Anterior interosseous nerve syndrome
Fascicular motor lesions of median nerve trunk

ABSTRACT

Objective: We sought to determine lesion sites and spatial lesion patterns in spontaneous anterior interosseous nerve syndrome (AINS) with high-resolution magnetic resonance neurography (MRN).

Methods: In 20 patients with AINS and 20 age- and sex-matched controls, MRN of median nerve fascicles was performed at 3T with large longitudinal anatomical coverage (upper arm/elbow/forearm): 135 contiguous axial slices (T2-weighted: echo time/repetition time $52/7,020$ ms, time of acquisition: $15$ minutes $48$ seconds, in-plane resolution: $0.25 \times 0.25$ mm). Lesion classification was performed by visual inspection and by quantitative analysis of normalized T2 signal after segmentation of median nerve voxels.

Results: In all patients and no controls, T2 lesions of individual fascicles were observed within upper arm median nerve trunk and strictly followed a somatotopic/internal topography: affected were those motor fascicles that will form the anterior interosseous nerve further distally while other fascicles were spared. Predominant lesion focus was at a mean distance of $14.6 \pm 5.4$ cm proximal to the humeroradial joint. Discriminative power of quantitative T2 signal analysis and of qualitative lesion rating was high, with $100\%$ sensitivity and $100\%$ specificity ($p < 0.0001$). Fascicular T2 lesion patterns were rated as multifocal ($n = 17$), monofocal ($n = 2$), or indeterminate ($n = 1$) by 2 independent observers with strong agreement (kappa $= 0.83$).

Conclusion: It has been difficult to prove the existence of fascicular/partial nerve lesions in spontaneous neuropathies using clinical and electrophysiologic findings. With MRN, fascicular lesions with strict somatotopic organization were observed in upper arm median nerve trunks of patients with AINS. Our data strongly support that AINS in the majority of cases is not a surgically treatable entrapment neuropathy but a multifocal mononeuropathy selectively involving, within the main trunk of the median nerve, the motor fascicles that continue distally to form the anterior interosseous nerve. Neurology® 2014;82:1–9

GLOSSARY

AIN = anterior interosseous nerve; AINS = anterior interosseous nerve syndrome; AUC = area under the curve; CI = confidence interval; DTI = diffusion tensor imaging; FDP = flexor digitorum profundus; FDPII = index finger; FDPIII = middle finger; FPL = flexor pollicis longus (thumb); IVlg = IV immunoglobulin; MRC = Medical Research Council; MRN = magnetic resonance neurography; NCS = nerve conduction studies; PQ = pronator quadratus (forearm); ROC = receiver operating characteristic; ROI = region of interest.

Spontaneous anterior interosseous nerve syndrome (AINS) is an uncommon peripheral neuropathy of unclear etiology.¹ Except for fine articular branches at the wrist, the anterior interosseous nerve (AIN) is an almost purely motor branch of the median nerve important for thumb and hand function.² It leaves the median nerve trunk at forearm level, immediately distally to the pronatorteres muscle, and innervates the flexor pollicis longus (FPL), pronator quadratus (PQ), and flexor digitorum profundus (FDP) muscle to the index and middle finger.³⁻⁴ AINS presents with spontaneous acute weakness of distal phalanx flexion of the thumb (FPL) and/or index finger (FDPII), middle finger (FDPIII), and forearm pronation (PQ). The severity and completeness of these motor symptoms vary substantially, as described originally.⁴ Typically, no sensory abnormalities are
detected by clinical or electrophysiologic examination. However, pain of different quality, intensity, and location may occur.\(^1,5\)

Usually median nerve conduction studies (NCS) are normal in AINS and thus unhelpful for lesion localization. EMG reveals typical patterns of muscle denervation compatible with a lesion of the AIN itself or, alternatively, of its motor fascicles located further proximally within the median nerve trunk. These fascicles continue distally in an ordered fashion of functional grouping to form the AIN. In fact, a more proximal lesion site has been suggested previously.\(^6,7\)

However, it has been difficult to obtain evidence of a more proximal lesion because NCS/EMG may not differentiate it from a lesion to the AIN itself. This study used high-resolution magnetic resonance neurography (MRN) to determine lesion sites and spatial lesion patterns of AINS and estimated its accuracy in discriminating between AINS and controls.

