{42} induces both the aberrant FLNA conformation and its recruitment to α 7nAChR (either by ICV A β_{42} infusion to wildtype mice or by *in vitro* A β_{42} incubation of postmortem control brain)^[13,15] and that A β_{42} and FLNA do not themselves interact.

Enabled by FLNA, A β_{42} , in monomeric or small oligomeric form^[51], signals via α 7nAChR to activate

kinases to hyperphosphorylate tau protein^[30,32,33,52]. We know that the linkage of altered FLNA is required for this A β signaling pathway because the novel drug candidate PTI-125 prevents the FLNA- α 7nAChR linkage and greatly reduces tau hyperphosphorylation^[13,15]. Hyperphosphorylated tau loses its ability to stabilize microtubules and dissociates from them, thereby increasing the pool of free phosphorylated tau that eventually appears in neurofibrillary tangles. We suggest that the signaling of A β_{42} via α 7nAChR contributes prominently to a variety of AD-related neuropathologies in addition to, or perhaps elicited by, tau hyperphosphorylation because these additional neuropathologies are also reduced by PTI-125's disruption of A β_{42} 's signaling via α 7nAChR^[13,15]. Alternatively, they may be related to the neuroinflammatory signaling that is also disrupted by PTI-125 as discussed below. An obvious consequence of the toxic signaling through α 7nAChR is that the normal function of α 7nAChR is impaired. Because α 7nAChR is an upstream regulator of the N-methyl-D-aspartate receptor (NMDAR)^[53,54], the impaired NMDAR signaling in AD brain and 3xTg AD mice is very likely related to the impaired signaling via α 7nAChR. This assertion is supported by the improvement in signaling function of both receptors by PTI-125^[13,15]. A β_{42} 's signaling to hyperphosphorylate tau also contributes to eventual formation of A β deposits and tau-containing neurofibrillary lesions^[55,56], because disrupting this signaling via PTI-125 markedly reduces both A β deposits and neurofibrillary lesions in 3xTg AD mice or ICV A β_{42} -infused wildtype mice^[13,15]. Finally, reiterating the improved receptor function by PTI-125 and implicating this toxic A β signaling pathway in cognitive impairment, PTI-125 also improved working and spatial memory and nesting behavior abnormalities in 3xTg AD mice^[13].

ALTERED FLNA ENABLES A β -INDUCED NEUROINFLAMMATION

The proteopathy of FLNA enables a second toxic signaling pathway of A β : its activation of the innate immune receptor TLR4^[13,15]. A β_{42} binds the CD14 co-receptor^[14], complexed with TLR4, to induce an aberrant FLNA linkage to TLR4^[13,15], which appears to reciprocally enable a sustained A β -mediated TLR4 activation [Figure 2]. Hence, the FLNA-TLR4 linkage, allowing A β activation of TLR4, promotes persistent inflammatory cytokine release and elicits neuroinflammation characteristic of AD. As with α 7nAChR, native FLNA in control brains does not associate with TLR4, unless treated with A β_{42} by ICV infusion to wildtype mice or by *in vitro* incubation of

