Title
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Permalink
https://escholarship.org/uc/item/47w3f88w

Journal
The Lancet. Neurology, 16(7)

ISSN
1474-4422

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Publication Date
2017-07-01

DOI
10.1016/s1474-4422(17)30157-6

Peer reviewed
Advances in progressive supranuclear palsy: new diagnostic criteria, biomarkers, and therapeutic approaches

Adam L Boxer, Jin-Tai Yu, Lawrence I Golbe, Irene Litvan, Anthony E Lang, Günter U Höglinger

Progressive supranuclear palsy (PSP), previously believed to be a common cause of atypical parkinsonism, is now recognised as a range of motor and behavioural syndromes that are associated with a characteristic 4-repeat tau neuropathology. New research criteria that recognise early presentations of PSP and operationalise diagnosis of the full spectrum of clinical phenotypes have been reported. The Movement Disorders Society PSP diagnostic criteria include syndromes with few or mild symptoms that are suggestive of underlying PSP pathology and could provide an opportunity for earlier therapeutic interventions in the future. These criteria also include definitions for variant PSP syndromes with different patterns of movement, language, or behavioural features than have been conclusively associated with PSP pathology. Data from new diagnostic biomarkers can be combined with the clinical features of disease to increase the specificity of the new criteria for underlying PSP pathology. Because PSP is associated with tau protein abnormalities, there is growing interest in clinical trials of new tau-directed therapies. These therapies are hypothesised to have disease-modifying effects by reducing the concentration of toxic forms of tau in the brain or by compensating for loss of tau function. Since tau pathology is also central to Alzheimer’s disease and chronic traumatic encephalopathy, a successful tau therapeutic for PSP might inform treatment of other neurodegenerative diseases.

Introduction

Progressive supranuclear palsy (PSP) was initially believed to be a cause of atypical parkinsonism; however, during the past decade, PSP was found to encompass a range of clinical phenotypes involving behavioural, language, and movement abnormalities. The classic movement disorder clinical phenotype, now referred to as Richardson’s syndrome (PSP-RS), was first described in 1964 by Steele, Richardson, and Olszewski. Since then, no effective treatments for this uniformly fatal disorder have been identified. However, because PSP is strongly linked to tau-protein abnormalities, both neuropathologically and genetically, there is an increased interest in clinical trials of new tau-directed therapies. PSP-RS is considered to be a rare disease, with a prevalence of about 5–7 cases per 100,000 people. A study in the UK showed a peak prevalence between the ages of 70 and 74 years of about 18 cases per 100,000 people. However, a study in Japan that included other PSP phenotypes in addition to PSP-RS found a total prevalence of 18 cases per 100,000 across all ages. This higher prevalence is consistent with estimates from autopsy series, and suggests that the prevalence of the full spectrum of PSP syndromes is substantially higher than prevalence estimates based on PSP-RS cases only. Findings from a cluster of PSP cases in an industrial city in France and a multicentre case-control study suggest that environmental risk factors affect PSP incidence.

In this Review, we describe advances in clinical diagnosis, neuropathology, genetics, biomarkers, and therapeutics of PSP. An important advance has been the development of the new International Parkinson’s and Movement Disorder Society (MDS) Criteria for the Diagnosis of PSP, which recognise early, suggestive forms of PSP, and operationalise diagnosis of non-Richardson’s PSP phenotypes.

The spectrum of progressive supranuclear palsy

The MDS PSP Diagnostic Criteria were based on a comprehensive literature review by the MDS PSP Working Group, followed by a consensus conference in March, 2016, in collaboration with patient advocacy groups. In this Review, we outline the essential components and guidelines of these new criteria; the detailed criteria have been published elsewhere. Most neurodegenerative diseases begin with a presymptomatic phase in which neuropathological changes accumulate, but have not yet crossed the threshold necessary to produce clinical symptoms. A wealth of evidence supports this sequence of pathological events in Alzheimer’s disease and Parkinson’s disease, and the description of mild asymptomatic PSP pathology in some clinically healthy elderly people suggests that a similar sequence of events might occur in PSP. Therefore, it is likely that PSP starts with a presymptomatic phase, in which neuropathological abnormalities begin to accumulate but clinical features are absent, continues with a suggestive-of-PSP (soPSP) phase, in which individuals develop mild or isolated symptoms but do not meet the full MDS research criteria for a possible or probable PSP syndrome, and culminates with a fully symptomatic stage that, in many cases, would meet the research criteria for PSP-RS or another clinical variant of PSP (vPSP; figure 1). As PSP progresses, many patients with vPSP syndromes eventually develop features of PSP-RS. Patients who only display a vPSP phenotype are difficult to conclusively diagnose before death.

Most patients with PSP syndromes eventually develop some or all of the clinical features of PSP-RS; however, in approximately two-thirds of the patients with neuropathologically defined PSP, as determined in brain bank studies, the initial presentation in the first 2 years is not...
PSP-RS. Other vPSP syndromes, named according to their predominant clinical features, might account for about one-third to two-thirds of initial presentations, and include PSP with predominant parkinsonism (PSP-P),

pure akinesia with gait freezing (formerly PAGF, and now PSP with progressive gait freezing [PSP-PGF]), corticobasal syndrome (PSP-CBS), primary progressive apraxia of speech or non-fluent variant primary progressive aphasia (nfvPPA; when caused by PSP, this disease is named PSP with predominant speech or language disorder [PSP-SL]), behavioural variant frontotemporal dementia (bvFTD; when caused by PSP, this disease is named PSP with predominant frontal presentation [PSP-F]), and PSP with predominant cerebellar ataxia (PSP-C; figure 2).

