PAPER

Voxel based morphometry reveals a distinct pattern of frontal atrophy in progressive supranuclear palsy

C Brenneis, K Seppi, M Schocke, T Benke, G K Wenning, W Poewe

See end of article for authors' affiliations
....

Correspondence to:
Dr C Brenneis, Department of Neurology, University Hospital, Innsbruck, Anichstrasse 35, 6020 Innsbruck, Austria;
christian.brenneis@uibk.ac.at

Received 25 March 2003
In revised form 3 July 2003
Accepted 9 July 2003
....

Background: Frontal lobe atrophy is a well known neuropathological feature of progressive supranuclear palsy (PSP), accompanied by characteristic neuropsychological deficits.

Objective: To determine subregional frontal lobe atrophy patterns in patients with PSP using voxel based morphometry (VBM).

Methods: VBM is an observer unbiased volumetry which allows the investigation of the entire brain. An optimised protocol for normalisation, segmentation, and correction for volume changes in preprocessing was used. Grey matter, white matter, and cerebrospinal fluid (CSF) partitions in 12 patients with probable PSP were compared with 12 healthy controls matched for age and sex.

Results: In PSP patients, the following cortical areas were decreased in volume ($p_{corr} < 0.05$): the prefrontal cortex, predominantly the medial frontal gyri and a cluster in the left lateral middle frontal gyrus; the insular region including the frontal opercula; both supplementary motor areas; and the left medio-temporal area (V5). White matter comparisons revealed a volume reduction in both frontotemporal regions and the mesencephalon. Analysis of the CSF compartment showed no significant regional changes between the groups.

Conclusions: Frontal atrophy in PSP predominantly involves mesio-frontal targets of striatal projections. This atrophy pattern probably accounts for cardinal PSP associated behavioural deficits.

Progressive supranuclear palsy (PSP) is one of the most frequent parkinsonian syndromes; its hallmarks are supranuclear gaze palsy, postural instability, and cognitive deficits.[1] Although consensus criteria for clinical diagnosis of PSP have been developed,[2] patients with PSP may be misdiagnosed as having idiopathic Parkinson's disease, multiple system atrophy, corticobasal degeneration, dementia with Lewy bodies, or Alzheimer's disease because of overlapping clinical features such as akinetic-rigid syndrome, dementia, and apraxia.[3–6] Impaired neuropsychological function is present in up to 60–70% of PSP patients,[7 8] with cognitive slowing deficits in executive functions, and attention being the most prominent findings.[9–12] Neuropathologically, PSP is characterised by the presence of abundant neurofibrillary tangles, tau positive astrocytes, and occasional ballooned argyrophilic neuronal degeneration involving the basal ganglia, brain stem, and frontal lobe.[2 13 14] Various functional imaging studies suggest that certain frontal lobe subregions are preferentially involved in PSP, including posterior or superior areas.[15 16] In the present study we used voxel based morphometry (VBM) to map the atrophy patterns within the frontal lobe of clinically diagnosed PSP patients. VBM is a magnetic resonance (MR) based volumetric tool, observer and region of interest (ROI) independent, allowing the determination in vivo of volumetric changes in grey matter, white matter, and cerebrospinal fluid (CSF).

METHODS

Patients and controls

Twelve patients with probable PSP diagnosed according to the NINDS-SPSP criteria and 12 controls matched for age and sex with normal T1 weighted MR images were included in the study. All patients were examined clinically by an experienced movement disorder specialist (GKW). Motor impairment as well as levodopa response were rated during the OFF state as defined by the CAPSIT protocol,[17] using the motor examination section of the unified Parkinson's disease rating scale (UPDRS-III) (KS).

Magnetic resonance protocol

A single MRI scan of all subjects was done on a 1.5 Tesla MR scanner (Magnetom Vision, Siemens). The imaging protocol comprised a sagittal T1 weighted FLASH three dimensional sequence with a repetition time (TR) of 9.7 ms, an echo time (TE) of 4 ms, a slice thickness of 1.5 mm, a matrix of 256×256, and a field of view of 230 mm.

