

## **Ultrasonographic identification of nerve pathology in neuralgic amyotrophy: enlargement, constriction, fascicular entwinement and torsion**

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### **Abstract**

*Objective:* To characterize the ultrasonographic findings on nerves in neuralgic amyotrophy.

*Methods:* Fourteen patients with neuralgic amyotrophy were examined using high resolution ultrasound.

*Results:* Four types of abnormalities were found: 1. Focal or diffuse nerve / fascicle enlargement (57%), 2. incomplete nerve constriction (36%), 3. complete nerve constriction with torsion (50%) (hourglass-like appearance), and 4. fascicular entwinement (28%). Torsions were confirmed intraoperatively and occurred on the radial nerve in 85% of the patients. A significant correlation was found between no spontaneous recovery of nerve function and constriction / torsion / fascicular entwinement ( $p=0.007$ ).

*Conclusion:* Ultrasonographic nerve pathology in neuralgic amyotrophy varies in order of severity from nerve enlargement to constriction to nerve torsion, with treatment moving from conservative to surgical. We postulate that the constriction caused by inflammation is the precursor of torsion and that the development of nerve torsion is facilitated by rotational movements of limbs.

**Key words:** neuralgic amyotrophy, high resolution ultrasound, constriction, nerve torsion, hourglass-like appearance

## Introduction

Neuralgic amyotrophy, also known as Parsonage-Turner syndrome, is a well characterized clinical entity with an idiopathic and a hereditary form. It has a highly typical presentation of acute severe neuropathic pain in the shoulder or the arm region, associated with a marked axonal lesion of one or several brachial plexus nerves, or rarely of other nerves.<sup>1</sup> The hereditary form is characterized by recurrent attacks and shows an autosomal dominant inheritance with mutations in the SEPT9 gene in over 50% of families.<sup>1,2</sup> The recurrence rate in the idiopathic form is also considerably higher (26.1%)<sup>3</sup> than what would be expected based on the incidence rate in the general population (2-4/100,000/year<sup>4,5</sup>). The disorder is assumed to be of autoimmune-inflammatory nature, as supported by histological evidence of inflammation<sup>6</sup> and also by the typical antecedent events such as intercurrent infection, surgery, child birth, and physical exertion, similar to the Guillain-Barré syndrome.

The prognosis of neuralgic amyotrophy is generally considered to be favorable with the neuropathic pain subsiding within a few weeks and the nerve palsy recovering in the following months to years. However, based on a large series of patients with neuralgic amyotrophy, the overall recovery was less favorable than previously assumed, as almost two-thirds of patients had persisting symptoms.<sup>3</sup> The cause of the incomplete or no nerve regeneration in some patients is unknown; however, recent studies reporting about a peculiar surgical finding of an “hourglass-like fascicular constriction” of the upper extremity nerves in large series of patients who had typical symptoms of neuralgic amyotrophy and no spontaneous recovery, may give a clue.<sup>7-9</sup> Since 1966, the “hourglass-like constriction” of nerves or nerve fascicles has been described in numerous case reports by surgeons as a surgical finding on different nerves including the posterior interosseous nerve (PIN)<sup>10-20</sup>, the median and the anterior interosseous nerves (AIN)<sup>15,20-25</sup>, the main trunk of the radial nerve<sup>17,26</sup>, the musculocutaneous nerve<sup>27</sup>, and the suprascapular and axillary nerves<sup>28</sup>. When available, histology showed inflammatory signs. The nerves were treated with neurolysis or resection and graft implantation with generally good recovery.<sup>8-9</sup> Interestingly, this type of nerve lesion and its possible causes have so far received little attention from the neurological community. However, the recent introduction of high resolution nerve ultrasound (HRUS) has given a new impetus to this area. It was found that – similar to the surgical

