Anti-Tau Trials for Alzheimer's Disease: A Report from the EU/US/CTAD Task Force

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Abstract

Efforts to develop effective disease-modifying treatments for Alzheimer's disease (AD) have mostly targeted the amyloid β (Aβ) protein; however, there has recently been increased interest in other targets including phosphorylated tau and other forms of tau. Aggregated tau appears to spread in a characteristic pattern throughout the brain and is thought to drive neurodegeneration. Both neuropathological and imaging studies indicate that tau first appears in the entorhinal cortex and then spreads to the neocortex. Anti-tau therapies currently in Phase 1 or 2 trials include passive and active immunotherapies designed to prevent aggregation, seeding, and spreading, as well as small molecules that modulate tau metabolism and function. EU/US/CTAD Task Force members support advancing the development of anti-tau therapies, which will require novel imaging agents and biomarkers, a deeper understanding of tau biology and the dynamic interaction of tau and Aβ protein, and development of multiple targets and candidate agents addressing the tauopathy of AD. Incorporating tau biomarkers in AD clinical trials will provide additional knowledge about the potential to treat AD by targeting tau.

Key words: Alzheimer's disease, tau, tauopathy, therapeutics, biomarkers.

Introduction

No new drugs have been approved by the US Food and Drug Administration (FDA) for the treatment of Alzheimer's disease (AD) since 2003 (1) despite the fact that an estimated 5.7 million Americans and 50 million people worldwide have AD today, and the prevalence is expected to grow to 152 million worldwide by 2050 (2, 3). AD clinical trials have failed at a very high rate: between 2002 and 2012, 99.6% of AD drugs tested failed to demonstrate clinical efficacy (1). Possible reasons for the high failure rate include targeting the wrong pathology or the wrong stage of disease (4, 5). Inappropriately designed trials and other methodological or unknown factors may have also contributed to treatment failures (6).

Despite the disappointments of the past 20 years, many experts in the Alzheimer's community see reasons for optimism, including the emergence of novel drugs addressing a broader array of mechanisms than in the past (7). A recent report on the status of the AD drug development pipeline identified 112 agents: 26 in Phase 3 studies, 75 in Phase 2 studies, and 23 in Phase 1 studies (8). Moreover, whereas most of the negative studies in recent years targeted brain amyloidosis and amyloid β (Aβ), current studies are targeting a broader repertoire of mechanisms, including tau pathology. Of the 26 agents in Phase 3, only one targets tau, while 9 of the agents

in Phase 2 (5 immunotherapies and 4 anti-aggregation agents) target tau (8).

Biology of tau and anti-tau therapeutics

The microtubule-associated protein tau, commonly referred to simply as tau, is found in a hyperphosphorylated form as insoluble, filamentous tangles and neuropil threads as well as dystrophic neurites in the AD brain (9). Along with plaques made up of aggregated Aβ protein, neurofibrillary tangles (NFTs) represent one of the hallmark pathologies of AD. Like Aβ, tau is found in several forms in the brain including monomers, oligomers, and fibrillary tangles (10). Tau pathology also plays a central role in other neurodegenerative diseases known collectively as tauopathies, including the primary tauopathies frontotemporal lobar degeneration with tau inclusions (FTLD-tau), Pick's disease, progressive supranuclear palsy (PSP), corticobasal degeneration (CBD), argyrophilic grain disease (AGD), and chronic traumatic encephalopathy (CTE) (11).

Six isoforms of tau exist; it binds to several other proteins; and it undergoes many post-translational modifications, all of which contribute to its multiple functions in the brain. Tau protein plays important roles in cytoskeletal stability, cell signaling, synaptic plasticity, and neurogenesis (12, 13). In the AD brain, NFTs and neuropil threads composed of aggregated hyperphosphorylated tau are thought to be the primary drivers of neurodegeneration, although the mechanisms underlying the pathogenic process and the exact relationships of tau to Aβ remain unclear. Evidence also strongly suggests that tau propagates or spreads between cells (14) and that neuroinflammation triggered by microglial activation and astrogliosis contributes to tau-associated pathogenesis. Microglia may contribute to tau spreading (15). While postmortem and tau positron emission tomography (PET) studies indicate that tau spreading is associated with disease progression (16, 17), there are many unanswered questions regarding the rate of seeding or the effects of tau spreading on neuronal biology. If the spread of tau is driving clinical and cognitive changes, this would support intervening at the earliest stages of the tau-related disease process.