**METHODS** Between April 2009 and March 2013, 24 consecutive patients with symptoms of AINS were referred to the Department of Neurology, Heidelberg University Hospital, Germany, or the Center for Neurology and Clinical Neurophysiology Neuer Wall, Hamburg, Germany. Twenty of 24 patients consented to undergo MRN and were scheduled prospectively (figure e-1 on the Neurology\(^6\) Web site at www.neurology.org). Nonsponstaneous AINS following trauma was not included. Twenty age- and sex-matched controls without symptoms or signs of median neuropathy or risk factors for neuropathy such as diabetes, alcoholism, or infectious diseases underwent the same imaging protocol.

**Standard protocol approvals, registrations, and patient consents.** The study was approved by the institutional ethics committee (S-057/2009). All subjects gave written informed consent to participate.

**Clinical and electrophysiologic examination.** All patients underwent clinical/electrophysiologic examinations performed by board-certified neurologists with at least 10 years of experience in clinical neurophysiology (H.K. or H.M.M.). Motor strength was recorded for FPL, FDPII, and FDPIII using the Medical Research Council (MRC) rating scale. Complete AINS was defined as weakness (MRC ≤4) of FPL and FDPII/III. PQ was not evaluated quantitatively. Incomplete AINS was defined as weakness (MRC ≤4) of FPL or FDPII. In all patients, motor and sensory NCS were performed on ipsilateral median/ulnar nerves and contralateral median nerve with surface stimulation at standard sites including the axilla.\(^4\) Compound muscle action potentials were recorded following supramaximal stimulation from abductor pollicis brevis and abductor digiti minimi muscle. Sensory nerve action potentials were obtained antidromically over second, third, and fifth digit. Furthermore, median and ulnar nerve F-waves and cortical median somatosensory evoked potentials were measured. Using concentric needle EMG, FPL, PQ, or FDPII was examined for signs of denervation.

**MRN.** All participants underwent MRN at Heidelberg University Hospital. MRN acquired nerve T2 signal at high spatial resolution and, at the same time, provided large proximal to distal coverage along the upper extremity. Participants were examined prone at 3T magnetic field strength (Magnetom VERIO, Siemens, Erlangen/Germany) using an 8-channel phased-array extremity coil. Three contiguous slabs were recorded with a 2D fat-saturated T2-weighted turbo spin echo pulse sequence (echo time/repetition time 52/7,020 ms, time of acquisition 5 minutes 16 seconds, in-plane resolution 0.25 × 0.25 mm, slice thickness 3 mm, interslice gap 0.3 mm, 45 slices). The 3T MRI combined with the employed extremity coil provided sufficient signal to resolve fascicles within median nerve. At lower field strength, such detail may not be achievable. Slab position was as follows: 1) distally: central forearm to humeroradial joint, 2) centrally: humeroradial joint to central upper arm, 3) proximally: central upper arm to axilla.

**Image and statistical data analysis.** Images were rated qualitatively with regard to the following items by 2 investigators (M.P., P.B.) blinded to all participant data.

1. Lesion determination: Dichotomous ratings on presence vs absence of lesions as evident by increased T2 signal of median nerve fascicles were obtained independently from both raters.

2. Lesion localization: Anatomical site of predominant lesion focus, i.e., the slice position (with reference to humeroradial joint) with strongest increase in T2 signal of fascicles, was determined by consensus.

3. Fascicular involvement: Dichotomous consensus ratings were obtained on whether increased T2 signal involved the entire nerve cross-section or only a partial area of nerve cross-section (fascicular lesion).

4. Longitudinal lesion pattern: Dichotomous ratings were obtained independently from both raters on multifocality vs monofocality. Multifocality: slices with increased fascicular T2 signal alternated with normal slices. Monofocality: single lesion focus over contiguous slices with normal T2 signal proximal and distal to it.

Further steps of quantitative analysis were undertaken. In controls, a region of interest (ROI) was defined by manual segmentation of the median nerve (ROI\(\text{median\_control}\)). ROI\(\text{median\_control}\) was derived in each control at 14.6 cm (tolerance of ±0.6 cm) proximal to the humeroradial joint. This distance corresponded to the mean distance in patients of the predominant lesion focus proximal to the humeroradial joint (14.6 ± 5.4 cm, table e-1).

