NeuroImage: Clinical 21 (2019) 101659

Contents lists available at ScienceDirect

NeuroImage: Clinical

journal homepage: www.elsevier.com/locate/ynicl

Diffusion tensor imaging in anterior interosseous nerve syndrome – functional MR Neurography on a fascicular level

Tim Godel[a,*], Mirko Pham[a,b], Henrich Kele[c], Moritz Kronlage[a], Daniel Schwarz[a], Merle Brunée[a], Sabine Heiland[a], Martin Bendszus[a], Philipp Bäumer[a,d]

[a] Department of Neuroradiology, Heidelberg University Hospital, Im Neuenheimer Feld 400, 69120 Heidelberg, Germany
[b] Department of Neuroradiology, Würzburg University Hospital, Josef-Schneider-Str. 11, 97080 Würzburg, Germany
[c] Center for Neurology and Clinical Neurophysiology, Neuer Wall 19, 20354 Hamburg, Germany
[d] Center for Radiology Dia.log, Vinzenz-von-Paul Str. 8, 84503 Altötting, Germany

ARTICLE INFO

Keywords:
Anterior interosseous nerve syndrome
Diffusion tensor imaging
Functional MR Neurography

ABSTRACT

Purpose: By applying diffusor tensor imaging (DTI) in patients with anterior interosseous nerve syndrome (AINS), this proof of principle study aims to quantify the extent of structural damage of a peripheral nerve at the anatomical level of individual fascicles.

Methods: In this institutional review board approved prospective study 13 patients with spontaneous AINS were examined at 3 Tesla including a transversal T2-weighted turbo-spin-echo and a spin-echo echo-planar-imaging pulse sequence of the upper arm level. Calculations of quantitative DTI parameters including fractional anisotropy (FA), mean diffusivity (MD), radial diffusivity (RD), and axial diffusivity (AD) for median nerve lesion and non-lesion fascicles as well as ulnar and radial nerve were obtained. DTI values were compared to each other and to a previously published dataset of 58 healthy controls using one-way Analysis of Variance with Bonferroni correction and p-values < .05 were considered significant. Receiver operating characteristic (ROC) curves were performed to assess diagnostic accuracy.

Results: FA of median nerve lesion fascicles was decreased compared to median nerve non-lesion fascicles, ulnar nerve and radial nerve while MD, RD, and AD was increased ($p < .001$ for all parameters). Compared to median nerve values of healthy controls, lesion fascicles showed a significant decrease in FA while MD, RD, and AD was increased ($p < .001$ for all parameters). FA of median nerve non-lesion fascicles showed a weak significant decrease compared to healthy controls ($p < .01$) while there was no difference in MD, RD, and AD. ROC analyses revealed an excellent diagnostic accuracy of FA, MD and RD in the discrimination of median nerve lesion and non-lesion fascicles in AINS patients as well as in the discrimination of lesion fascicles and normative median nerve values of healthy controls.

Conclusion: By applying this functional MR Neurography technique in patients with AINS, this proof of principle study demonstrates that diffusion tensor imaging is feasible to quantify structural nerve injury at the anatomical level of individual fascicles.

1. Introduction

AINS is a rare peripheral neuropathy of unclear etiology. In the spontaneous variant of AINS acute weakness of distal phalanx flexion of the thumb, index finger, middle finger, and forearm pronation occur as the major presenting symptoms without a clearly attributable traumatic origin (Kiloh and Nevin, 1952). In the past, distal entrapment of the AIN, an almost purely motor branch of the median nerve, was often

Abbreviations: AINS, Anterior interosseous nerve syndrome; AIN), anterior interosseous nerve; MRN, MR Neurography; DTI, Diffusor tensor imaging; TSE, turbo spin echo; EPI, echo-planar-imaging; FA, fractional anisotropy; MD, mean diffusivity; RD, radial diffusivity; AD, axial diffusivity; ANOVA, Analysis of Variance; CI, confidence interval; ROC, Receiver operating characteristic

* Corresponding author at: Department of Neuroradiology, Neurological University Clinic, Heidelberg University Hospital, Im Neuenheimer Feld 400, 69, 120 Heidelberg, Germany.

E-mail addresses: Tim.godel@med.uni-heidelberg.de (T. Godel), Pham_M@ukw.de (M. Pham), Kele@neurologie-neuer-wall.de (H. Kele), Moritz.kronlage@med.uni-heidelberg.de (M. Kronlage), Daniel.schwarz@med.uni-heidelberg.de (D. Schwarz), Merle@brunnee.de (M. Brunée), Sabine.heiland@med.uni-heidelberg.de (S. Heiland), Martin.bendszus@med.uni-heidelberg.de (M. Bendszus), p.baeumer@dialog-aoe.de (P. Bäumer).

https://doi.org/10.1016/j.nicl.2019.101659
Received 3 October 2018; Received in revised form 21 December 2018; Accepted 4 January 2019
Available online 09 January 2019

thought to be a principal side of symptom origination. Hence, surgical release at the forearm level was regularly favored as the therapeutic procedure of choice (Lake, 1974; Nigst and Dick, 1979).