findings – the preoperative ultrasound can detect a single or multiple hourglass-like constrictions on the nerve.<sup>9,29-30</sup> Moreover, another peculiar phenomenon, the surgical finding of nerve torsion, has occasionally been described in patients with neuralgic amyotrophy-like clinical presentation.<sup>31-34</sup> In a recent study, 11 surgically confirmed cases of nerve torsion also showed the typical feature of an hourglass-like appearance of the nerve on both the ultrasound and the magnetic resonance imaging (MRI).<sup>35</sup> Altogether, there is evidence that phenomena such as nerve constriction and torsion are associated with neuralgic amyotrophy, however, no unifying analysis of ultrasonographic findings in neuralgic amyotrophy is available. Moreover, any such analysis should start out from a firm clinical diagnosis, rather than vice versa.

In light of the above, the aim of our present study was to characterize and classify nerve pathology in neuralgic amyotrophy, as identified by the ultrasonography, in a systematic way. The retrospective analysis of a series of patients with neuralgic amyotrophy who underwent ultrasonography was performed, and the ultrasonographic findings were correlated with the clinical outcome and surgical findings. Finally, the possible mechanism of nerve constriction and torsion is discussed.

## Patients and Methods

Between 2012 and 2014, 14 patients (9 males and 5 females; age range: 27-80 years; mean age: 43.2 years) with a typical clinical presentation of neuralgic amyotrophy were examined at three centers, and the results were retrospectively analyzed. *Table 1* shows the summary of patient characteristics. De-identified data were used retrospectively in accordance with the Helsinki Declaration. An approval for the study plan was also obtained from the Institutional Ethics Committee.

The medical history of the patients was unremarkable apart from Patients 1 and 4. Patient 4 was operated with testicular malignancy 3 weeks before the presentation of PTS. Patient 1 was diagnosed with multifocal acquired demyelinating polyneuropathy (MADSAM) in 2009 following the sequential development of painless sensorimotor peroneal and ulnar nerve palsies with persistent conduction blocks at non-entrapment sites. Immunosuppressive treatment with corticosteroid followed by intravenous immunoglobulin was effective and the conduction blocks and thus the clinical signs of the peroneal and ulnar nerve palsies resolved promptly; the patient has been in remission since. However, in 2009, shortly after the institution of treatment and resolution of symptoms, a left radial nerve palsy developed, which was distinctly different from the previous episodes of the disease, suggesting the superposition of neuralgic amyotrophy. The palsy was associated with severe pain lasting for weeks and developed severe axonal loss that showed only slow and incomplete improvement in the ensuing years.

Antecedent events included infection, surgery, child birth, physical exertion, and autoimmune disease. No such events were identified from the history for 6 patients, three of which had recurrent episodes of neuralgic amyotrophy, raising the possibility of the hereditary form. Altogether 5/14 patients had recurrent attacks. Genetic testing of SEPT9 was not performed due to lack of access. Four patients received an oral corticosteroid treatment (Patients 4, 6, 11 and 12) during the acute phase, which reduced the pain, but had no effect on the nerve lesion. Patient 1 was already on the corticosteroid treatment when the neuralgic amyotrophy developed.

All patients underwent clinical, electrophysiological and ultrasound examination, and 8 patients also underwent MRI of peripheral nerves. Electrophysiological and ultrasound assessment, and MRI if

performed, included at the minimum all clinically affected nerves. Clinically affected nerves included the radial nerve / PIN (10/14 patients), the AIN (3/14 patients), the musculocutaneous nerve (2/14 patients), the suprascapular nerve (2/14 patients), the long thoracic nerve (1/14 patient), and the axillary nerve (1/14 patient). The electrophysiological testing showed typically severe axonal damage affecting motor nerves more than sensory nerves in all the clinically involved nerves. With the exception of Patient 1, signs of generalized neuropathy were not observed. The ultrasound examinations were carried out using the Philips HD15 XE Pure Wave device with a 5-12 MHz 50 mm linear array transducer (Patients 1-3), the Philips Equip5 device with a 5-18 MHz linear array transducer (Patients 4-9), the Siemens Acuson Antaris 5.0 device with a 13 MHz linear array transducer (Patients 10-13), and the Toshiba Aplio SSA-700A system with a 12 MHz PLT-1204 4.5 cm linear array transducer (Patient 14). To improve image quality, compound imaging software was used in all devices. In all patients, all clinically affected nerves were scanned in the transverse plane along their whole accessible length, for example, scanning was performed from the wrist to axilla for the median and radial nerves. The supraclavicular, interscalenic and paravertebral plexus brachialis was also examined in all patients, with some additional nerves in some patients. In the areas of abnormality, longitudinal scans were also obtained. The location, type and extent of the abnormality, including change in nerve echogenicity, size and structure were noted.