Neuropathological and imaging studies using PET suggest that tau aggregates are found in the entorhinal cortex and then the neocortex. If and how this drives neurodegeneration, what forms of tau are toxic, and the relationship of tau to amyloid in terms of toxicity remain unanswered questions. Tau pathology correlates much more closely to cognitive decline than does amyloid pathology (18, 19), and a recent study suggests that tau aggregation is linked to neurodegeneration and clinical manifestations of AD (20).

The complexity of tau biology provides many potential therapeutic targets to prevent tau production, aggregation, or spread at the level of transcription, phosphorylation, depolymerization, and transport. For example, preclinical studies indicate that antibodies against tau can prevent the trans-synaptic transmission of tau between neurons (21). A Phase 1 study of the humanized monoclonal antibody ABBV-8E12 showed acceptable safety and tolerability, which provided the basis for initiating a Phase 3 study in PSP patients to assess dose-related efficacy (22). The antibody is intended to prevent the trans-neuronal spread of the tau protein. Other monoclonal antibodies being assessed in early phase studies and targeting aspects of the tau protein include BIIB092, LY3303560, and RO7105705 (Table 1).

Current status of anti-tau therapies in the AD treatment pipeline

One putative anti-tau agent, TRx0237 was studied in a Phase 3 trial and failed to show a difference between different doses. Studies in mouse models suggested that the agent functioned as an aggregation inhibitor and reduced the number of tau positive neurons (23); no target engagement biomarker was included in trial to determine if this was achieved in humans (24). Subgroup analyses suggest that some patients may have benefited from therapy and further studies of this compound are underway (24). Table 1 summarizes the anti-tau agents that are currently being tested in Phase 1 or Phase 2 clinical trials. These include both passive and active immunotherapies with monoclonal antibodies as well as drugs that affect the molecular structure of tau to modulate its function or prevent phosphorylation.

Other anti-tau drugs are also in development for AD including epigallocatechin-3 gallate (EGCG), a polyphenolic flavanoid extracted from green tea 25, and AC Immune's tau morphomers, small molecules designed to inhibit aggregation and seeding and disaggregate already formed tau aggregates. Preclinical studies suggest that tau morphomers reduce pathological tau, improve cognition and function, and reduce microglia activation. Importantly, they are capable of crossing the blood-brain barrier.

Outcome measures and biomarkers

Tau PET imaging

Tau and Aβ aggregates in the brain have been investigated in several cohort studies, both neuropathologically at autopsy and in living people using PET (26-28). The overall picture emerging from these studies is that among cognitively normal individuals, about one-third have high amyloid, and among those with high amyloid about half also have high tau loads. A minority of cognitively normal individuals have sub-threshold levels of amyloid and high tau. The