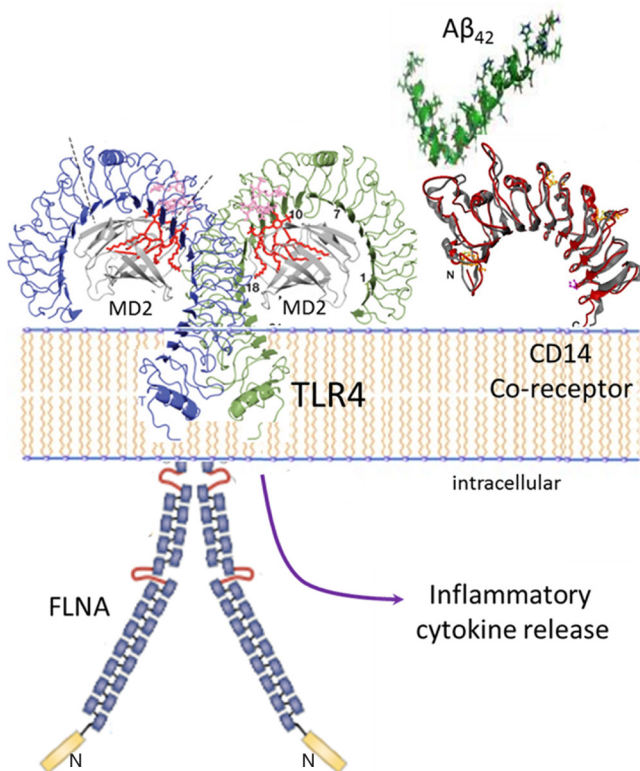


Figure 2: Altered FLNA linkage to TLR4 enables persistent A β_{42} -induced TLR4 activation and neuroinflammation. A β_{42} binds the CD14 co-receptor to induce FLNA recruitment to TLR4. As with $\alpha 7$ nAChR, the FLNA linkage likely alters the FLNA conformation. With A β_{42} binding CD14, altered FLNA linkage to TLR4 enables a sustained TLR4 activation, leading to substantial inflammatory cytokine release and the neuroinflammation characteristic of AD. FLNA: filamin A; A β : amyloid beta; $\alpha 7$ nAChR: $\alpha 7$ nicotinic acetylcholine receptor; TLR4: toll-like-receptor 4

control postmortem human brain^[13,15]. Like the FLNA recruited to $\alpha 7$ nAChR, FLNA that links to TLR4 in the presence of A β_{42} , or in AD postmortem brain or 3xTg AD mice, has an altered conformation^[13]. The question arises again whether A β_{42} binding to CD14 induces the FLNA linkage to TLR4 and the altered FLNA conformation in the process, or whether this linkage happens only after FLNA's conformation is altered. With two receptors seemingly controlling FLNA's conformation by recruitment, it is tempting to speculate that one linkage or the other induces the altered conformation, unleashing further aberrant and persistent receptor associations with FLNA. Notably, even in its non-diseased state, FLNA interacts with more than 90 different protein partners including a few receptors and many signaling molecules^[44]. With multiple interactions, it is possible that one or more specific protein interactions - induced by A β - could alter FLNA's conformation and subsequent behavior. If so, it is then possible that the alteration in FLNA could also affect its interaction with other protein partners and their functions, disrupting the integrity of circuitries

to propagate dysfunction in AD brains.

REVERSING FLNA'S ALTERED CONFORMATION

The primary evidence for the role of FLNA's altered conformation in A β_{42} 's toxic signaling via $\alpha 7$ nAChR and TLR4 comes from the small molecule therapeutic candidate PTI-125. The altered conformation of FLNA was first inferred from the efficacy (as well as safety) at relatively low doses of PTI-125 in mouse models and *in vitro*, despite a ubiquitous target. We subsequently determined that PTI-125 binds altered FLNA (in AD postmortem brain, in 3xTg AD mice or in ICV A β_{42} -infused mice) much more tightly than native FLNA (in control postmortem brain or in control mice): a femtomolar affinity was measured for altered FLNA vs. a substantially lower, picomolar affinity for native FLNA^[13]. Using the same isoelectric focusing point assessment that demonstrated FLNA's altered conformation, we further showed that PTI-125 binding, by *in vivo* treatment of mice or by *in vitro* incubation of postmortem AD brain, restores the native conformation of FLNA^[13]. By reversing the FLNA proteopathy, PTI-125 dramatically reduces FLNA's aberrant linkages to both $\alpha 7$ nAChR and TLR4, consequently reducing tau hyperphosphorylation and neuroinflammation^[13,15]. By attenuating A β 's pathogenic drive, PTI-125 treatment improved function of three key receptors: $\alpha 7$ nAChR, NMDAR and insulin receptors^[13,15]. The improved insulin receptor signaling may also reflect reduced neuroinflammation by PTI-125, as neuroinflammation has been linked to impaired insulin receptor function^[57]. Disrupting the FLNA-TLR4 linkage, PTI-125 potently and efficaciously reduced inflammatory cytokines by at least 80% in 3xTg AD mice and in ICV A β_{42} -infused mice^[13,15]. Correlating with the improved NMDAR function, synaptic plasticity was also improved by PTI-125 treatment of either 3xTg AD mice or A β_{42} -treated postmortem human control brain, evidenced by improved activity-dependent expression of the master synaptic plasticity regulator, activity-regulated, cytoskeleton-associated protein (Arc)^[13]. These beneficial effects of PTI-125 in AD mouse models and postmortem AD brain elucidate a critical role of the FLNA proteopathy in multiple toxicities of A β and tau, including neuroinflammation [Figure 3]. We also speculate that altered FLNA may alter actin dynamics, given the primary role of FLNA in the actin cytoskeleton.