A minimum of 6-month-long follow-up, respective to the onset of symptoms, was available in 11/14 patients. A minimum of 1-year-long follow-up was available in 5/14 patients.

Six patients underwent surgery based on the ultrasonographic findings and insufficient clinical recovery after 6 months.

Chi-square statistics was used where appropriate, with significance level set at  $<0.05$ .

## Results

*Supplementary Table S1* (available online) shows the summary of findings from all patients.

### *Ultrasonographic findings*

In general, four types of ultrasonographic abnormalities were distinguished in the clinically affected nerves (*Table 2*), which may present in combination within a patient or even within the same nerve:

1. Focal, multifocal, or diffuse *enlargement*, together with structural abnormalities such as complete loss of fascicular structure and hypoechogenicity in 8/14 (57%) patients (*Fig. 1*). This may affect the whole nerve or individual fascicles only, for example, as seen in the median nerve in cases of AIN palsy. This abnormality was occasionally observed in asymptomatic nerves as well.
2. Focal incomplete *constriction* (decrease of diameter) of the nerve or the nerve fascicle bordered by segmental nerve enlargement on either side in 5/14 (36%) patients. These together give a characteristic hourglass-like appearance to the nerve (*Fig. 2*). At the site of constriction, the hypoechogenic internal part of the nerve is still continuous.
3. Focal *complete constriction and hourglass-like appearance* in 7/14 (50%) patients (*Fig. 3*). In six cases (85%) the radial nerve was affected. In three patients, the main trunk at mid-arm level, and in other three the PIN fascicle at the elbow, just proximal to the division of the nerve, was affected. In the remaining one case the musculocutaneous and the suprascapular nerves were affected. In this type of abnormality, a hyperechogenic division is seen at the site of constriction, resulting in the interruption of the continuity of the internal part of the nerve. The segmental nerve enlargement bordering this constriction is typically of large degree, characterized with hypoechogenicity and loss of fascicular structure and is more pronounced on the proximal side. Both complete and incomplete constrictions can be single or multiple and are best depicted on longitudinal scans. On slow cross-sectional scanning, the site of constriction is seen as a sudden disappearance and then re-emergence of the nerve.
4. *Fascicular entwinement* in 4/14 (28%) patients. This phenomenon was observed in three radial nerve / PIN lesions (Patients 4-6) and one musculocutaneous nerve lesion (Patient 7), and is associated with the previous abnormalities. It is best seen on slow cross-sectional scanning over the affected

nerve segment, which shows the gradual 360 degrees rotation of the nerve fascicles around each other within the nerve, sometimes showing even two or three successive rotations (*Supplementary Video 1*, available online). On the longitudinal scans, instead of a normal parallel course, the ‘crisscrossing’ of fascicles may be seen at these sites (*Fig. 4*).

Out of the 8 patients who underwent a MRI of the peripheral nerves, the MRI findings were consistent with the ultrasound in three (nerve torsion in Patient 1 and 10, and median nerve fascicular lesion in Patient 13). In Patient 6, the MRI co-localized the nerve pathology with the ultrasound (enlargement and contrast enhancement), however the fascicular entwinement was not recognized. In the remaining three patients, the MRI was not informative as compared to the ultrasound.