**Presymptomatic PSP phase**

Presymptomatic PSP occurs in individuals who are asymptomatic but at high risk of developing symptoms of PSP. Currently, the presymptomatic phase can only be identified post mortem from evidence of PSP-associated neuropathological changes in individuals who are considered to be otherwise healthy. Because the new MDS PSP criteria focus on clinical diagnosis, they do not include the presymptomatic PSP phase, but the criteria are consistent with this notion. In one community-based autopsy series, PSP neuropathology was present in five (2.1%) of 233 individuals. Another two studies with similar methodology found PSP pathology in five (4.2%) of 119 elderly individuals in a clinically healthy cohort and in 29 (4.6%) of 626 individuals older than 60 years in a large forensic autopsy series in Japan. These numbers are in striking contrast to the low estimated prevalence of PSP-RS in epidemiological studies, which suggests that, if these findings are correct, most individuals with presymptomatic PSP do not develop overt disease.

**Suggestive-of-PSP phase**

soPSP refers to the early symptomatic phase of PSP that occurs before development of a fully symptomatic PSP syndrome, during which a few clinical symptoms or signs are clearly present, but do not warrant a diagnosis of PSP. Inherent in the definition of soPSP is some uncertainty as to whether the individual will progress to PSP-RS, vPSP, or to a non-PSP diagnosis. In the future, diagnostic biomarkers for PSP might help to mitigate this uncertainty. The soPSP category also includes individuals who have developed one or more major features of PSP-RS or of a vPSP syndrome, but do not fulfill diagnostic criteria for these syndromes (figure 1), such as individuals with isolated saccadic slowing or unexplained postural instability. A diagnosis of soPSP can be made only when individuals are suspected to have PSP pathology but do not fully meet the criteria for PSP diagnosis, and when other causes have been excluded. Recognition of individuals in the soPSP phase of disease might allow neuroprotective treatment to be initiated early enough to stabilise these patients before the onset of substantial disability.

**Symptomatic PSP phenotypes**

The clinical features of the different PSP phenotypes have been described in detail in several reviews. Importantly, the language and behavioural presentations of PSP can also frequently meet criteria for frontotemporal lobar

**Figure 1: Hypothetical model of the clinical trajectories of progressive supranuclear palsy**

Progressive supranuclear palsy is considered to be a pathological continuum from a presymptomatic phase, through a suggestive phase, to a fully symptomatic phase that, in many cases, would meet research criteria for possible or probable PSP-Richardson’s syndrome by the Movement Disorder Society criteria, or a variant PSP syndrome. Not all cases of presymptomatic or suggestive PSP will progress to a PSP phenotype. PSP=progressive supranuclear palsy.

**Figure 2: Clinical syndromes in progressive supranuclear palsy**

PSP=progressive supranuclear palsy. RS=Richardson’s syndrome. PSP-P=PSP with predominant parkinsonism. PSP-PGF=PSP with progressive gait freezing. PSP-CBS=corticobasal syndrome. nfvPPA=non-fluent variant primary progressive aphasia. PSP-SL=PSP with predominant speech or language disorder. bvFTD=behavioural variant frontotemporal dementia. PSP-F=PSP with predominant frontal presentation. PSP-C=PSP with predominant cerebellar ataxia. Relative proportions of each syndrome (illustrated by bar length) are speculative. PSP pathology means meeting neuropathological criteria for PSP. Mixed pathology means meeting neuropathological criteria for PSP plus another disorder such as Alzheimer’s or Parkinson’s disease. Other pathology means meeting neuropathological criteria for another disorder such as Parkinson’s disease, but not meeting criteria for PSP. Nomenclature reflect Movement Disorder Society PSP diagnostic criteria.
degeneration. We briefly describe each syndrome, as classified by the new MDS PSP criteria, in the following section, with particular attention to new evidence from the past 7 years. We also highlight the changes in nomenclature introduced by the new MDS PSP Criteria.

Richardson’s syndrome
PSP-RS refers to the classically described phenotype of PSP that was originally codified in the 1996 National Institute for Neurological Disorders and Society for PSP research criteria. The most frequently reported symptoms at onset are unexplained falls, unsteady gait, bradykinesia, subtle personality changes (apathy, disinhibition), cognitive slowing (bradyphrenia), executive dysfunction (difficulty planning or multitasking), slow, ataxic, spastic, and hypophonic speech, dysphagia, and impaired ocular movement (ie, slowing of vertical saccades, difficulty reading, or apraxia of eyelid opening). Vertical supranuclear gaze palsy is the definitive diagnostic feature, but its onset is variable, and might not present until 3–4 years after disease onset. Decreased velocity (slowing) and gain (amplitude) of vertical greater than horizontal saccadic eye movements and decreased or absent optokinetic nystagmus are early signs of PSP-RS that are detected at neurological examination.