A previous study using morphological MRN, however, described a strictly organized somatotopic internal fascicular lesion pattern not at the forearm level of the AIN itself but within the median nerve proximally at the upper arm level (Pham et al., 2014). Elevated signal intensity on T2-w sequences was exclusively found in these motor fascicles on upper arm level, forming the AIN more distally while other median nerve fascicles on upper arm level were spared. This study on the median nerve as well as subsequent studies on the radial and sciatic nerve demonstrated that structural and contrast resolution of current MRN technology is capable to delineate the somatotopic or radiculotopic intrinsic nerve architecture (Baumer et al., 2016; Baumer et al., 2015). MRN techniques, which rely on lesion detection by their T2-w contrast, however, provide only comparative signal characteristics and potentially suffer from inaccurate visual rating. Moreover, T2-w lesion contrast likely lacks specificity in diverse structural nerve pathologies and does not allow to differentiate demyelination or axonal loss as potential underlying pathophysiology.

Beyond this purely morphologic representation, functional MRN techniques, which have originally been developed for central nervous system disorders, are of increasing interest in the investigation of the peripheral nervous system (Kronlage et al., 2018; Godel et al., 2016; Godel et al., 2017; Kronlage et al., 2017). DTI is a functional and quantitative MRI technique that applies magnetic gradients in multiple orientations. Measurement of direction and magnitude of proton diffusion provides a quantitative and objective conclusion of peripheral nerve microstructural integrity (Naraghi et al., 2015). By applying DTI in patients with AINS, this proof of principle study aims to quantify the extent of structural damage of a peripheral nerve at the anatomical level of individual fascicles.

2. Subjects and methods

2.1. Clinical and demographic patient data

This study was performed in accordance with the Declaration of Helsinki, approved by the institutional ethics board (S398–2012) and written informed consent was obtained from all patients. Overall, 13 patients with symptoms of spontaneous AINS (5 male, 8 female, mean age 44.4 years, range 25–59 years) were prospectively examined at the Department of Neuroradiology of Heidelberg University Hospital. Patients were referred to our department with a clinical diagnosis of AINS due to muscle weakness and abnormal EMG results in the distribution of the AIN $<$ 6 months after symptom onset. In all patients a thorough electrophysiological examination was performed to exclude proximal and multifocal neuropathies as well as cervical radiculopathies.

Moreover, 58 healthy controls (29 males, 29 females, mean age 49.07 years, range 23–75 years) were part of a previously published prospective study (Kronlage et al., 2018) and served as controls for the assessment of quantitative median nerve parameters. Inclusion criteria for healthy controls were: $\geq$ 18 years, no medical history suspicious for AINS, absence of neuropathic pain or other sources of pain, diabetes mellitus, alcoholism, any malignant or infectious illness as risk factors for polyneuropathy. Exclusion criteria were any contraindications for MRI.

2.2. Imaging protocol

Examinations were conducted on a 3 Tesla Magnetic Resonance scanner (Magnetom SKYRA, Siemens Healthineers, Erlangen, Germany) between 4/2016 and 8/2018. All AINS patients underwent an MRN protocol including:

1. A transversal T2-weighted TSE sequence at upper arm level: repetition time/echo time 6980/52 ms, spectral fat saturation, slice thickness 3.0 mm, number of slices 45, interslice gap 0.3 mm, field of view 130 × 130 mm^2, acquisition matrix 512 × 358, pixel size 0.254 × 0.254 mm^2, number of excitations = 3, acquisition time 7:17 min.
2. A single-shot spin-echo EPI DTI sequence at upper arm level (b-value = 0 and 1000 s/mm^2 in 20 directions): repetition time 4400 ms; echo time 109 ms; fat saturation, spectral adiabatic inversion recovery; field of view 158 × 158 mm^2; matrix 128 × 128; slice thickness 3.0 mm; number of slices 18; slice gap 0%; phase oversampling 40%; number of averages 3; parallel imaging, generalized autocalibrating partial parallel acquisition; acceleration factor 3; number of reference lines 84; acquisition time 5:01 min.

Participants were examined in prone position using a 15-channel transmit-receive knee-coil (Siemens Healthcare) with the arm in elbow extension. The magic angle effect was avoided by aligning the longitudinal axis of the upper arm at an angle of 108° relative to the B0 field (Kastel et al., 2011).

2.3. Image postprocessing and analysis

Calculations of DTI parameters FA, MD, RD, and AD were obtained using the open source plugin DTI map for OsiriX (Pixmeo, Bernex, Switzerland) with a fixed noise threshold set at 13. Segmentation of ulnar and radial nerve circumferences as well as median nerve lesion and non-lesion fascicles were performed in the B0 map using a free-hand ROI (Fig. 1). All AINS patients showed elevated T2-w signal characteristics with the expected somatotopic distribution involving only motor median nerve fascicles at upper arm level. Thus, median nerve lesion and non-lesion fascicles at the upper arm level were recognizable and segmented in all AINS patients. Quantitative DTI values were averaged from 10 slices and mean values were calculated for each patient.