LIMITATIONS OF INTERPRETATION

There are limitations to our interpretations of our data.

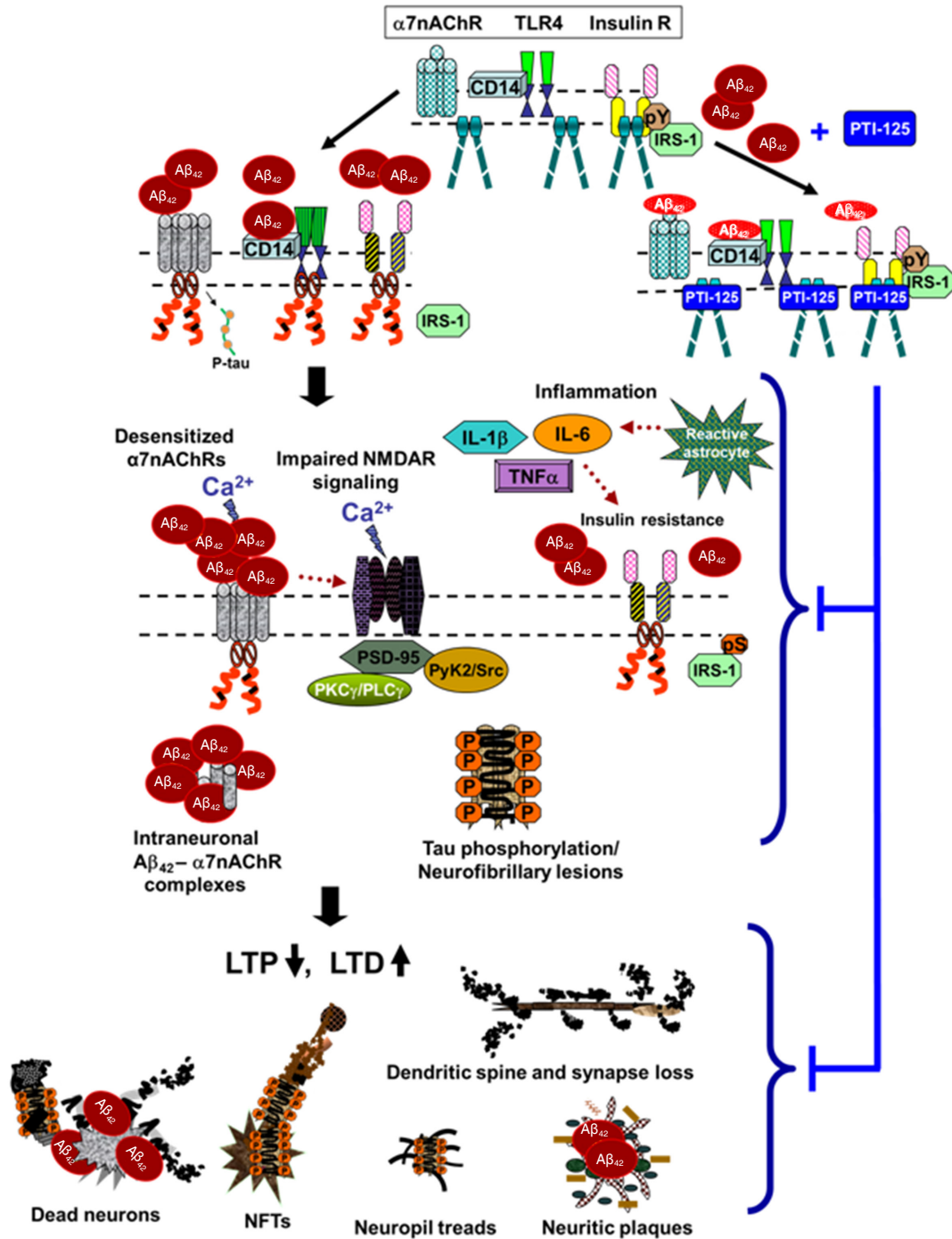


Figure 3: Proposed model of pathological consequences of altered FLNA-enabled Aβ₄₂ signaling via α7nAChR and TLR4. Soluble Aβ₄₂ monomers or small oligomers bind α7nAChR or CD14, complexed with TLR4, inducing recruitment of FLNA to these receptors. Dimers of native FLNA, coupled to insulin receptors but not to α7nAChR or TLR4, are depicted as straight rods; red curly FLNA depicts the altered form, which is recruited to α7nAChR and TLR4 (and possibly also insulin receptors). Enabled by altered FLNA’s new linkages, Aβ₄₂ activates α7nAChR to hyperphosphorylate tau and persistently activates TLR4 to induce inflammatory cytokine release (TNFα, IL-1β and IL-6) by reactive astrocytes. This neuroinflammation likely contributes to insulin receptor desensitization⁵⁷. Although the insulin receptor is constitutively associated with native FLNA, it is possible that altered FLNA also contributes to the insulin receptor dysfunction in AD. Aβ₄₂’s aberrant signaling through α7nAChR impairs function of α7nAChR and of NMDARs, restricting calcium influx through both receptors. Increasing Aβ₄₂ piling onto α7nAChR leads to intraneuronal Aβ₄₂-α7nAChR complexes. The hyperphosphorylated tau dissociates from microtubules, disrupting microtubule stability, axonal transport and neuronal function. Along with dysfunctional tau, impaired NMDARs reduce LTP and heighten LTD. Dendritic spines and synapses are lost. Neuritic plaques, neuropil treads and neurofibrillary tangles are formed, and neurons degenerate. FLNA: filamin A; Aβ: amyloid beta; α7nAChR: α7 nicotinic acetylcholine receptor; TLR4: toll-like-receptor 4; TNFα: tumor necrosis factor-α; IL: interleukin; AD: Alzheimer’s disease; NMDAR: N-methyl-D-aspartate receptor; LTP: long-term potentiation; LTD: long-term depression

First, the alteration in FLNA has not been directly demonstrated. It is implied by a shift in pI for FLNA in AD vs. control brain and supported by the differential binding affinities of PTI-125 to FLNA in control vs. AD brain. Representing an aggregate pKa for all amino acids in a protein, a shifted pI is assumed to reflect a change in structure. Second, the possibility exists that PTI-125 has additional significant targets besides FLNA's altered conformation that have confounded our interpretation