In patients, the median nerve was segmented on the slice harboring the predominant lesion focus. Two ROIs within the segmented median nerve were defined: 1) ROI\(\text{median\_lesion}\) comprised the area within nerve cross-section at the dorsal and radial/lateral aspect consistently showing increased T2 signal. 2) ROI\(\text{median\_no\_lesion}\) comprised the remainder of nerve cross-section excluding ROI\(\text{median\_lesion}\). For each subject, the mean T2 signal of the medial head of the biceps muscle was determined to calculate normalized median nerve T2 values as follows:

- **Control subjects:**
  \(\text{T2}\text{median\_control} = \frac{\text{ROI}\text{median\_control}}{\text{ROI}\text{muscle}}\)

- **Patients (lesioned fascicles):**
  \(\text{T2}\text{median\_lesion} = \frac{\text{ROI}\text{median\_lesion}}{\text{ROI}\text{muscle}}\)

- **Patients (normal-appearing fascicles):**
  \(\text{T2}\text{median\_no\_lesion} = \frac{\text{ROI}\text{median\_no\_lesion}}{\text{ROI}\text{muscle}}\)

Discriminative power was then evaluated by calculating sensitivity and specificity for qualitative and quantitative data. To objectify the average lesion focus on cross-section, intersubject image registration was performed with 6 degrees of freedom.
Before registration, images were flipped horizontally from right to left in patients with right sided symptoms to obtain comparability with patients affected contralaterally. Then, spatial maps of mean normalized T2 values were rendered for patients. Statistical analyses were calculated with STATA 12 (StataCorp LP, College Station, TX).

RESULTS Clinical findings. Mean age of patients was $46.4 \pm 11.1$ years (15 male/5 female) and $45.3 \pm 11.3$ in controls (15 male/5 female). Mean duration between symptom onset and clinical/electrophysiological examinations was 22 days (range 2–94) and 3.4 months (range 12 days to 9 months) between symptom onset and MRN. Detailed findings are given in table e-1. Complete AINS was observed in 15 and incomplete AINS in 5 patients. Sensory testing, sensory and motor NCS including F-waves, evoked potentials, and EMG of biceps/triceps were normal in all patients. EMG of FPL, FDPII, or PQ showed denervation in all patients. Pain before or at symptom onset was reported by 13 of 20 patients and varied with regard to quality, anatomical distribution, and time of onset relative to onset of motor symptoms. In the majority of these patients, pain was experienced as sharp or burning sensation at the medial aspect of elbow or upper arm.

Imaging findings and statistical image analysis. Figure 1 illustrates a complete array of T2 source images showing the predominant lesion focus of each patient.

Lesion determination and localization. T2 lesions of the median nerve were rated as present in all patients and absent in all controls (sensitivity 100%, specificity 100%, interrater agreement: Cohen kappa = 1). The positions of predominant lesion foci are given in table e-1. Their spatial distribution is illustrated in figure 1. Mean distance of predominant lesion focus was $14.6 \pm 5.4$ cm proximal to the humeroradial joint.

Fascicular involvement. In all patients but none of the controls, median nerve T2 lesions were present and involved only a partial area of the nerve cross-section (Cohen kappa = 1). The exact location of T2 signal increase was at the dorsal and radial/lateral aspect of the nerve cross-section. As illustrated on a somatotopic map of median nerve fascicles (figure 2), this lesion area corresponded precisely to the somatotopic/
topographic internal arrangement of a particular group of motor fascicles within the median nerve trunk at upper arm level: this fascicle group will form the AIN, which does not emerge from the median nerve trunk epineurium until further distally at forearm level.

Spatial lesion patterns and lesion extension. The longitudinal pattern of fascicular lesions was rated monococal for patients 1 and 2. For patient 3, no agreement was obtained (indeterminate). Patients 4–20 were rated multifocal (Cohen kappa = 0.83, p < 0.001). Figure 3 illustrates the 2 different longitudinal lesion patterns on contiguous slices. Patients with monofocal were not discernable from patients with multifocality by presence of painful symptoms, type of onset, or by other clinical/electrophysiologic findings (table e-1). In none of the patients did T2 lesions extend to the proximal extreme of coverage (axilla).