#### *Correlation of the clinical outcome and the ultrasonographic and intraoperative findings*

The assessment of the clinical recovery was possible in 11/14 patients who had at least a 6-month-long follow-up, respective to the onset of symptoms. A significant correlation was found between the lack of or non-substantial recovery of nerve function and the hourglass-like abnormality (incomplete or complete) / fascicular entwinement, in comparison to nerve enlargement alone ( $p=0.007$ ). All five patients with complete constriction (Patients 1, 4, 5, 10, and 14) and sufficient follow-up showed insufficient recovery of nerve function, and all underwent surgery. In all of these patients, the radial nerve was affected either at mid-arm level or at the elbow, immediately proximal to the division of the nerve. Three patients had a Tinel sign over the lesion. In each case, surgery showed constriction associated with torsion, involving the whole nerve or a fascicle (*Fig. 3*). In Patients 1, 10 and 14, severe single or multiple constrictions and torsions were seen on the main trunk of the radial nerve at the mid-arm level. Patient 1 with MADSAM neuropathy, whose nerve torsion was diagnosed in 2014, underwent a previous ultrasound examination in 2011. These results from 2011, the ultrasonographic signs of the MADSAM neuropathy were published earlier.<sup>36</sup> At that time it was seen that - unlike the other nerves affected by the MADSAM neuropathy with only segmental enlargement- the radial nerve showed a severe constriction at mid-arm level with internal nerve continuity still retained. It seems that by 2014 this constriction progressed into a torsion, but clinical recovery was hindered even at the stage of incomplete constriction. Neurolysis, detorsion and fixation of the nerve with an epineurium-



fascia suture was performed. Five months after the surgery, the follow-up ultrasound showed an enlarged irregular nerve with no hourglass-like abnormality, and an early on-going reinnervation was detected in the proximal forearm extensors. In Patient 10, the most proximal torsion site was resected and an end-to-end suture was performed. The recovery of wrist extension ensued. In Patient 14, detorsion and fixation was performed. However, no recovery ensued, and the follow-up ultrasound showed a recurrent torsion on the nerve. Then, a second operation was performed, the affected nerve segment was resected and a sural nerve graft was interposed. The follow-up showed early signs of functional recovery. Patients 4 and 5 showed constriction and torsion of the PIN fascicle within the radial nerve immediately proximal to its division at the elbow. In addition, the entwinement of the nerve fascicles was also confirmed, as suggested by the ultrasonographic findings of the rotation of fascicles around each other on the cross-sectional scan. During surgery, neurolysis, straightening of the course of the fascicles, and in Patient 5, the resection of the torsion site and an end-to-end suture was performed. Postoperative follow-up is pending. Patient 6, who showed marked swelling of the radial nerve above the elbow and multiple rotations of nerve fascicles without the characteristic hourglass-like constriction, also underwent surgery. Clinically he showed no recovery of the PIN function at 6 months. Surgery confirmed the severe entwinement of the fascicles proximal to the branching of the nerve (*Fig. 4*) (*Supplementary Video 1*, available online), and a marked constriction was seen on two of these fascicles that had to be resected and sutured. These two fascicles were on the PIN part of the radial nerve.

Histological assessment of the resected nerve segments of Patient 5 and 6 showed severe fibrosis interrupting the continuity of the nerve in both, and inflammatory infiltrates as well in Patient 5.

Regarding the clinical outcome of the nerve enlargement alone, our data are inconclusive at this time. There were four patients with only nerve enlargement and no constriction. Three of these patients are at 6 months follow-up, two of them are showing substantial recovery (Patients 8 and 9), and one is not showing recovery (Patient 2). The fourth patient (Patient 3) is at 2 years follow-up, and has showed substantial but incomplete recovery.