of its effects. We believe this is a remote possibility because: (1) PTI-125 showed no interactions in a lead profiling screen of 68 receptors, channels and transporters; (2) the binding affinity of PTI-125 in AD brain was virtually identical to its binding affinity for FLNA immunopurified from AD brain^[13], indicating a lack of other CNS targets; and (3) PTI-125 shows good CNS penetration and more than sufficient brain levels for a femtomolar target.

Both A β and tau as AD therapeutic targets have been questioned following multiple clinical trial failures, and this skepticism may extend to altered FLNA as a viable therapeutic target for AD. Furthermore, several partial agonists or positive allosteric modulators to α 7nAChR have also failed, challenging the significance of this A β signaling pathway. As commonly suggested, potential reasons for these failures include treating too late in disease progression, because neuropathology precedes symptoms by 10-25 years^[58,59], and the possible protective effect of amyloid^[60]. Additionally, agents that target aggregation of A β or tau may be downstream of significant dysfunction, as suggested by the pathways discussed here. Perhaps most importantly, the femtomolar interaction of A β ₄₂ with α 7nAChR imposes substantial competition for antibodies or small molecules seeking to compete directly with this interaction.

An additional caution to interpretation of our data may be our use of synthetic, monomeric A β ₄₂ rather than oligomeric A β , thought to be the most toxic A β species. Though transgenic mice generate both monomeric and oligomeric A β , A β ₄₂ *in vitro* forms a mixture of monomers and small oligomers as well, and both signal via α 7nAChR^[51].

Finally, despite the broad spectrum of beneficial effects demonstrated preclinically by PTI-125's reversal of FLNA's altered conformation, A β ₄₂ signaling via α 7nAChR and TLR4 are only two of many pathogenic cascades in AD. A variety of other approaches have demonstrated similar results in mouse models, and the difficulty of clinical translation remains. We believe our strongest data validating FLNA's altered conformation as a novel target for AD drug development are

those using postmortem human AD or A β ₄₂-treated control brain with postmortem interval < 10 h. PTI-125 demonstrated efficacy in postmortem human brain at concentrations as low as 1 pmol/L^[13].