Quantitative analysis of fascicular median nerve lesions. The mean normalized median nerve T2 value of 20 controls was $T_2^\text{median}_\text{control} = 1.19 \pm 0.05$. A similar value was found in patients for normal-appearing median nerve fascicles: $T_2^\text{median}_\text{no lesion} = 1.39 \pm 0.08$ ($p = 0.104$). In patients, however, the mean $T_2^\text{median}_\text{lesion} = 2.57 \pm 0.13$ of lesioned fascicles within the median nerve trunk was significantly higher compared with controls ($T_2^\text{median}_\text{lesion} \text{ vs } T_2^\text{median}_\text{control}; p < 0.0001$); it was also significantly higher compared with normal-appearing fascicles of patients ($T_2^\text{median}_\text{lesion} \text{ vs } T_2^\text{median}_\text{no lesion}; p < 0.0001$). Receiver operating characteristic (ROC) analysis of $T_2^\text{median}_\text{lesion} \text{ vs } T_2^\text{median}_\text{control}$ calculated an area under the curve (AUC) of 1.00 (95% confidence interval [CI] 1.00–1.00), corresponding to sensitivity and specificity of 100% at a cutoff of $\geq 1.7$ of normalized T2 signal. ROC analysis of $T_2^\text{median}_\text{lesion} \text{ vs } T_2^\text{median}_\text{no lesion}$ (lesioned fascicles vs normal-appearing fascicles of patients) revealed AUC = 0.98 (95% CI 0.94–1.00). Empirical values of normalized T2 signal for lesioned fascicles of patients are plotted against controls in figure 4.

Follow-up. In the majority of patients with multifocality, the administration of corticosteroids was elected as primary intervention. Their clinical response varied widely, with satisfactory recovery occurring in only some patients (table e-1). IV immunoglobulins (IVIg) were available for 4 patients, none of whom responded to corticosteroids, and were administered according to the ICE Study scheme.10 Upon IVIg, satisfactory improvement was observed in 2 of these 4 patients.

In patient 1 with monofocality, symptoms persisted after corticosteroids had been administered over 1 month (FPL 0). The monofocal proximal T2 lesion was discussed with the patient as a novel finding of unclear significance. It was mentioned that few cases had been described with torsion of motor median nerve fascicles at upper arm level, and that interfascicular neurolysis in some cases was followed by

![Figure 2](image-url)
were not corrected for.
The left of the schematic drawing of bony landmarks. Differences in individual arm lengths
The anatomical localization of the predominant lesion focus is shown on the metric scale to
anterior interosseous motor fascicles. These fascicles will form the anterior interosseous
monofocal and multifocal lesion pattern both follow the internal topography/somatotopy of
ative to the predominant lesion focus (at 9.2 cm in patient 2 and 22.2 cm in patient 8). The
Representative control subject (right). In each column, contiguous longitudinal high-resolution
Representative monofocal (left) and multifocal (middle) lesion patterns are compared to one
Figure 3 Monofocality and multifocality as 2 principal lesion patterns of
anterior interosseous nerve syndrome

Improvement.11-13 The patient opted for this surgical procedure. Epineurotomy was performed at the site of
T2 lesion. Markedly swollen fascicles at the dorsal and lateral aspects of median nerve emerged with torsion
around their longitudinal axis (figure 5). Careful mobilization and detorsion was performed. Follow-up until
8 months did not reveal any improvement and showed persistence of denervation with lack of voluntary activity
in EMG of FPL and PQ. After 8 months, a positive Hoffmann-Tinel sign at the mid-forearm level was
noticed. At 15 months, recovery to MRC 4 (from 0)
was noted for FPL. In the second patient (2) with
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Parsonage-Turner syndrome. From the distribution
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plines. Consequently, entrapment, e.g., by a fibrous
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peting views see AINS not as entrapment neuropathy,
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origin.1,4,5,25 Certain similarities with neuralgic should-
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involvement of the AIN in 4 patients.25

Improved lesion localization and determination of
spatial lesion patterns would permit us to better
understand the etiology of AINS and, in particular,
to understand if and at which anatomical site AINS
is potentially treatable by surgery. We prospectively
investigated a relatively large sample of 20 patients
with AINS and obtained detailed clinical/electrophys-
alogic data.

At the core of our study was MRN, providing
large longitudinal coverage including upper arm,
elbow, and forearm levels. With this protocol we
sought to determine lesion sites and longitudinal lesion
patterns by T2 signal analysis of median nerve fascicles.
Increased T2 signal has been shown to indicate nerve
injury of mechanical and nonmechanical origin, e.g.,

Figure 3 Monofocality and multifocality as 2 principal lesion patterns of
anterior interosseous nerve syndrome

Representative monofocal (left) and multifocal (middle) lesion patterns are compared to one
representative control subject (right). In each column, contiguous longitudinal high-resolution
imaging slices are displayed. Numbers on the left of patient images indicate slice position rel-
ative to the predominant lesion focus (at 9.2 cm in patient 2 and 22.2 cm in patient 8). The
monofocal and multifocal lesion pattern both follow the internal topography/somatotopy of
anterior interosseous nerve further distally but at lesion site are located within epineurium of median nerve trunk.
The anatomical localization of the predominant lesion focus is shown on the metric scale to
the left of the schematic drawing of bony landmarks. Differences in individual arm lengths
were not corrected for.