## Discussion

Neuralgic amyotrophy syndrome can be considered as an acute, monophasic, focal or multifocal inflammatory neuropathy affecting mainly the individual plexus brachialis nerves. According to van Alfen, who has analyzed the largest series of patients with neuralgic amyotrophy, neuralgic amyotrophy is under-recognized by neurologists despite an incidence rate similar to that of Guillain-Barré syndrome.<sup>3</sup> It is generally believed to be a benign condition with good prognosis, even though it was shown that about two-thirds of the patients have persisting pain and paresis.<sup>3</sup> The possible causes of this unfavorable outcome has not been hitherto addressed. On the other hand, for over 40 years hand surgeons-neurosurgeons have been publishing case reports of patients with a peculiar surgical finding of a non-traumatic, non-compressive hourglass-like constriction of the upper limb nerve lesions<sup>10-28</sup>, sometimes associated with nerve torsion<sup>31-34</sup>. Ochi et al. has even set up a classification of fascicular constriction, with four different types: recess, recess-bulging, rotation, and rotation-bulging.<sup>19</sup> These patients underwent surgery because the nerve lesion showed no spontaneous recovery. Where available, the clinical information suggested a neuralgic amyotrophy-like clinical picture with acute onset of pain and spontaneous nerve palsy. In a series of 5 patients, Pan et al. was the first to directly associate the hourglass-like constriction with neuralgic amyotrophy by observing their identical clinical presentation.<sup>7</sup> Recently, they have published a study on a series of 42 patients with an hourglass-like constriction, out of which 41 had a neuralgic amyotrophy-like presentation.<sup>8</sup> Furthermore, in all cases with histological assessment, an inflammatory cell infiltration of CD8 positive T lymphocytes was observed. The authors have come to the conclusion that the hourglass-like constrictions may be described as “under the rubric of neuralgic amyotrophy” and that the development of these constrictions may be the cause of the unfavorable outcomes in some patients with neuralgic amyotrophy. Also recently, Wu et al. have published a study on a series of 41 patients with spontaneous posterior interosseous nerve palsy with constrictions and have analyzed various treatment options.<sup>9</sup> They have concluded that surgical treatment is more effective than conservative treatment if no recovery ensues after 3 months, and have also emphasized the role of preoperative ultrasound in detecting these constrictions. In summary, it is beginning to be understood that

spontaneous nerve palsies with hourglass-like constrictions are not at all rare, may be a manifestation of neuralgic amyotrophy, and have an unfavorable outcome most likely necessitating surgical treatment. Strangely, however, until now this disorder has been almost completely ignored by the neurological community. Moreover, the ultrasonographic assessment of neuralgic amyotrophy is also completely lacking. In our present retrospective study of patients with neuralgic amyotrophy, we have attempted to categorize morphological alterations in neuralgic amyotrophy as detected by high resolution ultrasound with the aim of providing a preliminary framework for successful treatment.

*Table 2* summarizes the four categories of the ultrasonographic findings we have observed in our series of patients. Segmental or diffuse nerve enlargement, usually associated with hypoechogenicity and structural abnormality, is an unspecific sign of nerve pathology and is the typical finding in other types of dysimmune-inflammatory neuropathies such as chronic inflammatory demyelinating polyneuropathy (CIDP) as well.<sup>37-39</sup> One combination of clinical and ultrasonographic findings in this category, however, seems to be a characteristic for a neuralgic amyotrophy subtype: the uni- or bilateral AIN palsy associated with fascicular enlargement of the median nerve above the elbow. We have seen this in three cases in our small series of patients with neuralgic amyotrophy. In a recent a study by Pham et al., the fascicular lesion of the median nerve on the upper arm was also demonstrated by another imaging modality, MRI, on a series of 20 patients with spontaneous AIN palsy.<sup>40</sup> The clinical information about the patients from this study was suggestive of neuralgic amyotrophy as a cause, although the authors have not made a direct connection between the two.

