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An investigation of diffusion imaging techniques in the evaluation of spinocerebellar ataxia and multisystem atrophy

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Abstract

Multisystem system atrophy and spinocerebellar ataxia are rare neurodegenerative ataxias that can be difficult to diagnose, with important prognostic and treatment implications. The purpose of this study is to evaluate various methods of diffusion imaging and tractography in their effectiveness at differentiating these diseases from control subjects. Our secondary aim is determining whether diffusion abnormalities correspond with clinical disease severity. Diffusion imaging and tractography were performed on five patients and seven age-matched controls. Fractional anisotropy, generalized fractional anisotropy, and apparent diffusion coefficient values and corticospinal tract volumes were measured within various diffusion and probabilistic tractography models, including standard diffusion tensor and Q-ball tractography. Standard diffusion based fractional anisotropy and apparent diffusion coefficient values were significantly altered in patients *versus* controls in the middle cerebellar peduncles and central pons. Tractography based fractional anisotropy and generalized fractional anisotropy values were significantly lower in patients *versus* controls when corticospinal tracts were drawn in a craniocaudal direction (bilaterally using Q-ball imaging, only on the right using diffusion tensor imaging). The right corticospinal tract volume was significantly smaller in patients *versus* controls when created using Q-ball imaging in a caudocranial direction. There was no correlation between diffusion alteration and clinical symptomatology. In conclusion, various diffusion-based techniques can be effective in differentiating ataxic patients from control subjects, although the selection of diffusion algorithm and tract growth technique and direction is non-trivial.

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Conflicts of Interest/Disclosures

The authors declare that they have no financial or other conflicts of interest in relation to this research and its publication.

Keywords

Diffusion tensor imaging; Diffusion weighted imaging; Multisystem atrophy; Q-ball imaging; Spinocerebellar ataxia

1. Rationale and objectives

The neurodegenerative ataxias are a heterogeneous group of disorders that affect the cerebellum and its connections. Two groups of disorders that are especially difficult to diagnose are the autosomal dominant spinocerebellar ataxias (SCA) and the sporadic multisystem atrophy (MSA). A diagnosis of SCA is made via genetic testing, however only 60–75% of patients have a known genetic locus and when identified sporadically, only 20% have an identifiable locus [1,2]. A diagnosis of MSA is made per clinical criteria [3]. For both diseases, MRI is currently used mainly to exclude other diseases.

For both MSA and SCA, the roles of diffusion, diffusion tensor imaging (DTI) and Q-ball imaging (QBI) have not been thoroughly evaluated as a diagnostic tool to our knowledge. A handful of studies have been performed over the past 10 years, however, the current knowledge base is limited due to significant differences in technique, and varying results. Additionally, there is little data comparing the efficacy of the various techniques tested. The purpose of this study is to evaluate various methods of diffusion imaging and probabilistic tractography (DTI and QBI) including tract growth methods in their effectiveness at differentiating these diseases from control subjects. Some of the techniques tested have not previously been applied in this population. Secondary aims include determining whether diffusion abnormalities correspond with clinical disease severity.

2. Materials and methods

Five patients (three MSA cerebellar type, one MSA parkinsonian type, one SCA 2; normal allele 28 repeats, abnormal allele 42 repeats) and seven age-matched controls were prospectively recruited. Ataxic patient age and sex were as follows: 60-year-old woman, 36-year-old man, 65-year-old woman, 55-year-old man, and 65-year-old woman. One patient died during the study, with confirmation of her MSA cerebellar type with additional pathologic features of MSA parkinsonian type. Control subject exclusion criteria included extensive cerebral and cerebellar atrophy. One control subject was removed from the study for this reason as he represented an outlier that would have adversely affected the statistical analysis. Informed consent was obtained from all study participants. The diagnosis was confirmed by a senior neurologist subspecialized in movement disorders. The same neurologist examined patients on the day of the MRI using the Scale for the Assessment and Rating of Ataxia [4]. Institutional Review Board approval was granted on 10 December 2009.

2.1. MRI protocol

T1-weighted anatomical brain image and DTI were collected on a Siemens 3.0 Tesla Trio Tim whole body system with a 32-channel head coil (both Siemens Medical Solutions,

Erlangen, Germany). T1-weighted anatomical images were acquired using magnetization-prepared rapid acquisition with gradient echo with the following parameters: voxel size, 1 mm isotropic; repetition time (TR)/echo time (TE), 2300/2.91 ms; flip angle = 9°; in-plane matrix resolution, 256 × 256; slice, 256. DTI parameters were as follows: voxel size, 2 mm isotropic; TR/TE, 9400/89 ms; flip angle = 90°; in-plane matrix resolution, 128 × 128; slice, 72; b = 1000 s/mm², GRAPPA with acceleration factor of 2. Diffusion was measured in 64 directions with one b0 image.