2.4. Statistical analysis

Statistical analyses and data visualization were performed with GraphPad Prism 7.0 (GraphPad Software, La Jolla, USA). Mean values for FD, ADC, AD, and RD of each patient and nerve were calculated as described and tested for statistical significance using one-way ANOVA with Bonferroni correction. *P*-values of $<$ 0.05 were considered significant. All results are documented as mean values ± Standard Error of the Mean and 95% CI. ROC curves of quantitative DTI parameter of median nerve lesion and non-lesion fascicles as well as median nerve lesion fascicles and normative median nerve values of healthy controls were used to assess diagnostic accuracy.

3. Results

DTI parameters FA, MD, RD, and AD of median nerve lesion and non-lesion fascicles, ulnar nerve, and radial nerve were assessed in 13 patients with AINS (Fig. 1).

FA of median nerve lesion fascicles was significantly decreased to 0.33 ± 0.08 compared to median nerve non-lesion fascicles (0.50 ± 0.07, 95% CI: -0.25 to 0.07), ulnar nerve (0.55 ± 0.08, 95% CI: -0.30 to −0.13) and radial nerve (0.52 ± 0.11, 95% CI: -0.27 to −0.09). MD of median nerve lesion fascicles showed a significant increase to 1729.88 ± 318.97 10^{-6} mm^2/s compared to non-lesion median nerve fascicles (1188.67 ± 222.12 10^{-6} mm^2/s, 95% CI: 355.10 to 728.90), ulnar nerve (1040.17 ± 192.24 10^{-6} mm^2/s, 95% CI: 503.10 to 876.90) and radial nerve (743.87 ± 190.67 10^{-6} mm^2/s, 95% CI: 797.40 to 1171.00) (Bonferroni-adjusted $p < .001$). RD of median nerve lesion fascicles was significantly increased to 1366.61 ± 264.27 10^{-6} mm^2/s compared to median nerve non-lesion

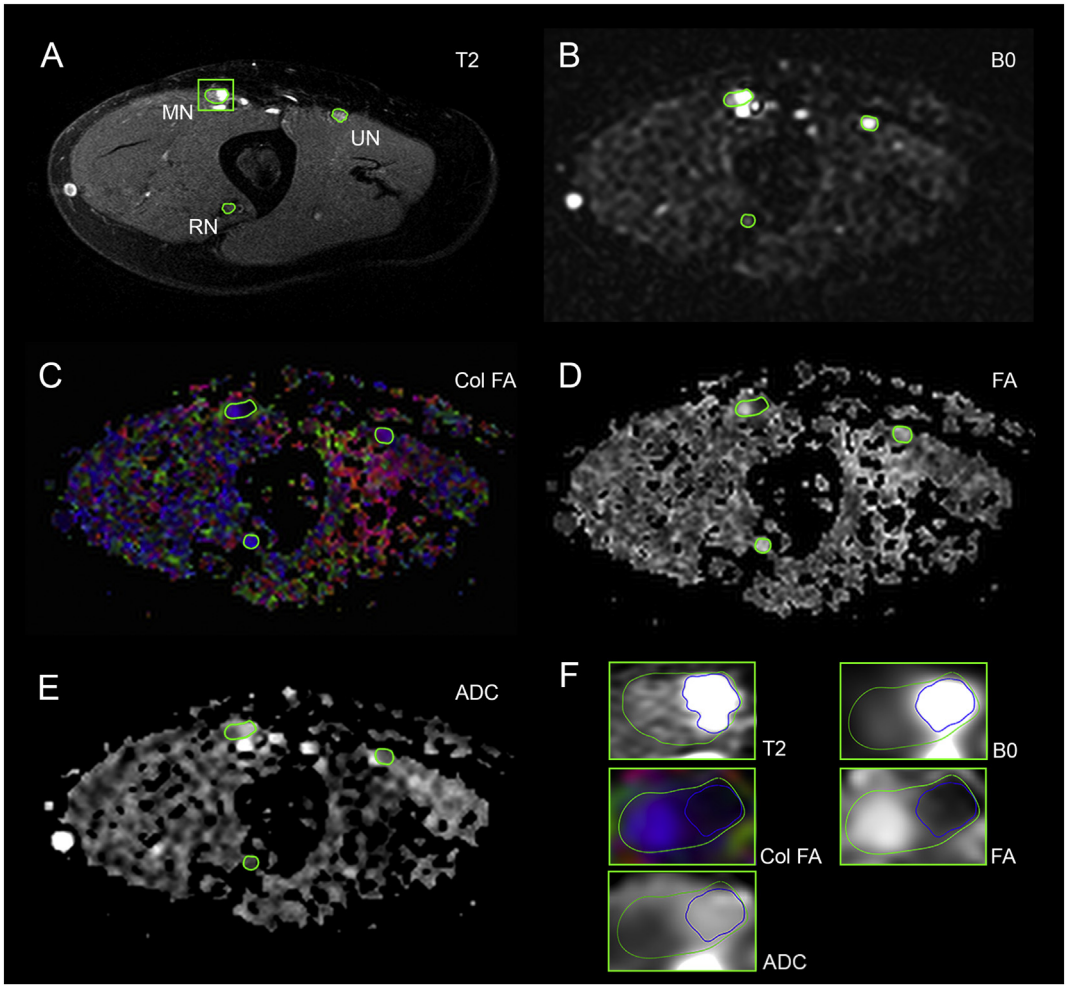

Fig. 1. Imaging analysis of DTI parameters of median nerve lesion and non-lesion fascicles, ulnar and radial nerve at the upper arm level. Segmentation of median nerve (MN) lesion and non-lesion fascicles as well as ulnar (UN) and radial nerve (RN) circumference was performed in the B0 image (B, F) under assistance of the T2 image (A). Then, DTI parameter maps for FA (C, D, F), MD (E, F) RD and AD (not shown) were calculated. Col FA (color-coded FA-map).