The findings of nerve constriction and torsion with an hourglass-like appearance and fascicular entwinement seem to be more specific for neuralgic amyotrophy. Single or multiple nerve or fascicular constrictions with or without torsion correspond to the constrictions reported and surgically treated by many surgeons, and associated with neuralgic amyotrophy by Pan et al<sup>8</sup>. Based on our observations, it seems that if the nerve continuity at the site of constriction is interrupted, and the nerve or nerve fascicle is divided by a hyperechogenic part, it is an indication that nerve torsion has also occurred at the site of constriction. This was intraoperatively confirmed in all of our patients who underwent surgery with this abnormality, and it is also supported by the only available systematic imaging study

on nerve torsion from Qi et al.<sup>35</sup> All of their cases were intraoperatively confirmed. It may be concluded that nerve torsion can be diagnosed with high reliability using ultrasound. The development of nerve torsion is clearly a sign of unfavorable outcome, as supported by our observations and the scarce literature data<sup>32-34</sup>, which necessitates surgical intervention. This is not surprising as the intraoperative picture is often of a severely thinned and twisted fibrotic nerve site which may have to be resected, and neuroorrhaphy or grafting applied. Concerning the outcome of constriction without torsion (with retained internal continuity of the nerve), our data are insufficient to draw conclusions; however, the above mentioned extensive data from the literature point to an incomplete spontaneous recovery and a need for surgical treatment in many of these patients as well. It is likely that the extent of constriction plays a role in both the degree of recovery and the choice of surgical intervention. Wu et al. classified constrictions in spontaneous PIN palsy as mild, moderate and severe, but they only used it as a guide in the choice of surgery (i.e., neurolysis versus resection).<sup>9</sup>

Another interesting and hitherto unreported finding, termed by us as fascicular entwinement, was observed in four of our patients (*Supplementary Video 1*, available online). The cross-sectional ultrasound showed the gradual rotation of fascicles within the nerve, suggesting the twisting of fascicles around each other, instead of a parallel course. This was confirmed intraoperatively in three of these patients with radial nerve / PIN involvement at the elbow. The fourth patient with musculocutaneous lesion is still under follow-up. Of the three operated patients, two also had ultrasonographic and intraoperative signs of nerve torsion. In one patient (Patient 6), the constriction and torsion was not evident on the ultrasound, and only an enlarged radial nerve and this fascicular entwinement was seen, but surgery revealed severe constriction on two fascicles as well, which was missed by ultrasound. The entwinement of fascicles is most likely another correlate of nerve torsion.

Regarding the mechanism of these morphological changes, based on the nature of the disease and pathological evidence from the literature<sup>7-9, 34</sup>, inflammation most likely plays a major role. Edema due to inflammation may first give rise to nerve enlargement. Adhesions, and local fixation of fascicles may also develop that lead to the thinning and constriction of the fascicles / nerves.<sup>8</sup> If the constriction increases, the likelihood of nerve torsion increases as proposed by Lundborg.<sup>41</sup> Ochi et al. have also

classified nerve torsion as a type of constriction.<sup>19</sup> We speculate that torsion occurs at a site of previous non-torsional constriction. In other words, constriction is the precursor of torsion (*Fig. 5*). This could be documented by ultrasound in Patient 1, where constriction pre-dated torsion. To put it simply, if one attempts to twist a round bar around its long axis, the point of twisting will preferentially occur at a site where the bar is the thinnest, i.e., the least resilient. However, why should torsion occur at all, even at sites of constriction? It is likely that additional factors such as the winding course of a nerve or rotational type arm movements may contribute. In all of our five intraoperatively confirmed torsion patients, torsion involved the radial nerve either at mid-arm level where it coursed around the humerus, or distally at the elbow where it was involved in rotational movements, which appears to support this notion. It is unclear though whether nerve constriction or torsion occurs exclusively in the context of neuralgic amyotrophy or it may complicate other inflammatory neuropathies as well. No such reports were identified in the literature until now.