Data analysis

SPM99 (Wellcome Department of Cognitive Neurology, Institute of Neurology, Queen Square, London, UK) implemented in Matlab 5.3 (Mathworks Inc, Sherborn, Massachusetts, USA) was used for prestatistical image processing and statistical analysis.

Template creation

To avoid potential bias from the scanner and normalisation process, a customised template was created including all T1 weighted images of the participating subjects. Each image was first spatially normalised into standardised MNI (Montreal Neurological Institute) space using a 12 parameter affine transformation and a non-linear normalisation by 7×8×7 basis functions. Following normalisation, a mean image was created which was smoothed with an 8 mm FWHM isotropic Gaussian kernel.

Normalisation and segmentation

The images of the subjects were warped to match the customised template applying a 12 parameter affine transformation and non-linear spatial normalisation using discrete cosine (7×8×7) basis functions. Following reslicing onto a small voxel size of 1×1×1 mm to minimise partial volume effects,[18] the images were segmented into grey matter, white matter, and CSF. A correction of intensity non-uniformity was incorporated to compensate for variations in tissue density values caused by the head position relative to the coil in the scanner. Therefore, the ''lot of correction'' algorithm as provided by SPM99 was applied to the images. To remove missegmented areas (for example, the dural venous sinus) from statistical analysis, the grey matter partitions were multiplied by a binary mask which was created with a function of SPM99 called brain extraction.

Modulation and smoothing

A modulation of the segmented partitions was undertaken to compensate for volume changes in non-linear spatial normalisation by multiplying the voxel densities with the Jacobian determinants.[19 20] This processing allows an analysis of the absolute amount of volume, whereas the unmodulated data would test for differences in concentration.

Finally, the modulated grey matter, white matter, and CSF partitions were convolved with a Gaussian kernel filter of 10×10×10 mm FWHM in order to render the data more normally distributed and to compensate for inexact spatial normalisation.[21]

Statistical analysis

The normalised, segmented, modulated, and smoothed data were statistically tested using the general linear model based on the Gaussian field theory. Global differences in voxel intensities were used as confounding covariate (ANCOVA); grand mean scaling was set at 100. The significance level was set at $p < 0.05$, corrected for multiple comparison across the entire brain volume. Brain stem atrophy is a well known phenomenon in PSP.[22 23] Therefore areas in the brain stem were corrected for small volumes with a radius of 20 mm at the peak maxima. Finally, the MNI coordinates of significant clusters were converted to Talairach coordinates.

RESULTS

Demographic and clinical features

Table 1 summarises the clinical findings. There was no significant difference in age between patients and controls (mean (SD): PSP, 67.5 (6.6) years; controls, 60 (5.8) years). The mean value of UPDRS motor subscore was 38.9 (10.9). The response to levodopa failed or was poor in 11 patients (<30% improvement of motor subscore); one patient improved moderately (<50%). Disease duration in the patients was 2.7 (0.9) years.

Voxel based morphometry

In PSP patients, significant ($p_{corr} < 0.05$) volume loss was observed in several cortical areas. The atrophy pattern

Figure 1 Significant clusters of grey matter loss in patients with progressive supranuclear palsy in comparison with controls ($p_{uncorr} < 0.001$). Clusters are superimposed onto a sagittal and axial mean image of the grey matter partitions of patients. MFG, medial frontal gyrus; MT/V5, mediotemporal area or area; V5SMA, supplementary motor area.

predominantly involved the medial frontal gyri of both hemispheres and the insular regions including the frontal opercula (fig 1). Additional clusters of atrophy were found in both supplementary motor areas, the left middle frontal gyrus on the lateral surface, and the left temporo-occipital region corresponding to area MT/V5.

The white matter comparison revealed a significant frontotemporal tissue reduction in both hemispheres. An infratentorial cluster of atrophy was obtained in the mesencephalon, comprising cerebral peduncles and central mesencephalon.