PSP-parkinsonism
PSP-P was first defined as a clinical phenotype of PSP on the basis of an autopsy series, in which a subset of patients had early features of Parkinson’s disease and a more benign disease course than patients with PSP would usually have. Patients with PSP-P often present with an asymmetric onset of tremor, bradykinesia, rigidity, a moderate initial response to levodopa therapy, and a slower rate of disease progression than patients with PSP-RS. The clinical presentation of PSP-P resembles idiopathic Parkinson’s disease sufficiently that the two disorders are difficult to distinguish early on. Later in the disease course, most patients develop features of PSP-RS and they are retrospectively diagnosed with PSP-P. It is impossible to conclusively diagnose patients with PSP-P premortem if they do not develop symptoms of PSP-RS. However, later in the disease course, levodopa-induced dyskinesias, autonomic dysfunction, and visual hallucinations are much less common in patients with PSP-P than in those with Parkinson’s disease, which can help to distinguish these diseases.

PSP with progressive gait freezing
Pure akinesia with gait freezing, now referred to as PSP-PGF, is a clinical phenotype of PSP that initially presents with an isolated gait disorder years before development of other PSP-RS features. PSP-PGF is characterised by progressive gait disturbance with start hesitation and subsequent freezing of gait, sometimes also involving difficulties with initiating or completing speech or writing, without tremor, rigidity, dementia, or eye movement abnormalities during the first 5 years of the disease. PSP-PGF has been reported to be highly predictive of PSP pathology.

PSP-corticobasal syndrome
CBS is the best recognised presentation of corticobasal degeneration, a 4-repeat tauopathy closely related to PSP. Clinically and genetically, there is substantial overlap between corticobasal degeneration and PSP neuropathology. The diagnostic research criteria for corticobasal degeneration acknowledge a syndrome caused by corticobasal degeneration pathology that resembles PSP-RS, which underscores this frequent overlap; both corticobasal degeneration and PSP feature 4-repeat tauopathy, but morphology, anatomical distribution, and biochemical features differ between these diseases. In contrast, PSP-CBS refers to the clinical CBS phenotype of neuropathologically defined PSP, characterised by a variable combination of progressive limb rigidity, apraxia, cortical sensory loss, alien limb, and bradykinesia, and that is unresponsive to levodopa. PSP-CBS is a rare presentation of PSP pathology and was present in only six of the 179 pathologically diagnosed PSP cases in the Queen Square Brain Bank series. Distinction of PSP-CBS from corticobasal degeneration-CBS based on clinical features is impossible ante-mortem and, for this reason, the new MDS PSP Criteria designate PSP-CBS as possible PSP, but probable 4-repeat tauopathy (either corticobasal degeneration or PSP pathology).

PSP-speech language
nfvPPA is a progressive syndrome characterised by either agrammatism in language production or effortful, halting speech with inconsistent speech sound errors and distortions (apraxia of speech). The MDS PSP criteria recognise a clinical phenotype of PSP that initially presents with predominant speech or language disorder features of nfvPPA, before developing motor features of PSP-RS. A longitudinal study of 13 patients with primary progressive apraxia of speech, which has similar initial symptoms to nfvPPA, found that five of these patients developed a syndrome similar to PSP-RS about 5 years after onset, and 22 of 25 patients with nfvPPA in a larger series were found to have tau pathology post mortem, most commonly 4-repeat tauopathy. Similar to PSP-CBS, the new PSP-CBS criteria designate PSP-SL as possible PSP, but probable 4-repeat tauopathy, because determination of which PSP-SL cases have PSP pathology based on clinical findings is impossible ante-mortem.

PSP with frontal presentation
PSP-F refers to cases with presentation with clinical features of behavioural variant frontotemporal dementia years before the presentation of motor features of PSP-RS. bvFTD is a clinical syndrome characterised by an early and progressive deterioration of personality, social
comportment, behaviour (such as apathy, rigidity, disinhibition, and hyperorality), and cognition.\(^{22}\) PSP-F is uncommon. Only three (4-5%) of 66 autopsy-proven PSP cases in the Mayo Clinic series\(^{25}\) presented with the behavioural and personality changes of bvFTD. However, a European series\(^{10}\) of autopsy-proven PSP suggested a higher prevalence of FTD-like symptoms at onset of 12 of 100 autopsy-confirmed PSP cases.

**PSP with predominant cerebellar ataxia**

PSP-C is a rare clinical phenotype. Patients present with cerebellar ataxia as the initial and principal symptom before developing cardinal features of PSP-RS, such as saccade impairments and falls, during the disease course. In contrast to the proportion of three cases of 22 patients reported in an earlier Japanese study,\(^{11}\) a Mayo Clinic autopsy study\(^{12}\) identified only five patients with PSP-C among 1085 pathologically confirmed PSP cases, four of whom were clinically misdiagnosed with multiple system atrophy type C. In these four patients, clinical features of PSP-C were similar to those of multiple system atrophy type C, but they did not have the dysautonomia required to meet criteria for a diagnosis of multiple system atrophy.\(^{13}\) Because PSP-C is difficult to diagnose ante-mortem, and ataxia is more frequently suggestive of neurodegenerative diseases other than PSP, this variant is not included in the new MDS PSP criteria.