fascicles (843.34 ± 208.44 10^{-6} mm^2/s, 95% CI: 331.40 to 713.80), ulnar nerve (649.66 ± 153.79 10^{-6} mm^2/s, 95% CI: 525.70 to 908.10) and radial nerve (478.76 ± 168.35 10^{-6} mm^2/s, 95% CI: 695.10 to 1077.00) (Bonferroni-adjusted $p < .001$). AD of median nerve lesion fascicles was significantly increased to 2320.15 ± 223.07 10^{-6} mm^2/s compared to median nerve non-lesion fascicles (1903.21 ± 328.87 10^{-6} mm^2/s, 95% CI: 165.80 to 673.40), ulnar nerve (1812.40 ± 316.70 10^{-6} mm^2/s, 95% CI: 255.60 to 763.20) and radial nerve (1260.68 ± 243.53 10^{-6} mm^2/s, 95% CI: 804.80 to 1312.00) (Bonferroni-adjusted p < .001), (Fig. 2).

Moreover, quantitative DTI parameters of median nerve lesion and non-lesion fascicles were compared to median nerve values of healthy controls (Fig. 3).

Compared to healthy controls, median nerve lesion fascicles showed a significant decrease in FA (0.33 ± 0.08 vs. 0.58 ± 0.08, 95% CI: -0.32 to −0.18) while MD (1729.88 ± 318.97 vs. 1153.00 ± 158.65 10^{-6} mm^2/s, 95% CI: 429.70 to 724.20), RD (1366.61 ± 264.27 vs. 727.00 ± 182.26 10^{-6} mm^2/s, 95% CI: 489.40 to 790.60) and AD (2320.15 ± 223.07 vs. 2000.56 ± 205.15 10^{-6} mm^2/s, 95% CI: 120.10 to 519.90) were increased (Bonferroni-adjusted $p < .001$ for all parameters). FA of median nerve non-lesion fascicles showed a weak, significant decrease compared to healthy controls (0.50 ± 0.07 vs. 0.58 ± 0.08, 95% CI: -0.15 to −0.01, Bonferroni-adjusted $p < .01$), while there was no significant difference in MD (1188.67 ± 222.12 vs. 1153.00 ± 158.65 10^{-6} mm^2/s, 95% CI: -112.30 to 182.20, Bonferroni-adjusted $p = .99$), RD (843.34 ± 208.44 vs. 727.00 ± 182.26 10^{-6} mm^2/s, 95% CI: -33.19 to 268.00, Bonferroni-adjusted $p = .32$), and AD (1903.21 ± 328.87 vs. 2000.56 ± 205.15 10^{-6} mm^2/s, 95% CI: -299.50 to 100.30, Bonferroni-adjusted p = .99).

ROC analyses of quantitative DTI parameters as a diagnostic tool for discrimination of median nerve lesion and non-lesion fascicles revealed an area-under-the-curve (AUC) of 0.97 for FA (95% CI: 0.91 to 1.00), 0.99 for MD (95% CI: 0.98 to 1.00), 1.00 for RD (1.00 to 1.00), and 0.91 for AD (95% CI: 0.80 to 1.00). ROC analyses for discrimination of median nerve lesion fascicles and normative median nerve values of healthy controls revealed an AUC of 0.99 for FA (95% CI: 0.97 to 1.00), 0.98 for MD (95% CI: 0.96 to 1.00), 0.99 for RD (95% CI: 0.96 and 1.00), and 0.89 for AD (95% CI: 0.80 to 0.99), (Fig. 4).

4. Discussion

This study examined DTI as a functional MRN technique in patients with spontaneous AINS and demonstrates its utility for lesion discrimination and quantitation at the anatomical level of individual fascicles.

FA is the most commonly used parameter in DTI as it is regarded as a general measure of nerve fiber integrity and decreased FA values are considered to be a quantitative biomarker of disturbed microstructural nerve integrity in various peripheral neuropathies (Kronlage et al., 2017; Basser et al., 1994; Hagmann et al., 2006; Guggenberger et al., 2012; Breckwoldt et al., 2015; Hiltunen et al., 2005; Hiltunen et al., 2012). In this study, decreased FA values were found in those fascicles