A more liberal significance level of $p_{uncorr} < 0.001$ detected grey matter of both primary sensorimotor cortices. Table 2 summarises Talairach's coordinates and z values of significant volumetric changes in PSP compared with controls.

DISCUSSION

To our knowledge this is the first volumetric study determining subregional frontal atrophy patterns in PSP patients using VBM. The fully automated whole brain technique avoids many of the constraints of ROI analysis but it incorporates a series of preprocessing steps that may cause systematic bias. It is therefore important to be cautious about ascribing volume differences to a disease effect. Furthermore it is also important to recognise the effect of variability on the ability of VBM to detect volume differences. In order to meet these potential limitations we have applied an optimised protocol to the images, which involved the creation of a customised template, eliminating missegmented grey matter areas, and modulating the segmented data by the

Table 1 Demographic and clinical data in patients with progressive supranuclear palsy (PSP) and controls

Group (n)	Age (years)	UPDRS-III	DD (years)	L-Dopa response: No or poor/moderate/good
PSP (12)	67.5 (6.6)	38.9 (10.9)	2.7 (0.9)	11/1/0
Controls (12)	60 (5.8)			

Values are mean (SD) or n.
DD, disease duration; UPDRS-III, unified Parkinson's disease rating scale – motor examination.

Table 2 Grey matter and white matter atrophy in progressive supranuclear palsy compared with normal controls

| Location | BA | Peak coordinates (mm) | | | Peak z score |
		x	y	z	
Grey matter					
Medial frontal gyrus					
Left	10	−3	50	−5	5.5
Right	10	5	51	−7	5.4
Left	10	−3	38	31	4.7
Right	10	4	28	35	4.7
Middle frontal gyrus					
Left	9	−50	36	11	4.0
Supplementary motor area					
Left	6	−6	−28	66	4.9
Right	6	8	−25	53	5.0
Insular cortex					
Left		−35	10	5	4.9
Right		44	1	0	5.9
Frontal operculum					
Left		−38	21	5	4.6
Right		38	22	5	4.6
Temporo-occipital region					
	19/39	−65	−50	11	
White matter					
Frontotemporal					
Left		−41	11	12	5.7
Right		37	13	13	5.2
Mesencephalon					
Left cerebral peduncle		−8	−12	−15	3.9
Right cerebral peduncle		8	−11	−15	4.4
Central		2	−18	−8	4.2

Anatomical location, Brodman area (BA), Talairach's coordinates (x, y, z), and z values of clusters with reduced volume (p<0.05 corrected for multiple comparison).

Jacobian determinants to compensate for the volume changes in spatial normalisation.[20]

Frontal lobe atrophy is widely regarded a key neuropathological feature of PSP.[24] Several studies have shown that the posterior frontal cortex is affected in most if not all patients with PSP.[3] [25–27] However, no systematic necropsy studies have been carried out investigating subregional cortical atrophy patterns. To date, a single three dimensional MRI volumetric study reported significant frontal lobe atrophy in PSP patients with a predilection for the posterior frontal cortex.[28]

Previous functional imaging studies have also shown abnormalities in several subregions of the frontal lobe in PSP patients. Glucose metabolism was reduced, particularly in the superior half of the frontal lobes[15] and in the motor/premotor regions[16]; a similar pattern of reduced regional cerebral perfusion in frontal lobe was reported in a SPECT study.[29] Furthermore, studies using proton magnetic resonance spectroscopy indicated neuronal loss or degeneration within the precentral region of PSP patients.[30] [31]