**PSP with mixed pathology**

Although strong associations exist between the hallmark neuropathological features of PSP and clinical features, there is an increased recognition that a subset of patients might have also other neuropathologies that affect their clinical phenotype. Various co-pathologies have been described in association with PSP including, most frequently, Alzheimer’s disease pathology, but also Parkinson’s disease pathology, TDP-43 deposition, argyrophilic grain disease, or cerebrovascular disease. In a study\(^{14}\) evaluating 64 cases of pathologically proven PSP, 36% of patients had concomitant Alzheimer’s disease, 20% had Parkinson’s disease, 1% had dementia with Lewy bodies, 44% had argyrophilic grain disease, 52% had cerebr al white matter rarefaction, and 25% had cerebral amyloid angiopathy.

**Neuropathology**

The National Institute of Neurological Disorders and Stroke neuropathological criteria for PSP were validated in 1996,\(^{15}\) and require the presence of neurofibrillary tangles or neuritopl threads (composed of tau protein), or both, in the basal ganglia and the brainstem. Microscopic features include neuronal loss, gliosis, neurofibrillary tangles, neuritopl threads, tufted astrocytes, and oloydendroglial coiled bodies.\(^{15}\)

The regional distribution of tau pathology and neuronal loss is a source of pathological and, consequently, clinical heterogeneity in PSP.\(^{22}\) More severe and widespread cortical tau pathology has been documented in PSP syndromes with more severe cortical symptoms ante-mortem, such as PSP-CBS,\(^{16}\) PSP-SL,\(^{17}\) and PSP-F, than in movement-predominant PSP syndromes, such as PSP-P and PSP-PGF. Brainstem-predominant PSP syndromes, such as PSP-P and PSP-PGF, have less severe cortical tau pathology and more severe degeneration in the globus pallidus, subthalam ic nucleus, and substantia nigra compared with PSP-RS.\(^{3}\)

**Genetics**

**MAPT polymorphisms and haplotypes**

The locus most strongly linked with risk of PSP is the gene for the microtubule-associated protein tau (MAPT)\(^{4}\). Genetic studies,\(^{4}\) including genome-wide association studies, have identified both an inversion polymorphism and haplotype-specific MAPT polymorphisms that affect the risk of PSP (figure 3). The odds ratio (OR) for PSP in carriers of the MAPT H1/H1 haplotype is 5.5, which is higher than the OR for the APOE ε3/ε4 genotype (–3.0) as a risk factor for Alzheimer’s disease.\(^{41}\) The underlying molecular mechanisms for PSP risk conferred by the H1 haplotype is unclear. A rare coding MAPT variant (152A→T) alters microtubule assembly and is a strong risk factor for both PSP and frontotemporal dementia.\(^{42}\)

**MAPT mutations**

PSP is a sporadic disease, but very rare familial forms of PSP have been described.\(^{43,44}\) and 12 (7%) of 172 patients with PSP-RS in one series\(^{45}\) fulfilled criteria for an autosomal dominant mode of inheritance; however, this finding was not replicated in a subsequent study.\(^{46}\) Although a causative mutation has not been identified for most familial cases, mutations in the MAPT gene have been identified as pathological mutations in several families with autosomal dominant pattern of disease inheritance, including some families with pathologically confirmed PSP.\(^{47}\) Notably, most of these variants are located in exon 10 and its splicing regulatory region (figure 3). Insoluble 4-repeat tau protein deposits are characteristic of PSP pathology, therefore mutations that enhance splicing in MAPT exon 10 might promote disease by enhancing production of 4-repeat tau isoforms.\(^{48}\)

**Emerging loci from genome-wide association studies**

The first large genome-wide association study\(^{49}\) in patients with PSP identified three new genetic risk factors: STX6, EIF2AK3, and MOBP. The mechanisms by which these
genes might increase risk for PSP are not known. Thetau-associated single nucleotide polymorphism near theMOBP gene correlates more strongly with increasedexpression of the SLC25A38 gene, which encodes theproteins apoptosin, than with MOBP expression.45 Apoptosin overexpression in transgenic mice increasescaspase-mediated tau cleavage, tau aggregation, synapticfunction, and gait and balance deficits.45 Loss-of-function ofEIF2AK3 in human beings appears to result in Wolcott-Rallison syndrome, a severe, childhood-onset disease with cerebellar tau pathology.46 These findings suggest that other genetic polymorphisms might alsoincrease the risk of PSP via their effects on tau.

**Advances in biomarkers**

PSP-RS is a distinctive clinical syndrome, usually easilydifferentiated from other parkinsonian disorders. However,insuggestive or variant cases, biomarkers might helptostandardize diagnostic accuracy. During the pastdecade, several neuroimaging, biological, andneurophysiological biomarkers have been described aspotentially helpful in differentiating PSP-RS from otherparkinsonian syndromes (table 1). However, an importantlesson learned from early studies is that the diagnosticvalue of these biomarkers cannot be established withoutadequately powered studies in cases confirmed by autopsy.For example, midbrain atrophy, alone or in combination

with other brainstem imaging measures, has beenrepeatedly identified as a biomarker of PSP, but couldnottell the difference between RS due to pathological changesassociated with PSP from pathological changes ofcorticobasal degeneration in some studies.47

There is an urgent need for diagnostic biomarkers thatcan detect PSP pathology in very mildly symptomatic orpresymptomatic individuals to enable early diagnosis andintervention with potentially disease-modifying therapies.Such biomarkers might permit the expansion of therapeutestudies to early disease stages in patients with vPSP orsoPSP. Biomarkers that reflect the pharmacodynamic effects of new therapies on their intended targets are also needed to support clinical trials.