**DISCUSSION** The internal longitudinal organization
of peripheral nerve fascicles was first studied in com-
prehensive fashion by Sunderland,14 who used surgical
dissection to trace fascicles from distal to proximal. In
this work, he described some degree of plexiform
exchange between fascicles at proximal nerve levels.
Other authors illustrated this finding as “intraneural
chaos,”15 which reflects that a concept of fascicular
somatotopy—the meaningful grouping of nerve
fascicles with regard to their function—has long been
negated for the peripheral nervous system.16 Later, when
the longitudinal course of fascicles became traceable on
histology, it could be established that somatotopy is
well-preserved despite some plexiform exchange
between fascicles.15 The clinical implications of
fascicular somatotopy have been reviewed in detail by
Stewart,16 who emphasized that fascicular nerve lesions
represent a major pitfall for lesion localization: typical
symptom patterns that resemble the functional
territory of a peripheral nerve trunk appear only if all
fascicles at the lesion site are compromised. However,
selective fascicular injury may result in symptoms not
following expected distributions. For example, if only
certain fascicles supplying distal muscles are selectively
injured at a more proximal site, the lesion would be
expected erroneously to involve a further distal nerve
branch to this muscle group. To prove the existence of
fascicular nerve lesions has been challenging because it
is difficult if not impossible to localize and objectify
these lesions by clinical/electrophysiologic findings.

In the case of AINS, the view of a neuropathy of the
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At the core of our study was MRN, providing
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sought to determine lesion sites and longitudinal lesion
patterns by T2 signal analysis of median nerve fascicles.
Increased T2 signal has been shown to indicate nerve
injury of mechanical and nonmechanical origin, e.g.,
in focal entrapment, after trauma, in multifocal motor neuropathy, and also in metabolic polyneuropathies such as diabetic polyneuropathy.

In AINS, we consistently found a strictly organized somatotopic/topographic internal fascicular lesion pattern within the median nerve at upper arm level: affected were those motor fascicles forming the AIN, which exits from the median nerve trunk further distally at forearm level. Other median nerve fascicles seemed to be spared. Our interpretation that this fascicular T2 lesion pattern corresponds to an exclusive or, at least, predominant involvement of the motor fascicles forming the AIN is based on its close resemblance to the position of the anterior interosseous fascicles as mapped by Jabaley et al. and on visual tracing of T2 lesion fascicles from proximally within the median nerve trunk to distally into the AIN itself, which was reliably recognizable at the given spatial resolution. We acknowledge limitations of both methods, e.g., interindividual variability and potential inaccuracy of visual rating. Therefore, we propose as future research aim to track lesion fascicles from proximal to distal by diffusion tensor imaging (DTI). However, so far, nerve DTI has not been implemented in humans at the submillimeter isotropic resolution needed to resolve fascicles. We further acknowledge that we cannot answer whether the extent of fascicular involvement differed between patients with complete and incomplete AINS, because it was beyond the limit of spatial resolution to determine the exact number of involved fascicles. It is noteworthy that fascicular lesions in some cases of AINS were detectable also by high-resolution ultrasound; however, lesion contrast and thus diagnostic performance of fascicular hypochogenicity seem to be inferior to nerve fascicle increase of T2 signal (figure e-2).

In addition, the longitudinal lesion pattern was analyzed on contiguous slices. Multifocality was found in the majority of patients and monofocality in only 2. Interestingly, there were no differences between these 2 distinct lesion patterns with regard to symptoms or clinical/electrophysiologic findings. The responses to therapeutic intervention were markedly heterogeneous in patients with both lesion patterns. This observation is in accordance with reported variable outcomes after therapeutic intervention in AINS and also with evidence that spontaneous recovery may occur in a substantial portion of patients.