Our study shows preferential volume loss of mesio-frontal areas in PSP patients compared with age and sex matched controls. It is well established that striatocortical projections are organised in several fronto-subcortical loops.[32] Mesio-frontal targets of striatal projections were found to be engaged in the regulation of motor initiation, response selection, motivation, and other goal directed behaviours. In addition to their motor impairment, most PSP patients show ''frontal'' behavioural symptoms such as apathy,[33] combined with an impairment of executive functions, action initiation and set shifting, and memory.[7] [11] [34–36] Thus preferential involvement of mesio-frontal areas in the pathology of PSP as seen in this study is in accordance with the pattern of neuropsychological dysfunction consistently found in PSP patients. A correlation of frontal neuropsychological deficits with frontal hypometabolism and total frontal atrophy has been documented.[28] [37]

VBM of the grey matter partition also showed a remarkable atrophy in the left temporo-occipital area and both insular regions. Atrophy of the insular cortex is seen in Alzheimer's disease, dementia with Lewy-bodies, and frontotemporal dementia,[38–41] but its precise clinical correlate remains unclear and requires further study. The atrophy in the temporo-occipital area could partly reflect atrophy of area MT/V5. This area participates in pathways mediating smooth pursuit and saccades,[42–44] oculomotor functions that are severely affected in PSP. Other components of the pursuit and saccade pathways include frontal eye fields, supplementary eye fields, thalamus, cerebellum, and brain stem.[43] Although these areas have all been incriminated in the oculomotor disorder of PSP, our present study failed to detect significant volume loss except for left sided area MT5/V5. The unilaterality of this finding as well as the lack of volume loss in other central oculomotor pathway components may again reflect conservative significance levels as well as the small sample size. Further studies are needed to establish the role of MT5/V5 in the pathogenesis of oculomotor disorders associated with PSP.

In contrast to a previous ROI based morphometric study,[45] the basal ganglia—including the putamen and caudate nucleus as well as the globus pallidus—were not significantly reduced in volume in our study. However, mesencephalic volume loss was significant, consistent with previous ROI based findings[22] [23] and probably reflecting the severe midbrain tau pathology that is present in most PSP patients.[3] The failure to detect basal ganglia volume loss probably reflects methodological limitations, including a rather conservative significance level.

Overall, VBM identified a distinct frontal atrophy pattern in PSP patients involving predominantly mesio-frontal areas.

We propose that mesio-frontal atrophy accounts for cardinal features of the PSP associated behavioural disorder, including deficits of cognitive and motor initiation.

....

Authors' affiliations

C Brenneis, K Seppi, T Benke, G K Wenning, W Poewe, Department of Neurology and Radiology, University Hospital, Innsbruck, Austria
M Schocke, Department of Radiology, University Hospital, Innsbruck