In summary, we have attempted for the first time to categorize the ultrasonographic nerve alterations in neuralgic amyotrophy. Our preliminary study and data from the literature show that nerve pathology can be reliably detected by ultrasound in neuralgic amyotrophy, and they range in order of severity from nerve enlargement to constriction to nerve torsion, with treatment moving from conservative to surgical. Limitations of our study include the small number of patients and the lack of systematic follow-up. In order to establish the time course of alterations, prospective studies with serial assessments are needed. However, it may be concluded that findings such as nerve constriction, torsion and fascicular entwinement appear to be rather specific signs in neuralgic amyotrophy, which have an unfavorable outcome and may explain the persistent symptoms of many conservatively treated patients with neuralgic amyotrophy. Indeed, an important message of our study is that however unusual it may be in an inflammatory neuropathy, surgery may be the necessary treatment in some patients with this condition. Careful assessment and follow-up if each patient are needed, and surgery should be indicated only when no or non-substantial reinnervation occurs after a reasonable amount of time has elapsed. Finally, we postulate that nerve torsion occurs at sites of previous constriction

caused by inflammation, i.e., constriction is the precursor of torsion, most likely further facilitated by normal rotational movements of limbs.

### **Abbreviations**

AIN: anterior interosseous nerve

CIDP: chronic inflammatory demyelinating polyneuropathy

HRUS: high resolution ultrasound

MADSAM: multifocal acquired demyelinating sensory and motor neuropathy

PIN: posterior interosseous nerve

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**Table 1**
**Summary of patient characteristics**

Case No.	Age (year)	Sex	Clinically affected nerve(s)	Antecedent event	Recurrent attacks	Time of first US after onset	Time of follow-up after onset	MRI	Surgery
1	44	M	Left RN	Autoimmune disease	-	4 years	4 years	+	+
-2	80	M	Right PIN	-	-	6 months	6 months	-	-
3	43	F	Bilat. AIN	Child birth	-	2 years	2 years	-	-
4	37	M	Left PIN	Surgery	-	6 months	1 year	+	+
5	41	F	Left RN	-	+	2 months	7 months	+	+
6	58	M	Left RN Left SSN	Physical exertion	-	1 week	6 months	+	+
7	31	F	Right MCN Right SSN Right RN	Child birth	+	2 months	2 months	-	-
8	27	M	Right LTN	-	-	6 months	6 months	-	-
9	44	M	Right AIN Right MCN	Physical exertion	-	2 weeks	6 months	-	-
10	44	M	Left RN	Infection	+	6 years	6 years	+	+
11	41	F	Right RN Right AN	-	+	14 days	5 months	+	-
12	31	F	Right RN	-	+	4 months	5 months	-	-
13	42	M	Left AIN	-	-	10 months	10 months	+	-
14	42	M	Left RN	Physical exertion	-	15 months	15 months	+	+

M: male; F. female; US: ultrasound; MRI: magnetic resonance imaging; RN: radial nerve; PIN: posterior interosseous nerve; SSN: suprascapular nerve; MCN: musculocutaneous nerve; LTN: long thoracic nerve; AIN: anterior interosseous nerve; AN: axillary nerve

**Table 2**

**Summary of the ultrasonographic findings in neuralgic amyotrophy**

Type of abnormality	Description
<i>Nerve enlargement</i>	<ul style="list-style-type: none"> <li>– Segmental or diffuse</li> <li>– May involve only one fascicle</li> <li>– Hypoechogenicity, loss of fascicular structure</li> </ul>
<i>Hourglass-like incomplete constriction</i>	<ul style="list-style-type: none"> <li>– Focal decrease of nerve diameter</li> <li>– Internal continuity of the nerve retained</li> <li>– Nerve enlargement on both sides of the constriction, more proximally</li> <li>– Best seen on longitudinal scans</li> </ul>
<i>Hourglass-like complete constriction (torsion)</i>	<ul style="list-style-type: none"> <li>– Hyperechogenic division of the nerve</li> <li>– Internal continuity of the nerve interrupted</li> <li>– Marked nerve enlargement on both sides of the constriction, more proximally</li> <li>– Best seen on longitudinal scans</li> </ul>
<i>Fascicular entwinement</i>	<ul style="list-style-type: none"> <li>– Rotation of fascicles around each other within a nerve</li> <li>– Best seen on slow dynamic cross-sectional scanning</li> <li>– Crossing of fascicles on longitudinal scans</li> </ul>

## Figure legends

### Figure 1

#### Nerves with enlargements

**A-B.** Longitudinal scans of the posterior interosseous nerve (**A**) entering the supinator muscle, and of the common radial nerve (**B**) at mid-arm level of Patient 7. Note the diffuse enlargement of the nerves with a diameter of 2 mm and 3.3 mm, respectively. Clinically the patient had a mild involvement of the radial nerve, as opposed to severe musculocutaneous and supraclavicular nerve lesions, which showed torsion.