Table 1. Phase 1 and 2 clinical Trials targeting tau in AD populations

Agent	Sponsor	Class of Agent	Population	Outcome Measures	Biomarkers
Phase 1					
NPT088	Proclara	Immunoglobulin conjugate delivers small molecule that disaggregates Aβ and tau protein aggregates	Probable AD; florbetapir PET+	Primary: AEs Secondary: PK, immunogenicity	Amyloid PET, MNI-960 PET, CSF and blood
63733657	Johnson & Johnson	Immunotherapy to stop tau seeding	SAD, MAD; CSF consistent with AD	Primary: AEs Secondary: PK, immunogenicity	CSF: total, free and bound tau
BIIB076	Biogen	Immunotherapy	Probable AD; CSF consistent with AD	Primary: AEs Secondary: PK,	MRI abnormalities
LY3303560	Lilly	Immunotherapy binds and neutralizes tau aggregates	MCI due to AD or mild-moderate AD	Primary: AEs Secondary: PK, immunogenicity	
ACI-35	AC Immune	Liposomal anti-pTau vaccine	Mild to moderate AD	Primary: AEs Secondary: PK, immunogenicity	
Phase 2					
AADvac1	Axon Neuroscience	Active immunotherapy	Mild AD	Primary: TEAEs Secondary: CDR-SB, Custom cognitive battery, ADCS-ADL, Immunogenicity	Exploratory: CSF biomarkers, MRI volumetry, FDG-PET
ABBV-8E12 (separate trial underway in participants with PSP)	Abbvie	Passive immunotherapy targets aggregated extracellular tau	MCI or probable AD; amyloid PET+	Primary: CDR-SB, AEs Secondary: UPSA-brief, MMSE, ADCS ADL, FAQ, RBANS, ADAS-cog, NPI, CGIC	Not stated
ANAVEX 2-73 (open label extension of Phase 2 study)	Anavex Life Sciences	Sigma-1 receptor agonist and muscarinic agonist to regenerate neurons	Mild to moderate AD	Primary: AEs Secondary: MMSE, ADCS-ADL, HAM-D	
AZD0530	Astra Zeneca	Src/abl kinase inhibitor to improve synaptic function and reduce tau phosphorylation	Mild AD	Primary: FDG-PET, AEs Secondary: ADAS-cog, MMSE, ADCS-ADL, CDR-SB	Brain atrophy, CSF biomarkers, including P-tau and T-tau
BIIB092 (TANGO) (separate trial underway in participants with PSP)	Biogen	Immunotherapy – targets N-terminally truncated tau	MCI or mild AD; amyloid+	Primary: AEs Secondary: CDR-SB	Anti-BIIB092 antibodies
IONIS MAPT Rx	Ionis Pharmaceuticals/Biogen	MAPT RNA inhibitor; antisense oligonucleotide to reduce tau production	Mild AD	Primary: AEs Secondary: pharmacokinetics	
Methylene Blue	Texas AD Research and Care Consortium	Tau protein aggregation inhibitor	Healthy aging, MCI, mild AD	Primary: task fMRI for multiple memory domains, NPS battery Secondary: cerebral blood flow	
Nicotinamide (Vitamin B3)	University of California, Irvine	Histone deacetylase inhibitor to reduce tau phosphorylation	MCI, AD	Primary: Change in CSF p-tau 231 Secondary: change in CSF total tau	
Nilotinib	Georgetown University	Tyrosine kinase inhibitor to reduce amyloid and tau production	AD	Primary: AEs Secondary: CSF nilotinib levels	
RO7105705 (TAURIEL in prodromal to mild; LAURIET in moderate AD.)	Roche/Genentech	Immunotherapy targets extracellular tau; hypothesized to intercept cell-to-cell spreading.	Study 1: proddromal to mild AD; Study 2: moderate AD	Primary: CDR-SB, AEs Secondary: RBANS, ADAS-cog, ADCS-ADL, Amsterdam ADL	Tau PET, immunogenicity
LY3303560	Lilly	Immunotherapy binds and neutralizes tau aggregates	Change in memory >6 months	Primary: iADRS Secondary: ADAS-cog, ADCS-ADL, CDR-SB, MMSE	Aggregated tau deposition, vMRI, immunogenicity

ADAS-cog = Alzheimer's Disease Assessment Scale, cognition subscale, ADCS-ADL = Alzheimer's Disease Cooperative Study – Activities of Daily Living Inventory, AEs= adverse events, CDR-SB = Clinical Dementia Rating Scale Sum of Boxes, CGIC = Clinical Global Impressions Scale, FAQ = functional activities questionnaire, fMRI = functional magnetic resonance imaging, HAM-D = Hamilton Psychiatric Rating Scale for Depression, iADRS=integrated AD rating scale, MMSE = Mini-mental state examination, NPI = neuropsychiatric inventory, NPS battery = neuropsychiatric symptoms battery, RBANS= Repeatable Battery for the Assessment of Neuropsychological Status, TEAEs = treatment-emergent adverse events. UPSA=University of California Performance Based Skills Assessment, brief version,

anatomic location of tau deposition may be important. These observations raise the possibility that quantifying progression of tau pathology may provide an early indicator of disease.

Johnson and colleagues have investigated the anatomical variability of amyloid and tau deposition in more than 400 individuals. These data indicate that distribution of tau in the rhinal cortex correlates with amyloid burden and that low amyloid individuals just starting to show elevations in tau are those most likely to be on the way to neocortical tauopathy. By the time tau levels have increased in the inferior temporal cortex, individuals may show significant impairments. These data support the hypothesis that amyloid is associated with tau spread.

Longitudinal data also provide support for these measures as useful for staging in order to establish a basis on which to measure change in serial imaging that could be useful in the clinical and clinical trial settings. Four stages were proposed:

Stage 0 – No signal exceeding background, consistent with Braak 0.

Stage 1 – Rhinal cortex signal emerging in a minority of low-amyloid clinically unimpaired individuals (allocortex, MTL) consistent with Braak I/II

Stage 2 – Inferior temporal signal emerging in the presence of high levels of fibrillar amyloid in clinically unimpaired individuals (corresponding to Braak stages III/VI)

Stage 3 – Additional neocortical binding in mild cognitive impairment (MCI) and AD patients (beyond inferior temporal; corresponding to Braak stages V/VI)

Figure 1 provides an example of images with high and low tau burden.