CONCLUSION

Abnormal FLNA is intertwined with the A β and tau proteopathies in AD. A β ₄₂ induces the altered conformation of FLNA, and altered FLNA enables sustained A β ₄₂ signaling via α 7nAChR and TLR4, possibly by securing high affinity binding of A β ^[13,15]. A β ₄₂'s toxic signaling via α 7nAChR activates kinases to hyperphosphorylate tau^[25-31], leading to its dysfunction and aggregation, and the FLNA-enabled A β ₄₂ activation of TLR4 enhances neuroinflammation^[13,15]. Moreover, the altered conformation of FLNA is an important catalyst of A β toxicities and tau dysfunction, including neuroinflammation and synaptic dysfunction. The novel therapeutic candidate PTI-125 offers the possibility of dampening these toxic cascades by restoring the native conformation of FLNA. In addition to its novel target, preferentially binding and reversing an altered protein conformation is a novel mechanism of action for any drug candidate. An advantage of its mechanism is that PTI-125 dramatically attenuates A β 's aberrant activation of both α 7nAChR and TLR4 without directly affecting these surface receptors. PTI-125 preserves tau's neuronal function, preserving axonal transport, and reduces A β -induced neuroinflammation and synaptic/dendritic damage while maintaining health of the receptors. AD is a disease of multiple dysfunctions. Interconnected with several toxicities of A β and tau and implicated in many AD-related neuropathologies, the proteopathy of FLNA represents an entirely new target for AD drug development.

DECLARATIONS

Authors' contributions

Wrote the manuscript: L.H. Burns

Performed all experimental studies on PTI-125 and edited the manuscript: H.Y. Wang

Financial support and sponsorship

The PTI-125 program was supported by NIH grants AG050301 and AG056166 (LHB), and a plasma-based companion diagnostic/biomarker is supported by NIH grant AG057329 (GBT).

Conflicts of interest

LHB is an employee of and HYW is a consultant to Pain Therapeutics Inc., who owns all rights to PTI-125

and related technology.

Patient consent

Not applicable.

Ethics approval

Not applicable.