REFERENCES

1 **Burn D**, Lees A. Progressive supranuclear palsy: where are we now? *Lancet Neurol* 2003;**1**:359.
2 **Hauw JJ**, Daniel SE, Dickson D, *et al.* Preliminary NINDS neuropathologic criteria for Steele-Richardson-Olszewski syndrome (progressive supranuclear palsy). *Neurology* 1994;**44**:2015–19.
3 **Daniel SE**, de Bruin VM, Lees AJ. The clinical and pathological spectrum of Steele-Richardson-Olszewski syndrome (progressive supranuclear palsy): a reappraisal. *Brain* 1995;**118**:759–70.
4 **Verny M**, Jellinger KA, Hauw JJ, *et al.* Progressive supranuclear palsy: a clinicopathological study of 21 cases. *Acta Neuropathol (Berl)* 1996;**91**:427–31.
5 **Litvan I**, Mangone CA, McKee A, *et al.* Natural history of progressive supranuclear palsy (Steele-Richardson-Olszewski syndrome) and clinical predictors of survival: a clinicopathological study. *J Neurol Neurosurg Psychiatry* 1996;**60**:615–20.
6 **Santacruz P**, Uttl B, Litvan I, *et al.* Progressive supranuclear palsy: a survey of the disease course. *Neurology* 1998;**50**:1637–47.
7 **Pillon B**, Dubois B. Cognitive and behavioral impairments. In: Litvan I, Agid Y, eds. *Progressive supranuclear palsy: clinical research approaches.* New York: Oxford University Press, 1992.
8 **Maher ER**, Smith EM, Lees AJ. Cognitive deficits in the Steele-Richardson-Olszewski syndrome (progressive supranuclear palsy). *J Neurol Neurosurg Psychiatry* 1985;**48**:1234–9.
9 **Cambier J**, Masson M, Viader F, *et al.* Frontal syndrome of progressive supranuclear palsy. *Rev Neurol (Paris)* 1985;**141**:528–36. [In French].
10 **Pillon B**, Gouider-Khouja N, Deweer B, *et al.* Neuropsychological pattern of striatonigral degeneration: comparison with Parkinson's disease and progressive supranuclear palsy. *J Neurol Neurosurg Psychiatry* 1995;**58**:174–9.
11 **Grafman J**, Litvan I, Gomez C, *et al.* Frontal lobe function in progressive supranuclear palsy. *Arch Neurol* 1990;**47**:553–8.
12 **Pillon B**, Dubois B, Ploska A, *et al.* Severity and specificity of cognitive impairment in Alzheimer's, Huntington's, and Parkinson's diseases and progressive supranuclear palsy. *Neurology* 1991;**41**:634–43.
13 **Jellinger KA**, Bancher C, Hauw JJ, *et al.* Progressive supranuclear palsy: neuropathologically based diagnostic clinical criteria. *J Neurol Neurosurg Psychiatry* 1995;**59**:106.
14 **Spillantini MG**, Bird TD, Ghetti B. Frontotemporal dementia and Parkinsonism linked to chromosome 17: a new group of tauopathies. *Brain Pathol* 1998;**8**:387–402.
15 **Foster NL**, Gilman S, Berent S, *et al.* Cerebral hypometabolism in progressive supranuclear palsy studied with positron emission tomography. *Ann Neurol* 1988;**24**:399–406.
16 **Goffinet AM**, De Volder AG, Gillain C, *et al.* Positron tomography demonstrates frontal lobe hypometabolism in progressive supranuclear palsy. *Ann Neurol* 1989;**25**:131–9.
17 **Defer GL**, Widner H, Marie RM, *et al.* Core assessment program for surgical interventional therapies in Parkinson's disease (CAPSIT-PD). *Mov Disord* 1999;**14**:572–84.
18 **Ashburner J**, Friston KJ. Nonlinear spatial normalization using basis functions. *Hum Brain Mapp* 1999;**7**:254–66.
19 **Ashburner J**, Friston KJ. Why voxel-based morphometry should be used. *Neuroimage* 2001;**14**:1238–43.
20 **Good CD**, Johnsrude IS, Ashburner J, *et al.* A voxel-based morphometric study of ageing in 465 normal adult human brains. *Neuroimage* 2001;**14**:21–36.
21 **Ashburner J**, Friston KJ. Voxel-based morphometry – the methods. *Neuroimage* 2000;**11**:805–21.
22 **Asato R**, Akiguchi I, Masunaga S, *et al.* Magnetic resonance imaging distinguishes progressive supranuclear palsy from multiple system atrophy. *J Neural Transm* 2000;**107**:1427–36.