Figure 1. Flortaucipir images with low (Braak I/II) and high (Braak III/VI) levels of tau. The individual whose image is shown on the left had low amyloid levels; the one shown on the right had high amyloid levels (images courtesy of Keith Johnson)
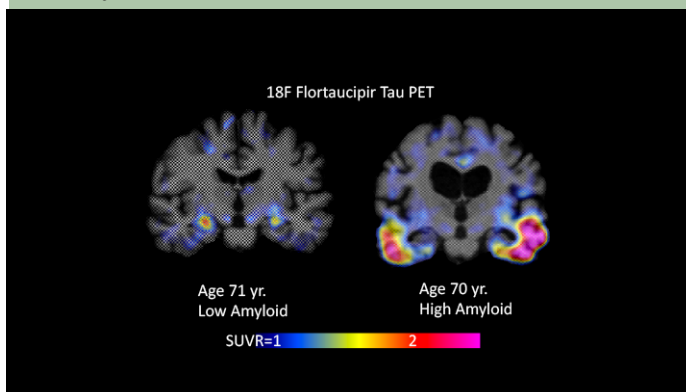
CSF and blood biomarkers of tau

A systematic review and meta-analysis of cerebrospinal fluid (CSF) and blood biomarkers showed that CSF levels of total tau (T-tau), phosphorylated tau (p-tau), Aβ42, and neurofilament light (NfL), and plasma levels of T-tau were associated with AD and MCI due to AD but with quite pronounced, assay-dependent variation between studies, and no or only weak correlation with CSF T-tau levels (29-31). With regard to P-tau, a semi-sensitive assay for tau phosphorylated at threonine 181 (similar to the most employed CSF test) with electrochemiluminescence detection has been developed (32). Using this assay, plasma P-tau concentration was higher in AD dementia patients than controls. Plasma P-tau concentration was associated with both Aβ and tau PET and more AD-associated than the corresponding plasma T-tau test, which are promising results in need of replication. While conventional plasma measures of Aβ42 and Aβ40 by ELISA do not show a consistent change in clinically diagnosed AD cases as compared with cognitively unimpaired elderly (29), recent studies of blood Aβ using single molecule array (Simoa) or mass spectrometry have shown a relationship between blood levels of Aβ 40/42 ratios and the brain burden of Aβ (33-35). NfL indicates axonal damage and can also be measured in blood (36). Blood NfL shows particular promise as a biomarker of neurodegeneration in AD (37, 38) but high levels are also found in many other disorders characterized by neurodegeneration (39, 40). Given that NfL is a general neurodegeneration marker and not specifically involved in AD pathophysiology, it may give more unbiased information than tau biomarkers in clinical trials. Furthermore, the correlation between CSF and blood levels of NfL is very high (36), which is not the case for blood measures of tau (30). Synaptic proteins, including dendritic protein neurogranin and the pre-synaptic growth-associated protein 43 (GAP-43), show marked increases in CSF and are seemingly specific for AD (41, 42). Emerging CSF biomarkers including neuron-specific enolase (NSE), visinin-like protein 1 (VLP-1), heart fatty acid binding protein (HFPAP), and YKL-40 (a marker of glial activation) show moderate associations with AD (29, 43).

CSF tau comprises many different tau fragments that reflect processing of secreted tau, and some of these fragments may prove to be useful diagnostically (44) or provide information about tau kinetics in neurons (45). New assays are being developed to measure additional endogenous tau fragments that may correlate with tau pathology. For example, one of these tau fragments, tau368, results from cleavage of tau by asparagine endopeptidase (AEP) at position 368. The result of this is tau hyperphosphorylation, impaired microtubule assembly, and aggregation of truncated tau in neurofibrillary tangles (46). Inhibiting AEP may represent a novel therapeutic strategy for neurodegenerative disease (47). Tau368 can be measured in CSF and a first small study shows an association with longitudinal increase in tau PET tracer retention (48). Further, mass spectrometry studies show that CSF tau is

specifically cleaved to a mid-domain fragment between amino acids 222-225 (45). Using an assay based on an end-specific tau x-224 monoclonal antibody, increased CSF levels were found in AD, while tau224 levels were low in other tauopathies (49). Exosomal tau has been evaluated as a biomarker but the studies have not been replicated and it is presently not possible to draw any conclusion on whether or not exosomal tau is a biomarker for AD.