2.2. Imaging analysis

2.2.1. Standard fractional anisotropy/ADC ROI analysis—Analyses were conducted using FSL 4.1 (www.fmrib.ox.ac.uk/fsl/). T1-weighted anatomical image was skull-stripped using the brain extraction tool (BET; part of FSL tools), and regions of interest (ROI) were created for each subject based on the anatomical image using FSLview. A radiology resident blinded to the clinical data drew the ROI and a neuroradiologist with 6 years of experience then confirmed their placement. The ROI were placed in the bilateral frontal and cerebellar white matter as well as bilaterally in the posterior limb of the internal capsules, cerebral peduncles (CP), superior cerebellar peduncles, and middle cerebellar peduncles (MCP). ROI were also placed in the ventral pons, central medulla and the body, genu, and splenium of the corpus callosum (Fig. 1). All ROI measured 5 mm² except within the internal capsule (4 mm²) and superior cerebellar peduncles (2 mm × 4 mm) — these were altered due to the size constraints of the location. Diffusion images were eddy current corrected, and b0 image was co-registered to their anatomical images using FLIRT. Fractional anisotropy (FA) maps were estimated by FMRIB (define) Diffusion Toolbox (FDT). Average FA and apparent diffusion coefficient (ADC) values within each ROI were calculated.

2.2.2. DTI versus QBI based tractography—In DTI based tractography, a diffusion tensor model was fitted at each voxel by FDT. We applied the Bayesian Estimation of Diffusion Parameters Obtained using Sampling Techniques (BedpostX) tool that accounts for two crossing fibers per voxel. A burning period of 1000 iterations was performed before starting the sampling. In Q-ball based tractography, using a real spherical harmonics basis, single q-shell constant solid angle orientation distribution function (ODF) estimation (50 samples, peak threshold = 30% of maximum ODF value, SH lmax = 4) was performed by Qboot command in FSL. A minimum threshold of 0.4 was used for a local maxima to be considered an ODF peak. Probabilistic tractography was performed with probtrackx command in FSL.

2.2.3. “Seed mask” versus “seed/waypoint mask” method—Masks of CP and posterior limbs of the internal capsules (PLIC) needed for tractography were drawn in each individual’s diffusion space, guided by directional colored FA tensors. A mid-sagittal exclusion mask was used to prevent fibers from crossing the midline (Fig. 2).

Both “seed mask” (Fig. 3) and “seed/waypoint mask” (Fig. 4) methods were analyzed. In the “seed mask” method, both CP and PLIC masks are used as seed masks, which generate a connectivity distribution between a group of seed masks. This option repeatedly samples tracts from every seed mask, and retains only those tracts that pass through at least one of

the other seed masks, i.e. CP + PLIC (Fig. 3). The “seed/waypoint mask” method means one mask was used as seed mask and the other mask as a waypoint mask when performing tractography. An additional termination mask was also used (Fig. 4).

2.2.4. Tract volume and tract-based FA and generalized fractional anisotropy analysis

The voxel containing the maximum connectivity with the seed mask was identified and 10% of the average number of tracts passing through this voxel and six surrounding voxels were used as a threshold to the pathways to remove unlikely connections. From the remaining fibers that make up the desired pathways, we calculated the volume of the tracts and mean FA and generalized fractional anisotropy (GFA) of the voxels included in the tract using the `fsstats` command in FSL.

2.3. Statistical analysis

Statistical analysis was performed using the Statistical Package for the Social Sciences (SPSS Inc., Chicago, IL, USA). Non-parametric Mann–Whitney test was used for comparison of standard FA and ADC ROI values between patient and control groups. Pearson correlation tests were performed between FA/ADC values and Scale for the Assessment and Rating of Ataxia scores. Paired samples marginal homogeneity test was performed to compare the tract-based FA and GFA and tract volume between BedpostX and Qboot models and between patients and controls.

3. Results

3.1. Standard diffusion based FA/ADC ROI analysis

As a group, the mean FA values of the ataxic patients were lower within the left MCP ($p < 0.011$) and right MCP ($p < 0.006$) as well as the ventral pons ($p < 0.018$) compared with control subjects. The ataxic patient group also had higher mean ADC values within the left MCP ($p < 0.018$), right MCP ($p < 0.006$), central medulla ($p < 0.011$), and ventral pons ($p < 0.018$). No correlation was found in the above areas between the degree of FA/ADC value alteration and clinical symptomatology as measured by the Scale for the Assessment and Rating of Ataxia score.