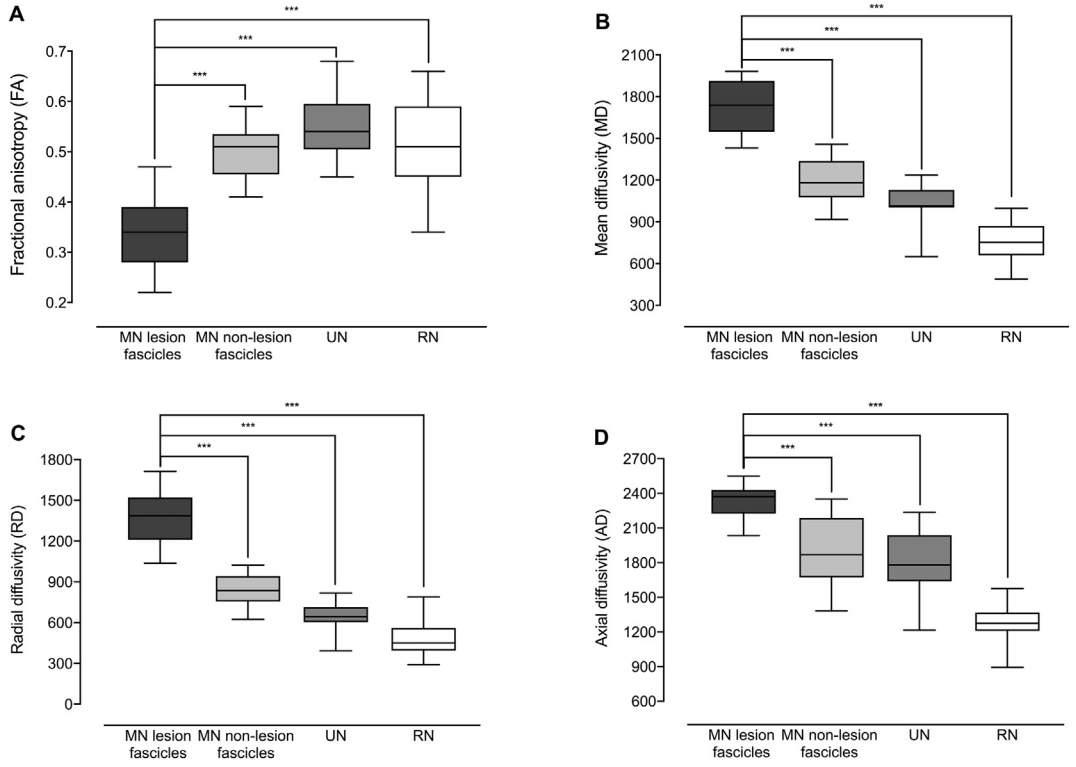

Fig. 2. Quantitative analysis of DTI parameters of median nerve lesion and non-lesion fascicles, ulnar and radial nerve in AINS patients. Compared to median nerve (MN) non-lesion fascicles, ulnar nerve (UN) and radial nerve (RN), lesion fascicles of the median nerve show a decrease in FA and an increase in MD, RD and AD (***p-value: < 0.001).

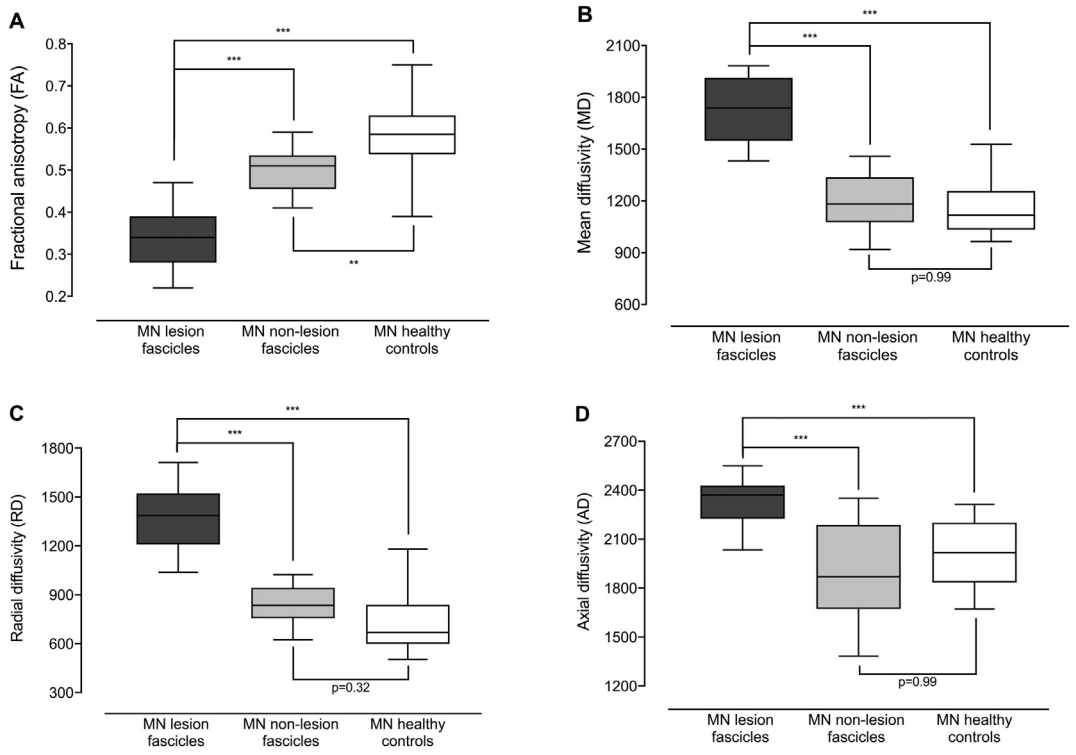

Fig. 3. Quantitative evaluation of median lesion and non-lesion fascicles of AINS patients in comparison to healthy controls. Compared to the median nerve of healthy controls, median nerve lesion fascicles of AINS patients showed a decrease in FA while MD, RD and AD were increased. Non-lesion median nerve fascicles of AINS patients showed a weak significant decrease in FA compared to the median nerve of healthy controls while there was no difference in MD, RD and AD. (***p-value: < 0.001, **p-value: < 0.01).