The varying measures of tau report on different aspects of AD biology. In the amyloid, tau, neurodegeneration (ATN) Framework for AD diagnosis (50), tau PET and CSF p-tau are viewed as reporters of the presence and spread of tau pathology, whereas CSF t-tau, fluorodeoxyglucose PET, and MRI atrophy are seen as reporters of neurodegeneration. Recent evidence suggests that the soluble forms of tau are increased in production with greater amyloid plaque burden (45), while aggregated forms of tau appear at later stages of AD pathophysiology, closer to symptom onset. Tau markers --- tau PET, p-tau, t-tau --- measure different aspects of AD from this perspective.

For use in clinical trials of anti-tau agents, CSF biomarkers of amyloid and tau are needed to provide evidence of target engagement, enable enrichment of trials with appropriate participants, and show downstream effects of treatment (51). Lowering of CSF p-tau may suggest an effect on tau phosphorylation; however, more studies are needed to evaluate how CSF p-tau relates to brain pathology. Biomarker studies in recent clinical trials of the anti-amyloid antibodies bapineuzumab, gantenerumab, and BAN-2401 suggest that declines in CSF p-tau, t-tau, neurogranin and NfL indicate a downstream effect of Aβ immunotherapy on neurodegeneration, tau pathology, and synaptic degeneration (52-54).

Fully automated CSF immunoassays of AD biomarkers are now available, and in a study comparing fully automated CSF immunoassay with amyloid PET imaging, a multinational group of investigators found that the CSF tau/Aβ ratio was as accurate as amyloid PET in predicting clinical progression among patients with MCI (55) .

Challenges and unanswered questions

While the development of tau-targeted therapies is seen by many in the AD research community as one of the highest priority efforts, the complexity of tau protein processing gives rise to many challenges that have slowed development of tau-based therapies (56). Among the questions raised by the Task Force were these:
- What is known about the normal physiological function of tau, and are there potential negative/untoward consequences of reducing tau?
- What is the effect of tau suppression on spatiotemporal deposition of tau?
- What degree of tau lowering should be targeted to achieve an optimal therapeutic effect?
- What other factors may contribute to tau-based neurodegeneration (e.g., inflammation, aging, or vascular factors?)
- What is the relationship of amyloid-beta and tau?
- What is the relationship of soluble forms of tau and aggregated tau deposits?
- What is the role of microglia activation in the development of tau pathology?
- Since most tau is intracellular, will targeting it extracellularly be sufficient; or is there a window of time during which limiting extracellular tau would show a treatment benefit?
- What happens downstream when an antibody binds to tau? Is it sequestered or disposed of through cellular mechanisms or the glymphatic system 57 and does this result in downstream preservation of neurons?
- What are the best tau epitopes or tau fragments to target?
- Which tau fragments correlate best with AD-type neurodegeneration in CSF or in plasma?
- Which p-tau variants in CSF or blood correlate best with tau pathology in AD, or can differentiate AD from other tauopathies?
- Are there differential rates of change in tau deposition across the anatomy?
- What regions should tau PET target to demonstrate target engagement, and how should tau PET be developed for use in clinical trials to predict treatment response or measure treatment effect?
- What will be required to make tau PET useful clinically for diagnosis, prognosis, or prediction of treatment response?
- Do trials for anti-tau agents require similar structures as for Aβ-targeting agents even though the dynamics of the protein are different?
- What is the best population, taking into account the ATN stage, to target?
- Should anti-tau clinical trials focus on subpopulations and if so, which subpopulations?
- Would the best path forward for anti-tau agents be to test them in combination trials with Aβ-targeting agents or drugs that target other pathologies such as neuroinflammation?
- How can tau-PET be used to stage AD?
- What are the best tau-related outcomes for AD trials?

Conclusions

Anti-tau therapies are beginning to populate the AD drug development pipeline, mostly in Phase 1 and Phase 2 trials. However, anti-tau treatments have not yet shown evidence of a treatment effect in patients. The Task Force concluded that the development of anti-tau treatment will be determined by multiple trials and will require contributions from industry, academia, and advocacy

groups.

The Task Force also called for incorporating CSF tau measures in all anti-tau trials. At a later date, tau PET may also be a viable option. For a biomarker to accurately assess target engagement and for pharmacodynamic studies, assays need to be designed specifically for the therapeutic antibody in addition to general tau-based assays. Such assays would enable exploration of whether a change in a specific tau species indicates that the therapeutic antibody binds tau in the brain parenchyma and if bound tau is secreted into the CSF.

Most Task Force members agreed that anti-tau trials are justified because AD symptoms are likely driven by the spread of tau and its degenerative effects, as well as by amyloid. However, most members also agreed that the specific tau-based mechanisms that will likely provide a treatment effect from anti-tau therapy are unclear and that significant observational and trial related studies will help better inform which tau targets will be most effective.

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