REFERENCES

- Frost B, Diamond M. Prion-like mechanisms in neurodegenerative diseases. *Nat Rev Neurosci* 2010;11:155-9.
- Sengupta U, Nilson A, Kaye R. The role of amyloid- β oligomers in toxicity, propagation, and immunotherapy. *EBioMedicine* 2016;6:42-9.
- Yin R, Tan L, Jiang T, Yu J. Prion-like mechanisms in Alzheimer's disease. *Curr Alzheimer Res* 2014;11:755-64.
- Eisenberg D, Jucker M. The amyloid state of proteins in human diseases. *Cell* 2012;148:1188-203.
- Rasmussen J, Jucker M, Walker L. A β seeds and prions: how close the fit? *Prion* 2017;11:215-25.
- Nelson R, Sawaya M, Balbirnie M, Madsen A, Riekel C, Grothe R, Eisenberg D. Structure of the cross-beta spine of amyloid-like fibrils. *Nature* 2005;435:773-8.
- Alonso A, Zaidi T, Grundke-Iqbal I, Iqbal K. Role of abnormally phosphorylated tau in the breakdown of microtubules in Alzheimer disease. *PNAS* 1994;91:5562-6.
- Friedhoff P, von Bergena M, Mandelkova EM, Mandelkow E. Structure of tau protein and assembly into paired helical filaments. *Biochimica et Biophysica Acta* 2000;1502:122-32.
- Alonso A, Grundke-Iqbal I, Barra H, Iqbal K. Abnormal phosphorylation of tau and the mechanism of Alzheimer neurofibrillary degeneration: sequestration of microtubule-associated proteins 1 and 2 and the disassembly of microtubules by the abnormal tau. *PNAS* 1997;94:298-303.
- Hoover B, Reed M, Su J, Penrod R, Kotilinek L, Grant M, Pitstick R, Carlson G, Lanier L, Yuan L, Ashe K, Liao D. Tau mislocalization to dendritic spines mediates synaptic dysfunction independently of neurodegeneration. *Neuron* 2010;68:1067-81.
- Ittner L, Ke Y, Delerue F, Bi M, Gladbach A, van Eersel J, Wölfing H, Chieng B, Christie M, Napier I, Eckert A, Staufenbiel M, Hardeman E, Götz J. Dendritic function of tau mediates amyloid-beta toxicity in Alzheimer's disease mouse models. *Cell* 2010;142:387-97.
- Kowall N, Kosik K. Axonal disruption and aberrant localization of tau protein characterize the neuropil pathology of Alzheimer's disease. *Ann Neurol* 1987;22:639-43.
- Wang HY, Lee KC, Pei Z, Khan A, Bakshi K, Burns L. PTI-125 binds and reverses an altered conformation of filamin A to reduce Alzheimer's disease pathogenesis. *Neurobiol Aging* 2017;55:99-114.
- Gambuzza M, Sofó V, Salmeri F, Soraci L, Marino S, Bramanti P. Toll-like receptors in Alzheimer's disease: a therapeutic perspective. *CNS Neurol Disord Drug Targets* 2014;13:1542-58.
- Wang H-Y, Bakshi K, Frankfurt M, Stucky A, Goberdhan M, Shah S, Burns L. Reducing amyloid-related Alzheimer's disease pathogenesis by a small molecule targeting filamin A. *J Neurosci* 2012;32:9773-84.
- Näslund J, Haroutunian V, Mohs R, Davis K, Davies P, Greengard P, Buxbaum J. Correlation between elevated levels of amyloid beta-peptide in the brain and cognitive decline. *JAMA* 2000;283:1571-7.
- Gandy S, Simon A, Steele J, Lublin A, Lah J, Walker L, Levey A, Krafft G, Levy E, Checler F, Glabe C, Bilker W, Abel T, Schmeidler J, Ehrlich M. Days-to-criterion as an indicator of toxicity associated with human Alzheimer amyloid- β oligomers. *Ann Neurol* 2010;68:220-30.
- Stancu I-C, Vasconcelos B, Terwel D, Dewachter I. Models of β -amyloid induced Tau-pathology: the long and "folded" road to understand the mechanism. *Mol Neurodegen* 2014;9:51.
- Medeiros R, Castello N, Cheng D, Kitazawa M, Baglietto-Vargas D, Green K, Esbenshade T, Bitner R, Decker M, LaFerla F. $\alpha 7$ Nicotinic receptor agonist enhances cognition in aged 3xTg-AD mice with robust plaques and tangles. *Am J Pathol* 2014;184:520-9.