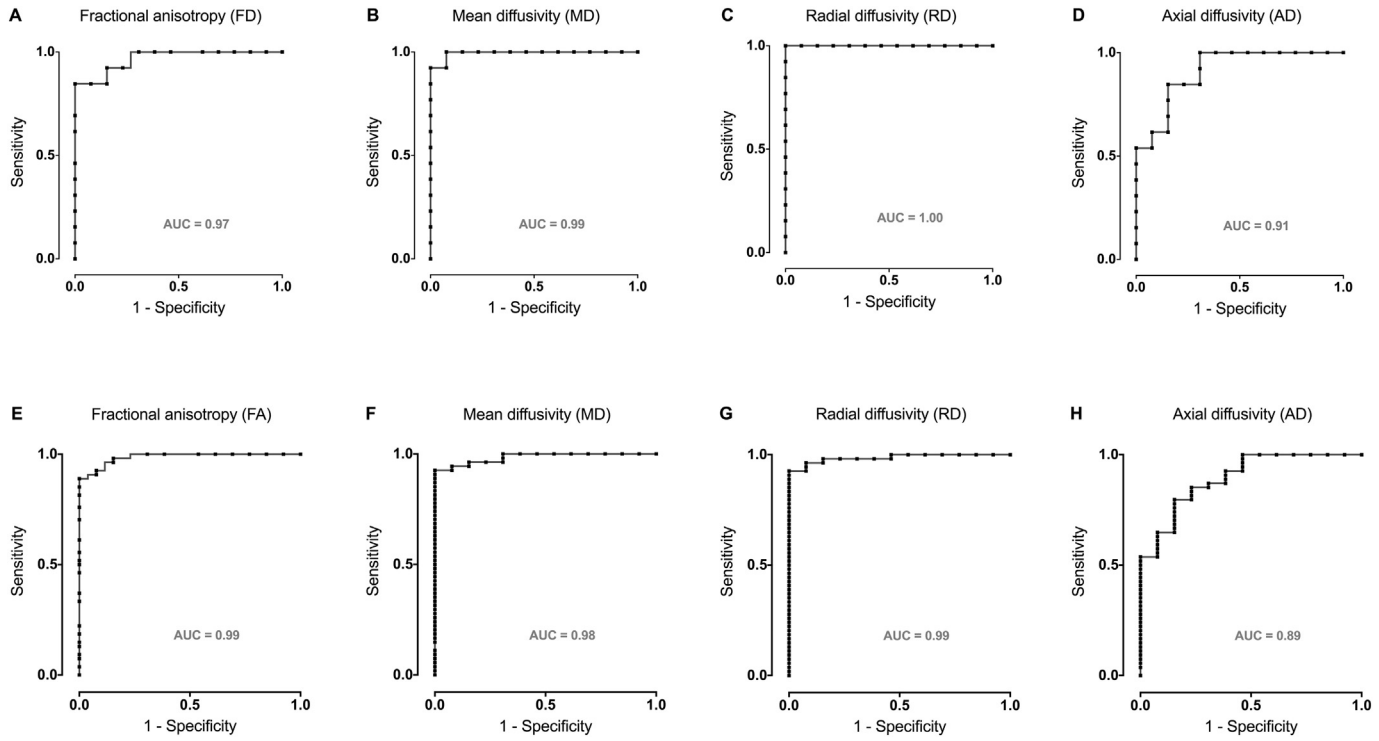

Fig. 4. ROC analyses of quantitative DTI parameters. ROC analyses between median nerve lesion and non-lesion fascicles (A-D) as well as median nerve lesion fascicles and median nerve values of healthy controls (*E*-H) revealed that FA, MD and RD are highly accurate parameters in the differentiation of lesion and non-lesion fascicles in AINS patients as well as in the discrimination of lesion-fascicles and normative median nerve values of healthy controls.

of the median nerve, which were conspicuous by T2-w signal and which were somatotopically corresponding to the purely motor fascicles of the upper arm median nerve that forms the AIN more distally at the forearm. This finding as well as concomitantly acquired ROC analyses strongly support the previously proposed theory of a disturbed microstructural integrity of the median nerve at upper arm level (Pham et al., 2014). Non-lesion median nerve fascicles, however, also showed slightly decreased FA values compared to normative values of healthy controls. A previous study using quantitative DTI in subclinical ulnar neuropathy at the elbow revealed that FA was a more sensitive marker compared to signal intensity on T2-w sequences as the current standard of reference (Baumer et al., 2014). This altered microstructural nerve integrity of apparently healthy fascicles in T2-w could be attributed to the fascicular-inflammatory lesion pattern in AINS where seldom AIN fascicles are affected completely. Clinical experience shows that AINS could occur incompletely and not all muscles innervated by AIN are affected. On the other hand, AINS could also be accompanied by an additional denervation of the pronator teres muscle.