**MRI**

Atrophy of the midbrain and superior cerebellar pedunclesis a useful marker in differentiating PSP-RS from otherparkinsonian syndromes and can be tracked longitudinallywith diffusion tensor imaging.45 In a cohort includingpatients with pathologically confirmed PSP, multiple systematrophy, Parkinson’s disease, or corticobasal degeneration andmatched healthy controls, conventional structural MRI was more specific but less sensitive than clinical diagnosis of PSP, and the hummingbird and morning glory flower signsexhale 100% specificity for PSP but lower sensitivity (68-4% for the hummingbird sign and 50.0% for the morning glory sign).46 Another cohort study47 that included patients with pathologicallyconfirmed cases of PSP found that the magnetic resonanceparkinsonism index (MRPI) yielded sensitivity of 100% and specificity of 99.2–100.0% for PSP-RS. The pons:midbrain ratio, as calculated from conventional MRI, had high specificity and sensitivity for the diagnosis of pathologically confirmed PSP.48 In studies of the early stages of PSP,49 MRPI was also able to predict development of PSP-RS in unclassifiable parkinsonism, and eye movement abnormalities in PSP.50

Resting-state functional MRI (fMRI) is also a promisingimaging biomarker for PSP. An intrinsic connectivitynetwork anchored at the dorsal midbrain showsdisruptions in PSP that are correlated with pathologicaland clinical features.51

**PET using fluorodeoxyglucose (FDG), ^18F-AV1451, andother ligands**

FDG-PET in patients with 4-repeat tauopathy, includingPSP variants (confirmed at autopsy), showed hypometabolism in the frontal cortex, caudate, midbrain, andthalamus.52,53 PSP-related metabolic co-variance patternsmight also help with differential diagnosis.54 However,despite these observations, the diagnostic utility ofFDG-PET in PSP is not well established.

The development of tau-specific PET imaging ligands offers the opportunity for in-vivo topographical mapping andquantification of tau aggregation and deposition in parallel with clinical assessments of PSP.55
ligand, $^{18}$F-AV1451, binds specifically to neurofibrillary tangles and paired helical filament-tau in Alzheimer’s disease, and produces high-quality images in living patients, but its utility in measurement of patients with PSP is still uncertain. Previous data have suggested weak AV1451 binding to aggregated 4-repeat tau in autopsy tissue slices from patients with PSP. Preliminary PET data in patients suggest that AV1451 binds more strongly to areas of known tau pathology in patients with more advanced PSP-RS compared with age-matched healthy controls. Several other novel selective tau tracers, including $^{11}$C-PBB3, have also been reported to bind to tau in patients with PSP, but insufficient data exist at this time to gauge their potential utility.

**CSF and blood biomarkers**

Several studies have attempted to identify CSF biomarkers that would allow accurate diagnosis of PSP. None of these studies were done in cases confirmed at autopsy. CSF phospho-tau and total tau concentrations in patients with PSP are normal or low relative to healthy controls, in contrast with those in patients with Alzheimer’s disease, in whom phospho-tau and total tau concentrations are increased. Several CSF studies showed 2–5 times increased neurofilament light chain concentrations in patients with PSP compared with healthy controls, Parkinson’s disease, Parkinson’s disease dementia, and dementia with Lewy bodies, but not when compared with CBS and multiple system atrophy. The only CSF biomarker that changed over time in a multicentre PSP clinical trial was neurofilament light chain concentration. Neurofilament light chain concentrations can now be measured in blood reliably, and patients with PSP-RS have elevated concentrations of plasma neurofilament light chain compared with age-matched healthy controls and patients with Parkinson’s disease. Baseline plasma neurofilament light chain concentrations predicted disease progression over the course of a year, as measured by various clinical and MRI measures.

### Table 1

<table>
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<tr>
<th>Potential uses</th>
<th>Bedside diagnosis</th>
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<th>Progression biomarker</th>
<th>Diagnostic biomarker</th>
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<td>Ratio differentiated pathologically confirmed PSP from Parkinson’s disease and multiple system atrophy, predicted gaze palsy and other Richardson’s syndrome signs (in clinically diagnosed cases)</td>
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(Table 1 continues on next page)
Physiological biomarkers

Slowing of vertical saccades to a greater extent than horizontal saccades is a distinctive feature of PSP-RS. Decreases in saccade velocity and gain account for the most characteristic PSP ocular motor deficits, and have been shown to be very specific findings that allow differentiation of autopsy-confirmed PSP from other disorders. Profound changes in saccade velocity and gain over the course of 1 year have been shown in two cases of PSP that were confirmed by autopsy. Retinal optical coherence tomography is another promising biomarker for PSP, but remains in an early stage of investigation.