23 **Warmuth-Metz M**, Naumann M, Csoti I, *et al.* Measurement of the midbrain diameter on routine magnetic resonance imaging: a simple and accurate method of differentiating between Parkinson disease and progressive supranuclear palsy. *Arch Neurol* 2001;**58**:1076–9.
24 **Jellinger K**, Brancher C. Neuropathology. In: Litvan I, Agid Y, eds. *Progressive supranuclear palsy: clinical research approaches.* New York: Oxford University Press, 1992.
25 **Hof PR**, Delacourte A, Bouras C. Distribution of cortical neurofibrillary tangles in progressive supranuclear palsy: a quantitative analysis of six cases. *Acta Neuropathol (Berl)* 1992;**84**:45–51.
26 **Hanihara T**, Amano N, Takahashi T, *et al.* Distribution of tangles and threads in the cerebral cortex in progressive supranuclear palsy. *Neuropathol Appl Neurobiol* 1995;**21**:319–26.
27 **Verny M**, Duyckaerts C, Agid Y, *et al.* The significance of cortical pathology in progressive supranuclear palsy. Clinico-pathological data in 10 cases. *Brain* 1996;**119**:1123–36.
28 **Cordato NJ**, Pantelis C, Halliday GM, *et al.* Frontal atrophy correlates with behavioural changes in progressive supranuclear palsy. *Brain* 2002;**125**:789–800.
29 **Johnson KA**, Sperling RA, Holman BL, *et al.* Cerebral perfusion in progressive supranuclear palsy. *J Nucl Med* 1992;**33**:704–9.
30 **Tedeschi G**, Litvan I, Bonavita S, *et al.* Proton magnetic resonance spectroscopic imaging in progressive supranuclear palsy, Parkinson's disease and corticobasal degeneration. *Brain* 1997;**120**:1541–52.
31 **Abe K**, Terakawa H, Takanashi M, *et al.* Proton magnetic resonance spectroscopy of patients with parkinsonism. *Brain Res Bull* 2000;**52**:589–95.
32 **Mega MS**, Cummings JL. Frontal-subcortical circuits and neuropsychiatric disorders. *J Neuropsychiatry Clin Neurosci* 1994;**6**:358–70.
33 **Litvan I**, Mega MS, Cummings JL, *et al.* Neuropsychiatric aspects of progressive supranuclear palsy. *Neurology* 1996;**47**:1184–9.
34 **Pillon B**, Deweer B, Michon A, *et al.* Are explicit memory disorders of progressive supranuclear palsy related to damage to striatofrontal circuits? Comparison with Alzheimer's, Parkinson's, and Huntington's diseases. *Neurology* 1994;**44**:1264–70.
35 **Litvan I**. Progressive supranuclear palsy revisited. *Acta Neurol Scand* 1998;**98**:73–84.
36 **Bak T**, Hodges JR. The neuropsychology of progressive supranuclear palsy. *Neurocase* 1998;**4**:89–94.
37 **Blin J**, Baron JC, Dubois B, *et al.* Positron emission tomography study in progressive supranuclear palsy. Brain hypometabolic pattern and clinicometabolic correlations. *Arch Neurol* 1990;**47**:747–52.
38 **Rombouts SA**, Barkhof F, Witter MP, *et al.* Unbiased whole-brain analysis of gray matter loss in Alzheimer's disease. *Neurosci Lett* 2000;**285**:231–3.
39 **Price JL**, Morris JC. Tangles and plaques in nondemented aging and ''preclinical'' Alzheimer's disease. *Ann Neurol* 1999;**45**:358–68.
40 **Van Hoesen GW**, Parvizi J, Chu CC. Orbitofrontal cortex pathology in Alzheimer's disease. *Cereb Cortex* 2000;**10**:243–51.
41 **Baron JC**, Chetelat G, Desgranges B, *et al.* In vivo mapping of gray matter loss with voxel-based morphometry in mild Alzheimer's disease. *Neuroimage* 2001;**14**:298–309.
42 **Petit L**, Haxby JV. Functional anatomy of pursuit eye movements in humans as revealed by fMRI. *J Neurophysiol* 1999;**82**:463–71.
43 **Leigh RJ**, Zee DS. *The neurology of eye movements.* New York: Oxford University Press, 1999.
44 **O'Driscoll GA**, Wolff AL, Benkelfat C, *et al.* Functional neuroanatomy of smooth pursuit and predictive saccades. *Neuroreport* 2000;**11**:1335–40.
45 **Schulz JB**, Skalej M, Wedekind D, *et al.* Magnetic resonance imaging-based volumetry differentiates idiopathic Parkinson's syndrome from multiple system atrophy and progressive supranuclear palsy. *Ann Neurol* 1999;**45**:65–74.