- Inestrosa N, Godoy J, Vargas J, Arrazola M, Rios J, Carvajal F, Serrano F, Farias G. Nicotine prevents synaptic impairment induced by amyloid- β oligomers through $\alpha 7$ -nicotinic acetylcholine receptor activation. *Neuromolecular Med* 2013;15:549-69.
- Dziewczapolski G, Glogowski C, Masliah E, Heinemann S. Deletion of the alpha 7 nicotinic acetylcholine receptor gene improves cognitive deficits and synaptic pathology in a mouse model of Alzheimer's disease. *J Neurosci* 2009;29:8805-15.
- Ni R, Marutle A, Nordberg A. Modulation of $\alpha 7$ nicotinic acetylcholine receptor and fibrillar amyloid- β interactions in Alzheimer's disease brain. *J Alzheimers Dis* 2013;33:841-51.
- Ondrejcek T, Wang Q, Kew J, Virley D, Upton N, Anwyl R, Rowan M. Activation of $\alpha 7$ nicotinic acetylcholine receptors persistently enhances hippocampal synaptic transmission and prevents A β -mediated inhibition of LTP in the rat hippocampus. *Eur J Pharmacol* 2012;677:63-70.
- D'Andrea M, Nagele R. Targeting the alpha 7 nicotinic acetylcholine receptor to reduce amyloid accumulation in Alzheimer's disease pyramidal neurons. *Curr Pharm Des* 2006;12:677-84.
- Tong M, Arora K, White M, Nichols R. Role of key aromatic residues in the ligand-binding domain of alpha7 nicotinic receptors in the agonist action of beta-amyloid. *J Biol Chem* 2011;286:34373-81.
- Wang H, Lee D, Davis C, Shank R. Amyloid peptide A β (1-42) binds selectively and with picomolar affinity to alpha7 nicotinic acetylcholine receptors. *J Neurochem* 2000;75:1155-61.
- Wang H, Li W, Benedetti N, Lee D. $\alpha 7$ Nicotinic acetylcholine receptors mediate β -amyloid peptide-induced tau protein phosphorylation. *J Biol Chem* 2003;278:31547-53.
- Wang HY, D'Andrea MR, Peterson PA, Shank RP, Reitz AB. beta-Amyloid(1-42) binds to alpha7 nicotinic acetylcholine receptor with high affinity. Implications for Alzheimer's disease pathology. *J Biol Chem* 2000;275:5626-32.
- Dineley K, Bell K, Bui D, Sweatt J. β -Amyloid peptide activates $\alpha 7$ nicotinic acetylcholine receptors expressed in xenopus oocytes. *J Biol Chem* 2002;277:25056-61.
- Hu M, Waring J, Gopalakrishnan M, Li J. Role of GSK-3 β activation and alpha7 nAChRs in A β (1-42)-induced tau phosphorylation in PC12 cells. *J Neurochem* 2008;106:1371-7.
- Zhang L, Xie J, Yang J, Cao Y. Tyrosine phosphatase STEP61 negatively regulates amyloid β -mediated ERK/CREB signaling pathways via $\alpha 7$ nicotinic acetylcholine receptors. *J Neurosci Res* 2013;91:1581-90.
- Wang HY, Li W, Benedetti N, Lee D. $\alpha 7$ nicotinic acetylcholine receptors mediate β -amyloid peptide-induced tau protein phosphorylation. *J Biol Chem* 2003;278:31547-53.
- Dineley K, Bell K, Bui D, Sweatt J. β -Amyloid peptide activates $\alpha 7$ nicotinic acetylcholine receptors expressed in xenopus oocytes. *J Biol Chem* 2002;277:25056-61.
- Wang HY, Bakshi K, Shen C, Frankfurt M, Trocme-Thibierge C, Morain P. S 24795 limits β -amyloid - $\alpha 7$ nicotinic receptor interaction and reduces Alzheimer's disease-like pathologies. *Biol Psychiatry* 2010;67:522-30.
- Wang HY, Stucky A, Liu J, Shen C, Trocme-Thibierge C, Morain P. Dissociating beta-amyloid from alpha 7 nicotinic acetylcholine receptor by a novel therapeutic agent, S 24795, normalizes alpha 7 nicotinic acetylcholine and NMDA receptor function in Alzheimer's disease