Therapeutic approaches

PSP is a uniformly fatal disease. Patients with PSP-P often initially experience a symptomatic benefit from levodopa therapy, as do a few patients with PSP-RS; however, this benefit is transient in most cases and has no known effect on disease duration. Physical therapy is helpful, and leads to measurable improvements on clinical rating scales. Pretarsal botulinum toxin injections might be effective for apraxia of eyelid opening. Several randomised placebo-controlled clinical trials with small numbers of patients have been performed in patients with PSP-RS (table 2); however, none of these studies showed efficacy other than for co-enzyme Q10, which showed a modest symptomatic benefit in a small, 6-week study, but this result was not replicated in a larger, albeit underpowered, 12-month study. Deep brain stimulation of the pedunculopontine nucleus has been attempted in patients with advanced PSP-RS; however, no clear benefits were observed, and there were unacceptable side-effects. The rapid gain of knowledge on the pathogenesis of PSP has facilitated the implementation of a series of clinical studies with hypothesis-driven, disease-modifying therapeutic approaches targeting tau or mitochondrial dysfunction. Of these, three clinical trials were adequately powered to possibly show small to moderate

Physiological biomarkers

<table>
<thead>
<tr>
<th>Potential uses</th>
<th>Post-mortem validation</th>
<th>Key insights</th>
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<tr>
<td>Bedside diagnosis</td>
<td>Animal models</td>
<td>Progression biomarker</td>
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<td>Phospho181 Tau</td>
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<td>Spontaneous and evoked blink rate</td>
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<td>Retinal thickness</td>
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<tr>
<td>Quantitative</td>
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Table 1: Potential biomarkers for progressive supranuclear palsy

CBD=corticobasal degeneration. PSP=progressive supranuclear palsy. DTI=diffusion tensor imaging.
disease-modifying effects: the Neuroprotection and Natural History in Parkinson’s Plus Syndromes (NNIPPS) study of riluzole, a phase 2 trial of tideglusib, and a phase 2–3 trial of davunetide. All three trials failed to show efficacy on primary or secondary clinical endpoints. An important limitation of these studies was the absence of a pharmacodynamic biomarker able to show that the experimental drug engaged its physiological target and produced its hypothesised biological effect. Thus, it is possible that the studies were negative because the proposed mechanism of action did not operate in human beings in the same manner as in animal models.

<table>
<thead>
<tr>
<th>Mode of action</th>
<th>Disease</th>
<th>Phase</th>
<th>ClinicalTrials.gov identifier</th>
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<tbody>
<tr>
<td>TPI-28784</td>
<td>Microtubule stabiliser Alzheimer’s disease, corticobasal degeneration, PSP</td>
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<td>NCT01966666, NCT02133846</td>
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<td>AADvac1</td>
<td>Tau active vaccination Alzheimer’s disease</td>
<td>1</td>
<td>NCT01850238</td>
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<tr>
<td>AGI-35</td>
<td>Tau active vaccination Alzheimer’s disease</td>
<td>1</td>
<td>Not available</td>
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<td>TRKv0237</td>
<td>Tau-aggregation inhibitor Alzheimer’s disease, behavioural variant frontotemporal degeneration</td>
<td>3 (both negative)</td>
<td>NCT01689233, NCT01689246, NCT01626278</td>
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<td>Abb-BE12 or CZN-BE12</td>
<td>Anti-tau monoclonal antibody PSP, Alzheimer’s disease</td>
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<td>NCT02494024, NCT02880956</td>
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<tr>
<td>BMS-986168</td>
<td>Anti-tau monoclonal antibody PSP</td>
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<td>NCT01460094, NCT03068468</td>
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<td>Salutaris</td>
<td>Inhibitor of tau acetylation PSP</td>
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<td>NCT02422485</td>
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<td>Young plasma transfusions</td>
<td>Rejuvenation PSP</td>
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<td>NCT02460731</td>
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<td>Various</td>
<td>O-GlcNAcase inhibitors PSP</td>
<td>Animal studies Not available</td>
<td></td>
</tr>
<tr>
<td>Tau antisense oligonucleotides</td>
<td>Reduce tau gene expression Various</td>
<td>Animal studies Not available</td>
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</table>

PSP=progressive supranuclear palsy.

**Table 2: Planned or ongoing clinical trials involving tau therapeutics**

Three categories of intervention are under development. (1) Modulation of MAPT gene expression, with antisense oligonucleotides or splicing modulators. (2) Modulation of tau protein post-translational modifications, including phosphorylation, acetylation, and O-GlcNAc modification; degradation by the UPS and autophagy pathways; and modulation of the UPR. (3) Inhibition of tau propagation via trans-synaptic pathways or mediated by microglia. Modulating inflammation might alter tau pathology.

**Figure 4: Potential therapeutic targets for progressive supranuclear palsy**

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Neurodegeneration in PSP is strongly associated with tau pathology, but the mechanisms by which tau abnormalities lead to cell dysfunction and death are not well understood. Two types of tau dysfunction are thought to lead to neurodegeneration: loss of tau function or toxic gain of tau function. These mechanisms are not mutually exclusive, and it is possible that toxic gain-of-function in one cellular compartment might lead to loss of tau function in others.