While FA values of the median nerve lesion and non-lesion fascicles were decreased in AINS patients, MD values of median nerve lesion fascicles as a surrogate of the extracellular space were elevated. This finding is in accordance with previous studies, where a similar an inverse FA/MD relationship was found (Kronlage et al., 2017; Heckel et al., 2015). MD of non-lesion median nerve fascicles, however, showed no difference to healthy controls. This could be a hint that FA is the most sensitive parameter in DTI.

Although MD is a direction-independent measure of proton diffusion, nerve tissue might be more precisely characterized by measuring diffusivity parallel to fiber orientation (AD) as well as perpendicular to fiber orientation (RD). While conventional MRN techniques, which rely on lesion detection by their T2-w contrast, are unable to differentiate the axonal and myelin compartment in peripheral nerves, quantitative DTI may potentially be capable to provide this additional information. Evidence from the central nervous system as well as from recent DTI studies investigating peripheral neuropathies suggest that increased RD reflects damage to myelin integrity, whereas changes in AD might be more specific for axonal degeneration (Kronlage et al., 2017; Heckel et al., 2015; Budde et al., 2007; DeBoy et al., 2007; Della Nave et al., 2011).

A previous study investigating quantitative DTI parameters in correlation to electrophysiology found, that electrophysiological parameters representing myelin sheath integrity correlated significantly with RD whereas AD correlated significantly with CMAP as a marker of axonal integrity in a subgroup of healthy volunteers with subclinical neuropathy. According to this model, a disturbance of axonal integrity should be characterized by a decrease in FA and an increase in RD with a concomitant decreased AD profile (Heckel et al., 2015).

In a subsequent study we assessed DTI measures as quantitative biomarkers in chronic inflammatory demyelinating polyneuropathy (CIDP) and analyzed their diagnostic accuracy according to electrophysiology (Kronlage et al., 2017). Thereby, all DTI measures showed strong correlations to established electrophysiological parameters as the standard of reference. In general, decreases in structural nerve integrity (FA) were mainly due to an increased RD, non-altered AD and a decreased NCV, indicating a primarily demyelination. In a subgroup of patients with severe CIDP and suspected secondary axonal neuropathy, however, decreased CMAP values were accompanied with a decreased FA, but an increase in AD. This finding is somewhat contrary to the model by Heckel et al. (Heckel et al., 2015) and to well-established models of the CNS (Lin et al., 2016). Thus, the authors hypothesized, that AD is quite susceptible to nerve edema and accurately reflects axonal integrity only in the absence of nerve edema (Kronlage et al., 2017). On the other hand, increased AD profiles were found in in degenerating axons of patients with Friedreich's ataxia (Della Nave et al., 2011) as well as for peripheral neuropathies of various etiologies (Breckwoldt et al., 2015).

In the present study, DTI parameters RD and AD show a profile quite similar to those we have seen in patients with severe CIDP and suspected secondary axonal neuropathy (increase in RD and AD). The vast majority of AINS patients of our previous study (Pham et al., 2014) as

well as the present study show muscle denervation by electromyography, while nerve conduction remains normal. Thus, we recommend to interpret AD as a potentially suitable biomarker of axonal damage very carefully, especially in terms of potentially coexisting nerve edema, inflammation and demyelination.

Anti-inflammatory therapy and surgical dissection of median nerve trunk epineurium at upper arm level seem to be the principle therapeutic options in spontaneous AINS (Pham et al., 2014; Nagano, 2003). However, clinical outcome after therapeutic interventions are quite variable and there is evidence that spontaneous recovery might occur in a minority of patients as well (Lake, 1974; Vichare, 1968; Huffmann and Leven, 1976). Thus, new diagnostic parameters as those presented in this study have to be evaluated as the type of underlying pathophysiological process might directly influence the therapeutic procedure and prognosis.

A limitation of this study is that patients were not prospectively preselected to their electrophysiological results, so we can't differentiate between overlapping effects of primary demyelination with secondary axonal neuropathy and primary axonal damage. For this purpose, further longitudinal studies should correlate neurophysiological measures with DTI parameters and the clinical course of disease in patients with spontaneous AINS.

5. Conclusions

By applying this functional MR Neurography technique in patients with AINS, this proof of principle study demonstrates that diffusion tensor imaging is feasible to quantify structural nerve injury at the anatomical level of individual fascicles.

Acknowledgements

We thank all patients for their valuable cooperation in this study. T.G. is supported by a postdoctoral fellowship from the Medical Faculty of the University of Heidelberg and received a research grant of Amicus Therapeutics. M.B. received grants from the German Research Council (SFB 1158). S.H. was supported by a grant from the German Research Council (SFB 1118).