3.2. Tractography based FA and GFA analysis

While both “seed mask” and “seed/waypoint mask” tract based analysis showed non-significant trends towards lower FA/GFA values in ataxic patients, only the “seed/waypoint mask” method revealed statistically significant differences when tracts were grown from PLIC → CP (bilaterally using QBI, only on the right using DTI), as shown in Table 1 and 2.

When comparing tractography methods, GFA values (QBI) were almost always lower than FA values (DTI) in both patients and controls, often significantly so (Table 3, 4).

3.3. Tract volume analysis

There was a non-significant trend towards smaller corticospinal tract (CST) volumes in patients *versus* controls as well as a significantly smaller volume in the right corticospinal tract volume when measured using QBI and the “seed/waypoint mask” method from CP

(seedpoint) to PLIC (waypoint) (Table 5, 6). When comparing the two tractography methods directly (DTI *versus* QBI), there was a non-significant trend towards higher CST volumes when using QBI, and a significantly higher volume using the “seed/waypoint mask” method in control subjects on the right CST when measured from CP (seedpoint) to PLIC (waypoint) (Table 7, 8).

4. Discussion

This study evaluated the utility of various diffusion-based methods in the evaluation of patients with MSA and SCA type 2. FA, GFA, and ADC values were used as surrogates for white matter tract integrity and demonstrated the regions most affected in these diseases: the MCP, ventral pons, and central medulla. This is consistent with known pathologic changes in MSA involving the transverse pontocerebellar fibers and MCP as well as known cerebellar and brainstem atrophy in SCA type 2.

Other authors have shown that FA and ADC values can help distinguish between MSA and controls, SCA and controls, SCA1 and SCA2, and between MSA-parkinsonion type and Parkinson’s disease [5,6,7,8,9,10,11,12,13,14,15]. However, wide variations in ROI placement (both location and technique), software, and measurement technique (FA *versus* ADC) make true comparison with our study difficult. For instance, one study placed the ROI directly on the DTI pictures, perhaps limiting their anatomic accuracy. All of the above studies agreed with our assessment of MCP involvement and most agreed with our assessment of pontine involvement.

Upon review of the above literature, there appears to be some variation between studies regarding the relative sensitivity of FA *versus* ADC, however, few studies evaluated both, and comparison between studies can be difficult due to the above stated technical differences. In our study, ADC proved to be more sensitive within the central medulla. We theorize that some of these differences may be attributable to the possibility of regions with complex fiber orientation artificially lowering the FA value but not affecting the ADC value.

While no correlation was found between the degree of diffusion abnormality and the patient’s Scale for the Assessment and Rating of Ataxia score, this may very well have been due to the small sample size. A few other studies have found a correlation between FA or ADC values in various ROI and clinical symptomatology [16,17,18,19,20], however, the variations in measurement methods (FA *versus* ADC) as well as clinical scoring systems used (Scale for the Assessment and Rating of Ataxia, International Cooperative Ataxia Rating Score, and “cerebellar score”) limits comparison with our study.

The significantly smaller CST volume in the ataxic group, seen using QBI in the caudal-cranial direction, and the sometimes significant trend for larger CST volumes when using QBI *versus* DTI suggest that QBI is a more sensitive method for mapping these complex fiber tracts. The limitation of DTI is that it assumes a single multivariate Gaussian diffusion within an individual voxel [21,22]. If there are multiple fiber populations within an individual voxel, tensor fitting forces the results into a single diffusion ellipsoid [23]. QBI overcomes these challenges in representing complex fiber tracts and several studies have

proven its accuracy in depicting neural fiber tissue microstructure [24,25]. This likely explains its increased sensitivity in our study. To our knowledge, no prior MRI studies have evaluated CST volumes in this patient population.

Probabilistic tractography also proved to be valuable in differentiating ataxic patients from control subjects, however the choice of tractography model and tract direction were non-trivial in this analysis. The best method in our study for differentiating ataxic patients from control subjects was QBI tractography in the cranial-caudal direction. Again, the increased accuracy of QBI for evaluating complex fiber tracts (like the pontocerebellar tracts involved in these ataxias) likely explains its increased sensitivity over standard DTI tractography in differentiating our two groups. In terms of tract direction, our cranial-caudal tractography excluded tracts superior to the PLIC (not known to be affected in these ataxias) but included white matter tracts inferior to the CP within the brainstem and cerebellum (known to be affected in these ataxias); our caudal-cranial tractography excluded tracts inferior to the CP but included tracts superior to the PLIC. This likely explains the increased accuracy in our study when using the PLIC as a seed point and the CP as a waypoint.