**Tau loss-of-function therapies**

The rationale for using microtubule stabilisers for the treatment of PSP is based on the notion that these drugs can compensate for the microtubule dysfunction that might result from loss of tau function (figure 4). Several microtubule-stabilising drugs have been developed, and three have been explored in clinical trials of neurodegenerative disease. Davunetide is a microtubule-stabilising octapeptide that showed benefits in transgenic mouse models of tauopathy. However, a large clinical trial of davunetide for PSP-RS did not show efficacy. TPI-287, a new blood–brain barrier-permeable taxane, has entered phase 1 clinical trials for Alzheimer’s disease, PSP, and amyloid-negative PET CBS (table 2).

**Tau gain-of-function therapies**

Evidence that tau propagates between cells in a prion-like manner raises the possibility that blocking spread of pathogenic tau with anti-tau antibodies might be a viable approach to tauopathy treatment (figure 4). Passive immunisation with anti-tau monoclonal antibodies not only suppresses tau pathology but also improves cognitive or motor function in tau transgenic mouse models. Certain three-dimensional conformations of tau seem particularly pathogenic and can be targeted by specific antibodies. Two N-terminal tau-directed monoclonal antibodies, BMS-986168 and Abb-8E12, have progressed to phase 2 clinical trials for PSP (table 2). Active vaccination against tau epitopes is also under investigation, and two tau vaccines have entered human clinical trials: AADvac1 and ACI-35.

**Small molecules targeting tau aggregation or post-translational modifications**

In PSP, tau aggregates into neurofibrillary tangles and neurophil threads. Therefore, inhibition of tau assembly and disassembly are potential therapeutic approaches. Methylene blue derivatives, particularly leuco-methylthioninium bis(hydromethanesulfonate; LMTM), were investigated in phase 3 clinical trials for Alzheimer’s disease and behavioural variant frontotemporal degeneration; however, both trials were negative, which casts doubt on the potential use of LMTM in treatment of PSP.

Hyperphosphorylation of tau is a well studied post-translational modification and has historically been a focus for drug development (figure 4). Inhibition of glycogen synthase kinase 3 (GSK-3) reduces tau phosphorylation in vitro, and GSK-3 could be a therapeutic target for treatment of PSP. However, the GSK-3 inhibitor tideglusib was not efficacious in a phase 2 clinical trial for PSP, and a clinical trial of lithium, hypothesised to work by a similar mechanism, was stopped because of poor tolerability (ClinicalTrials.gov, number NCT00703677). Several studies suggest that acetylation of soluble tau species might precede hyperphosphorylation, and that inhibition of this process could be a potential therapeutic strategy. Salsalate, a tau acetylation inhibitor, has entered a phase 1 clinical trial for PSP (table 2). Finally, inhibitors of the enzyme O-GlcNAcase, which cleaves the post-translational modification O-GlcNac, protected against neurodegeneration in tau transgenic mice. Clinical trials of O-GlcNAcase inhibitors are planned for PSP.

**Antisense oligonucleotides and splicing modulators**

Downregulation of tau gene expression might be beneficial in tauopathies by preventing build-up of toxic forms of tau. A study showed the feasibility of reducing human tau protein concentrations with MAPT antisense oligonucleotides both in vitro and in vivo. Exon 10 splicing is regulated by a hairpin RNA structure that is destabilised by pathological MAPT point mutations. Normalisation of the 3-repeat/4-repeat tau ratio with antisense oligonucleotides or splicing modulators might also be viable therapeutic approaches. Both antisense oligonucleotides and small molecules have been developed to stabilise the hairpin and inhibit 4-repeat tau expression. Intrathecally administered antisense oligonucleotides have been used in clinical trials in patients with amyotrophic lateral sclerosis with SOD1 mutations, and a similar delivery approach might be used in PSP in the future.

**Other strategies**

A growing body of evidence suggests that microglial activation drives tau pathology and contributes to the spread of pathological tau in the brain (figure 4). Data from animal studies suggest that therapeutic strategies that target microglia-specific fractalkine receptors (such as CX3CR1) and interleukin-1β signalling could also help stop the spread of tau. Other strategies under development to target tau pathology include enhanced degradation of misfolded tau or neurofibrillary tangles by various proteolytic systems, including autophagy pathways and the unfolded protein response, drugs that target mitochondrial dysfunction, cell replacement, and young adult (<30 years of age)
plasma transfusions designed to reverse brain ageing.” A phase 1 study in a small number of patients with PSP given young plasma transfusions is underway (table 2).

Conclusions and future directions

There are no effective therapies for PSP; however, insights into the pathophysiology and ontogeny of PSP during the past decade have been fruitful in developing new experimental drugs that have entered clinical trials. Both neuropathological and genetic data suggest a central role of the tau protein in PSP pathogenesis. The new MDS diagnostic criteria for PSP expand the clinical spectrum of PSP by incorporating conditions suggestive of PSP and a variety of symptomatic PSP phenotypes. Several promising biomarkers for PSP have been described to aid in differential diagnosis and evaluation of novel therapeutics. Numerous clinical trials are planned, which offer promise for the possibility of effective PSP therapies. Since tau pathology is also central to Alzheimer’s disease and chronic traumatic encephalopathy, it is believed that a successful tau therapeutic for PSP would also inform the treatment of other neurodegenerative diseases.