Declaration of interest

None.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Basser, P.J., Mattiello, J., LeBihan, D., 1994. MR diffusion tensor spectroscopy and imaging. Biophys. J. 66 (1), 259–267.
Baumer, P., Pham, M., Ruetters, M., et al., 2014. Peripheral neuropathy: detection with diffusion-tensor imaging. Radiology 273 (1), 185–193.
Baumer, P., Weiler, M., Bendszus, M., Pham, M., 2015. Somatotopic fascicular organization of the human sciatic nerve demonstrated by MR neurography. Neurology 84 (17), 1782–1787.
Baumer, P., Kele, H., Xia, A., et al., 2016. Posterior interosseous neuropathy: Supinator syndrome vs fascicular radial neuropathy. Neurology 87 (18), 1884–1891.
Breckwoldt, M.O., Stock, C., Xia, A., et al., 2015. Diffusion tensor imaging adds diagnostic accuracy in magnetic resonance neurography. Investig. Radiol. 50 (8), 498–504.
Budde, M.D., Kim, J.H., Liang, H.F., et al., 2007. Toward accurate diagnosis of white matter pathology using diffusion tensor imaging. Magn. Reson. Med. 57 (4), 688–695.
DeBoy, C.A., Zhang, J., Dike, S., et al., 2007. High resolution diffusion tensor imaging of axonal damage in focal inflammatory and demyelinating lesions in rat spinal cord. Brain 130 (Pt 8), 2199–2210.
Della Nave, R., Ginestroni, A., Diciotti, S., et al., 2011. Axial diffusivity is increased in the degenerating superior cerebellar peduncles of Friedreich's ataxia. Neuroradiology 53 (5), 367–372.
Godel, T., Pham, M., Heiland, S., et al., 2016. Human dorsal-root-ganglion perfusion measured in-vivo by MRI. NeuroImage 141, 81–87.
Godel, T., Baumer, P., Pham, M., et al., 2017. Human dorsal root ganglion in vivo morphometry and perfusion in Fabry painful neuropathy. Neurology 89 (12), 1274–1282.
Guggenberger, R., Markovic, D., Eppenberger, P., et al., 2012. Assessment of median nerve with MR neurography by using diffusion-tensor imaging: normative and pathologic diffusion values. Radiology 265 (1), 194–203.
Hagmann, P., Jonasson, L., Maeder, P., et al., 2006. Understanding diffusion MR imaging techniques: from scalar diffusion-weighted imaging to diffusion tensor imaging and beyond. Radiographics 26 (Suppl. 1), S205–S223.
Heckel, A., Weiler, M., Xia, A., et al., 2015. Peripheral nerve diffusion tensor imaging: assessment of axon and myelin sheath integrity. PLoS One 10 (6), e0130833.
Hiltunen, J., Suortti, T., Arvela, S., et al., 2005. Diffusion tensor imaging and tractography of distal peripheral nerves at 3 T. Clin. Neurophysiol. 116 (10), 2315–2323.
Hiltunen, J., Kirveskari, E., Numminen, J., et al., 2012. Pre- and post-operative diffusion tensor imaging of the median nerve in carpal tunnel syndrome. Eur. Radiol. 22 (6), 1310–1319.
Huffmann, G., Leven, B., 1976. interosseous anterior syndrome. Study in 4 cases of our own and in 49 cases from the literature (author's transl). J. Neurol. 213 (4), 317–326.
Kastel, T., Heiland, S., Baumer, P., et al., 2011. Magic angle effect: a relevant artifact in MR neurography at 3 T? AJNR Am. J. Neuroradiol. 32 (5), 821–827.
Kiloh, L.G., Nevin, S., 1952. Isolated neuritis of the anterior interosseous nerve. Br. Med. J. 1 (4763), 850–851.
Kronlage, M., Pitarokoili, K., Schwarz, D., et al., 2017. Diffusion tensor imaging in chronic inflammatory demyelinating polyneuropathy: diagnostic accuracy and correlation with electrophysiology. Investig. Radiol. 52 (11), 701–707.
Kronlage, M., Schwehr, V., Schwarz, D., et al., 2018. Peripheral nerve diffusion tensor imaging (DTI): normal values and demographic determinants in a cohort of 60 healthy individuals. Eur. Radiol. 28 (5), 1801–1808.
Lake, P.A., 1974. Anterior interosseous nerve syndrome. J. Neurosurg. 41 (3), 306–309.
Lin, M., He, H., Schifitto, G., Zhong, J., 2016. Simulation of changes in diffusion related to different pathologies at cellular level after traumatic brain injury. Magn. Reson. Med. 76 (1), 290–300.
Nagano, A., 2003. Spontaneous anterior interosseous nerve palsy. J. Bone Joint Surg. (Br.) 85 (3), 313–318.
Naraghi, A.M., Awdeh, H., Wadhwa, V., et al., 2015. Diffusion tensor imaging of peripheral nerves. Semin. Musculoskelet. Radiol. 19 (2), 191–200.
Nigst, H., Dick, W., 1979. Syndromes of compression of the median nerve in the proximal forearm (pronator teres syndrome; anterior interosseous nerve syndrome). Arch. Orthop. Trauma Surg. 93 (4), 307–312.
Pham, M., Baumer, P., Meinck, H.M., et al., 2014. Anterior interosseous nerve syndrome: fascicular motor lesions of median nerve trunk. Neurology 82 (7), 598–606.
Vichare, N.A., 1968. Spontaneous paralysis of the anterior interosseous nerve. J. Bone Joint Surg. (Br.) 50 (4), 806–808.