When directly comparing QBI tractography with standard DTI tractography, the QBI GFA values were significantly lower than the DTI FA values in both patients and control subjects. This further reinforces the fact that the choice of QBI or DTI is non-trivial in the analysis of these patients, and that comparison between studies must be made with caution (meaning one must compare “apples to apples”). To our knowledge, no prior studies have evaluated the effects of tractography growth direction and tractography technique (QBI *versus* DTI) in this patient population.

The major limitation of our study was its small sample size. There was difficulty in recruiting patients due to the rarity of the disease and difficulty in bringing disabled patients to the hospital for elective imaging. This limited the overall statistical evaluation of our data, including further possible analysis of differences between different MSA and SCA subtypes and more thorough correlation with clinical symptomatology. We feel though that our novel analyses as well as technique comparisons are both valid and important.

5. Conclusion

Diffusion imaging can be effective in differentiating patients with MSA and SCA from control subjects, although the choice of diffusion algorithm and tract growth technique and direction are non-trivial. We found that ROI based measurements in the MCP, ventral pons, and central medulla were effective. Probabilistic tractography using DTI and QBI was also effective, with QBI being more sensitive. CST volume analysis was marginally effective. No correlation between diffusion abnormality and clinical severity was found. Close attention to and eventually standardization of diffusion technique should be made when pursuing further research, and when analyzing the current literature.

Acknowledgments

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Fig. 1.
Region of interest placement on a sample patient's axial (surround) and sagittal (center) on T1-weighted MRI for fractional anisotropy/white matter apparent diffusion coefficient analysis.

Fig. 2.

Individual masks (horizontal blue bars) were drawn on coronal slices of the cerebral peduncle and posterior limb of internal capsule for the left and right hemisphere. A mid-sagittal exclusion mask (vertical green bar) was placed to exclude fibers that cross to the opposite hemispheres from analysis.

Fig. 3.

The “seed mask” method generates a connectivity distribution between a group of seed masks. This option repeatedly samples tracts from every seed mask, and retains only those tracts that pass through at least one of the other seed masks. Probabilistic tractography results are generated independently in each hemisphere analysis and shown on this sample coronal image.

Fig. 4.

(Left) Probabilistic tractography using the posterior limb of internal capsule (PLIC) (upper blue lines) as seed mask and cerebral peduncle (CP) (lower blue lines) as waypoint mask. With additional termination mask (pink lines), the unrelated connectivity superior to the seed mask is excluded. Probabilistic tractography results are generated independently in each hemisphere and shown on this sample coronal image. (Right) Probabilistic tractography in the opposite direction, using the CP (lower blue lines) as seed mask and PLIC (upper blue lines) as waypoint mask, shown on this sample coronal image. Notice that these two tract directions cover different portions of the corticospinal tracts.

Table 1

FA/GFA comparison between ataxia and control subjects Seed/waypoint method

DTI = diffusion tensor imaging, cp = cerebral peduncles, FA = fractional anisotropy, GFA = generalized fractional anisotropy, plic = posterior limbs of the internal capsules, QBI = Q-ball imaging.

Table 2

FA/GFA comparison between ataxia and control subjects Seed mask method

DTI = diffusion tensor imaging, FA = fractional anisotropy, GFA = generalized fractional anisotropy, QBI = Q-ball imaging.

Table 3

FA/GFA comparison between DTI and QBI Seed/waypoint method

DTI = diffusion tensor imaging, cp = cerebral peduncles, FA = fractional anisotropy, GFA = generalized fractional anisotropy, plic = posterior limbs of the internal capsules, QBI = Q-ball imaging.

Table 4

FA/GFA comparison between DTI and QBI Seed mask method

DTI = diffusion tensor imaging, cp = cerebral peduncles, FA = fractional anisotropy, GFA = generalized fractional anisotropy, plc = posterior limbs of the internal capsules, QBI = Q-ball imaging.

Table 5
CST volumes in ataxic patients *versus* control subjects Seed/waypoint method

CST = corticospinal tract, DTI = diffusion tensor imaging, cp = cerebral peduncles, L = left, plic = posterior limbs of the internal capsules, QBI = Q-ball imaging, R = right.

Table 6CST volumes in ataxic patients *versus* control subjects Seed mask method

CST = corticospinal tract, DTI = diffusion tensor imaging, cp = cerebral peduncles, L = left, plic = posterior limbs of the internal capsules, QBI = Q-ball imaging, R = right.

Table 7

CST volume comparison between DTI and QBI Seed/waypoint method

CST = corticospinal tract, DTI = diffusion tensor imaging, cp = cerebral peduncles, plic = posterior limbs of the internal capsules, QBI = Q-ball imaging.

Table 8
CST volume comparison between DTI and QBI Seed mask method

CST = corticospinal tract, DTI = diffusion tensor imaging, cp = cerebral peduncles, plc = posterior limbs of the internal capsules, QBI = Q-ball imaging.