There is still a lot of work to be done. Although many clues have emerged from genetics, cell biology, and neuropathological studies of PSP and other tauopathies, the cellular mechanisms of PSP pathogenesis remain elusive. Transcellular spread of tau pathology is an attractive hypothesis with clear therapeutic implications, but evidence in human beings has yet to be convincingly shown. Moreover, it is unclear how well findings in preclinical tauopathy models will translate to patients.

Important challenges remain for clinicians. Many patients are still diagnosed too late, and that would preclude benefit from a disease-modifying therapy once an intervention is available. Although the new diagnostic criteria might alleviate this problem, international efforts will be necessary to better educate physicians and to establish reliable biomarkers for early and accurate differential diagnosis. These developments will enable clinical trials at early stages of disease, when new therapies are most likely to be efficacious. Such biomarkers will need to be validated in autopsy–confirmed cases. Tau-sensitive PET imaging is an attractive potential biomarker, but the low affinity of ligands for tau in PSP post-mortem specimens raises concerns about the utility of these tracers, which are not ready for widespread use yet.

Large, multicentre clinical trials have been successfully implemented in patients with PSP-RS, but PSP remains a rare disease. If several tau therapeutic programmes reach late-stage clinical development, there could be insufficient numbers of eligible patients to enrol in large, competing clinical trials. Careful planning and international partnerships involving patients, families, academic and industry researchers, and advocacy groups will be necessary to ensure the success of such studies. Moreover, ensuring that clinical trial results, data, and biospecimens are rapidly shared will also be crucial for advancing therapeutic development.

Contributors

ALB generated the outline, wrote sections of and revised the manuscript, reviewed the medical literature, and edited the figures. J-TY performed literature searches, wrote the first draft, produced the figures, and revised the manuscript. LIG, IL, AEL, and GUH contributed to the discussion, initial draft, and revision of the manuscript. AEL also edited the figures.

Declaration of interests

ALB receives research support from the National Institutes of Health (R01AG038791, U54NS092089), the University of California, the Tau Consortium, CBD Solutions, the Bluefield Project to Cure FTD, the Alzheimer’s Association, and the following companies: Avid, Biogen, Bristol-Myers Squibb, C2N Diagnostics, Cortice Biosciences, Eli Lilly, Forum Pharmaceuticals, Genentech, Roche, and TauRx; has served as a consultant for Abbvie, Asceneuron, Celgene, Ionis Pharmaceuticals, Janssen, Merck, and Novartis; serves on a Data and Safety Monitoring Board for Neurogenetics Pharmaceuticals; and has stock in Delos and stock options in Alexion. LIG is supported by research funding from Bristol-Myers Squibb, AbbVie, and the American Parkinson’s Disease Association; and consults for BMS, AbbVie, SFO Research, and the University of California. IL is supported by the Parkinson Study Group, Michael J Fox Foundation, AVID Pharmaceuticals, C2N Diagnostics/Abbvie, and Bristol-Myers Squibb; was member of the advisory boards for Cypressus, Lundbeck, Biogen, and Bristol-Myers Squibb; is a member of the Biote/Parkinson Study Group Medical Advisory Board; and receives her salary from the University of California, San Diego, CA, USA. AEL has served as an advisor for Abbvie, Aclara, Avanti Pharmaceuticals, Bristol-Myers Squibb, Ceregene, Lilly, Merck, and UC Berkeley; has received honoraria from Medtronic, Teva, UCB, and AbbVie; has received grants from Brain Canada, Canadian Institutes of Health Research, Edmond J Safra Philanthropic Foundation, Michael J Fox Foundation, the Ontario Brain Institute, National Parkinson Foundation, Parkinson Society Canada, Physicians Services Incorporated (PSI), and W Garfield Weston Foundation; and has received publishing royalties from Saunders, Wiley-Blackwell, Johns Hopkins Press, and Cambridge University Press. GUH has received research support from CurePSP, the German Academic Exchange Service (DAAD), German Centre for Neurodegenerative Diseases (DZNE), German Research Foundation (DFG), German Ministry of Education and Research (BMBF), the Sellas Life Sciences Group, and Neurophere; has served as a consultant for Abbvie, Asceneuron, Bristol-Myers Squibb, Novartis, Roche, and UCB; and has received honoraria for scientific presentations from Abbvie, Roche, Teva, and UCB. J-TY declares no competing interests.

Acknowledgments

ALB is supported by National Institutes of Health (grant numbers. U54NS092089, R01AG038791, and U01AG045390) and the Tau Research Consortium. IL receives support from the US National Institutes of Health (grant nos. P50 AG053513, T35 HL007491, U01NS086659, and U54NS092089). GUH is funded by the Deutsche Forschungsgemeinschaft (DFG, HO2402/6-2 and Munich Cluster for Systems Neurology SyNergy).
Incipient progressive supranuclear palsy is more common than expected and may comprise clinicopathological subtypes: a forensic autopsy series. Acta Neuropathol 2017; 133: 809–23.