Monofocality in our cohort was rare. In one patient, surgical exploration with dissection of median nerve trunk epineurium (epineurotomy) revealed fascicular torsion precisely at the lesion site, which was localized by imaging (figure 5). After interfascicular neurolysis and detorsion, clinical recovery was observed in this patient. The rationale to offer such individually tailored surgical therapy guided by a novel imaging
sign was based on several case reports of median nerve fascicular torsion. Nagano and colleagues reported the largest series to date and described an "hourglass-like fascicular constriction" between 2 and 7.5 cm above the elbow in 22 patients. Nagano reported good recovery after interfascicular neurolysis in 21 of 22 patients but stressed that "we do not know whether this recovery was spontaneous or due to the neurolysis." Fascicular torsion as a causative factor for AINS will remain difficult to prove. Some plausible explanations for its occurrence have been offered, particularly high mobility of AIN fascicles promoting torsion during elbow flexion, or initial inflammation and edema followed by intraneural adhesions, which increase traction forces on anterior interosseous fascicles.

The histopathologic alterations underlying the observed T2 lesions remain unclear because biopsies at the lesion site are unethical. It is also difficult to explain by which pathophysiologic mechanisms proximal lesions are associated with functional compromise. It seems attractive to speculate that the accumulation of multifocal proximal injury is involved in the manifestation of symptoms and may result in further distally located functional or structural compromise, as believed to occur in other neuropathies such as diabetic polyneuropathy or the noncompressive polyneuropathy associated with type 2 neurofibromatosis.

The significance of our results may be 2-fold. This study is the first to provide strong diagnostic evidence by imaging for the existence of fascicular/partial nerve lesions in a spontaneously occurring neuropathy. The existence of fascicular nerve lesions had been assumed before but could not be objectified so far by NCS/EMG studies. Invasive near-nerve recordings or even intraneural fascicular stimulation by needle microneurography would be necessary to detect selective fascicular conduction abnormalities. Both techniques are not readily available in humans and have not been reported in AINS. Noninvasive stimulation with surface electrodes for motor or sensory NCS typically remain normal and therefore nonlocalizing in AINS. EMG detects denervation in muscles supplied by the AIN; however, this finding is nonlocalizing: it cannot discriminate between injury to the AIN itself and a more proximal lesion of anterior interosseous fascicles within the median nerve trunk.

As second major implication, the predominance of lesions at upper arm level in all patients strongly supports that AINS is not an entrapment neuropathy of the AIN itself nor of its branches, at least in our cohort. The observation of selective fascicular lesions following motor somatotopy clearly suggests that AINS is a motor fascicular neuropathy of the median nerve trunk. The observation of multifocality in the majority of patients argues in favor of an immune-mediated inflammatory origin and against any surgical treatment options either at forearm or upper arm level, at least in these multifocal cases.
AUTHOR CONTRIBUTIONS
Dr. Pham: study design, analysis and interpretation of data, acquisition of data, writing of manuscript. Dr. Baumer: acquisition of data, interpretation of data, revising manuscript for intellectual content. Dr. Meinck: acquisition of data, interpretation of data, revising manuscript for intellectual content. Dr. Schiefer: interpretation of data, revising manuscript for intellectual content. Dr. Weiler: interpretation of data, revising manuscript for intellectual content. Dr. Bendszus: study supervision, study design, interpretation of data, revising manuscript for intellectual content. Dr. Kele: study design, acquisition of data, analysis and interpretation of data, writing of manuscript.

ACKNOWLEDGMENT
The authors thank Dr. Thomas Dombert for documentation of the intraoperative field of patient 1 and for his permission to use the 2 intraoperative photographs of figure 5; and Prof. Dr. Sabine Heiland, Division of Experimental Radiology, Department of Neuroradiology, Heidelberg University Hospital, for assistance in setting up the MRN protocol and help in revising the manuscript.

STUDY FUNDING
This study was funded by a project grant from the German Osteoarthritis Foundation (P215-A482) and supported by a postdoctoral fellowship from the Medical Faculty of Heidelberg University (P.B.).

DISCLOSURE
M. Pham receives project grants from the German Osteoarthritis Foundation (Deutsche-Arthrose-Hilfe e.V.: P215-A482) and the EFSD/Disclosure.org for full disclosures. M. Bendszus receives a project grant from the Medical Faculty of Heidelberg University, Germany. H. Meinck, J. Schiefer, and M. Weiler report no disclosures. M. Pham receives project grants from the German Osteoarthritis Foundation (Deutsche-Arthrose-Hilfe e.V.: P215-A482) and the EFSD/Disclosure.org for full disclosures.

Received July 25, 2013. Accepted in final form October 10, 2013.

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