- brain. *J Neurosci* 2009;35:10961-73.
36. Wang H, Lee D, D'Andrea M, Peterson P, Shank R, Reitz A. beta-Amyloid(1-42) binds to alpha7 nicotinic acetylcholine receptor with high affinity. Implications for Alzheimer's disease pathology. *J Biol Chem* 2000;275:5626-32.
 37. Lauren J, Gimbel D, Nygaard H, Gilbert J, Strittmatter S. Cellular prion protein mediates impairment of synaptic plasticity by amyloid-beta oligomers. *Nature* 2009;457:1128-32.
 38. Um J, Kaufman A, Kostylev M, Heiss J, Stagi M, Takahashi H, Kerrisk M, Vortmeyer A, Wisniewski T, Koleske A, Gunther E, Nygaard H, Strittmatter S. Metabotropic glutamate receptor 5 is a coreceptor for Alzheimer A β oligomer bound to cellular prion protein. *Neuron* 2013;79:887-902.
 39. Dinamarca M, Weinstein D, Monasterio O, Inestrosa N. The synaptic protein neuroligin-1 interacts with the amyloid β -peptide. Is there a role in Alzheimer's disease? *Biochemistry* 2011;50:8127-37.
 40. Zheng-Fischhöfer Q, Biernat J, Mandelkow E, Illenberger S, Godemann R, Mandelkow E. Sequential phosphorylation of Tau by glycogen synthase kinase-3 β and protein kinase A at Thr212 and Ser214 generates the Alzheimer-specific epitope of antibody AT100 and requires a paired-helical-filament-like conformation. *Eur J Biochem* 1998;252:542-52.
 41. Wang J, Xia Y, Grundke-Iqbal I, Iqbal K. Abnormal hyperphosphorylation of tau: sites, regulation, and molecular mechanism of neurofibrillary degeneration. *J Alzheimers Dis* 2013;33:S123-39.
 42. Oueslati A. Implication of alpha-synuclein phosphorylation at S129 in synucleinopathies: what have we learned in the last decade? *J Parkinsons Dis* 2016;6:39-51.
 43. Stossel T, Condeelis J, Cooley L, Hartwig J, Noegel A, Schleicher M, Shapiro S. Filamins as integrators of cell mechanics and signalling. *Nature* 2001;2:138-45.
 44. Nakamura F, Stossel T, Hartwig J. The filamins: organizers of cell structure and function. *Cell Adh Migr* 2011;5:160-9.
 45. Vadlamudi R, Li F, Adam L, Nguyen D, Ohta Y, Stossel T, Kumar R. Filamin is essential in actin cytoskeletal assembly mediated by p21-activated kinase 1. *Nat Cell Biol* 2002;4:681-90.
 46. Yue J, Huhn S, Shen Z. Complex roles of filamin-A mediated cytoskeleton network in cancer progression. *Cell Biosci* 2013;3:7.
 47. Penzes P, Vanleeuwen J. Impaired regulation of synaptic actin cytoskeleton in Alzheimer's disease. *Brain Res Rev* 2011;67:184-92.
 48. Stucky A, Bakshi K, Friedman E, Wang H. Prenatal cocaine exposure upregulates BDNF-TrkB signaling. *PLoS One* 2016;11:e0160585.
 49. Ui N. Conformational studies on proteins by isoelectric focusing. *Ann N Y Acad Sci* 1973;209:198-209.
 50. Pace C, Grimsley G, Scholtz J. Protein ionizable groups: pK values and their contributions to protein stability and solubility. *J Biol Chem* 2009;284:13285-9.
 51. Lilja A, Porras O, Storelli E, Nordberg A, Marutle A. Functional interactions of fibrillar and oligomeric amyloid- β with alpha7 nicotinic receptors in Alzheimer's disease. *J Alzheimers Dis* 2011;23:335-47.
 52. Zhang L, Xie J, Yang J, Cao Y. Tyrosine phosphatase STEP61 negatively regulates amyloid β -mediated ERK/CREB signaling pathways via α 7 nicotinic acetylcholine receptors. *J Neurosci Res* 2013;91:1581-90.
 53. Snyder E, Nong Y, Almeida C, Paul S, Moran T, Choi E, Nairn A, Salter M, Lombroso P, Gouras G, Greengard P. Regulation of NMDA receptor trafficking by amyloid-beta. *Nat Neurosci* 2005;8:1051-8.
 54. Wang H, Stucky A, Liu J, Shen C, Trocme-Thibierge C, Morain P. Dissociating beta-amyloid from alpha 7 nicotinic acetylcholine receptor by a novel therapeutic agent, S 24795, normalizes alpha 7 nicotinic acetylcholine and NMDA receptor function in Alzheimer's disease brain. *J Neurosci* 2009;35:10961-73.
 55. Bloom G. Amyloid- β and tau: the trigger and bullet in Alzheimer disease pathogenesis. *JAMA Neurol* 2014;71:505-8.
 56. Lloret A, Fuchsberger T, Giraldo E, Viña J. Molecular mechanisms linking amyloid β toxicity and Tau hyperphosphorylation in Alzheimer's disease. *Free Radic Biol Med* 2015;83:186-91.
 57. Talbot K, Wang H, Kazi H, Han L, Bakshi K, Stucky A, Fuino R, Kawaguchi K, Samoyedny A, Wilson R, Arvanitakis Z, Schneider J, Wolf B, Bennett D, Trojanowski J, Arnold S. Demonstrated brain insulin resistance in Alzheimer's disease patients is associated with IGF-1 resistance, IRS-1 dysregulation, and cognitive decline. *J Clin Invest* 2012;122:1316-38.
 58. Bateman RJ, Xiong C, Benzinger T, Fagan A, Goate A, Fox N, Marcus D, Cairns NJ XX, Blazey TM, Holtzman DM, Santacruz A, Buckles V, Oliver A, Moulder K, Aisen PS, Ghetti B, Klunk WE, McDade E, Martins RN, Masters CL, Mayeux R, Ringman JM, Rossor MN, Schofield PR, Sperling RA, Salloway S, Morris JC; Dominantly Inherited Alzheimer Network. Clinical and biomarker changes in dominantly inherited Alzheimer's disease. *N Engl J Med* 2012;367:795-804.
 59. Trojanowski JQ, Vandeerstichele H, Korecka M, Clark CM, Aisen PS, Petersen RC, Blennow K, Soares H, Simon A, Lewczuk P, Dean R, Siemers E, Potter WZ, Weiner MW, Jack CR Jr, Jagust W, Toga AW, Lee VM, Shaw LM; Alzheimer's Disease Neuroimaging Initiative. Update on the biomarker core of the Alzheimer's disease neuroimaging initiative subjects. *Alzheimers Dement* 2010;6:230-8.
 60. Hefter D, Kaiser M, Weyer S, Papageorgiou I, Both M, Kann O, Müller U, Draguhn A. Amyloid precursor protein protects neuronal network function after hypoxia via control of voltage-gated calcium channels. *J Neurosci* 2016;36:8356-71.