**C.** Longitudinal scan of the asymptomatic common radial nerve above the elbow of Patient 4. Note the segmental mild enlargement and loss of fascicular structure of the nerve (arrow). The diameter increased from 1.2 mm to 2 mm.

**D.** Cross-sectional scan of the median nerve at the elbow of Patient 9 with AIN palsy. Note the enlargement of a single fascicle within the nerve (arrow).

**E-F.** Cross-sectional scans of the right (**E**) and left (**F**) interscalenic plexus brachialis of Patient 8 with right long thoracic nerve lesion. Note the enlargement of the upper-middle part of the plexus on the right side (arrow).

### Figure 2

#### Nerves with hourglass-like incomplete constrictions

**A.** Longitudinal scan showing the constriction of a fascicle of the median nerve associated with AIN palsy in Patient 13

**B.** Longitudinal scan showing the constriction of the posterior fascicle of the plexus brachialis associated with radial and axillary nerve lesion in Patient 11.

**C.** Longitudinal scan showing multiple constrictions of the main trunk of the radial nerve of Patient 12, who had multiple episodes of neuralgic amyotrophy, most likely of hereditary type, affecting the radial nerve.

### Figure 3

#### **Nerves with hourglass-like complete constrictions, corresponding to nerve torsions**

**A-C.** The ultrasonographic (**A**), MRI (**B**) and intraoperative (**C**) images of the main trunk of the radial nerve at mid-arm level of Patient 1 (intraoperative image courtesy of K. Dévay [MD], Budapest, and 3TMRI image courtesy of P. Barsi [MD], Budapest).

**D-F.** The ultrasonographic (**D**), MRI (**E**) and intraoperative (**F**) images of the main trunk of the radial nerve at mid-arm level of Patient 10 (intraoperative image courtesy of TN Lehmann, [MD]Bad Saarow, and 3TMRI image courtesy of K. Stock, [MD] Dessau). Note that the ultrasound images show the abnormality more clearly in comparison to the MRI images. The intraoperative images confirm the torsion of the nerve at a severely constricted area, associated with marked swelling of the nerve proximal and distal to the constriction-torsion site.

**G-H.** The ultrasonographic (**G**) and the intraoperative (**H**) images of the radial nerve at the elbow of Patient 5 (intraoperative image courtesy of K. Dévay, [MD] Budapest). Note on the intraoperative image the severe fascicular constriction and torsion of the PIN part of the nerve (long arrow) associated with marked swelling of the fascicle proximal to the lesion. Note also how the fascicle giving rise to the superficial radial nerve (short arrows) rotates around the PIN fascicle, showing the phenomenon of fascicular entwinement.

### Figure 4

#### **Fascicular entwinement**

**A-B.** The ultrasonographic (**A**) and the intraoperative (**B**) images of the radial nerve immediately proximal to its division at the elbow of Patient 6. Note on the ultrasound image (**A**) how the fascicles seem to cross each other (arrow). This phenomenon was better seen in dynamic cross-sectional scanning where the fascicles within the radial nerve rotated around each other several times



(*Supplementary Video 1*, available online). Fascicular entwinement was confirmed intraoperatively (thick arrow) (**B**). Two fascicular constrictions were also seen (the thin arrow points to one).

## **Figure 5**

### **Putated mechanism of nerve torsion**

Schematic representation of the nerve inflammation first leading to edema. Adhesions, fixation may also occur resulting in constriction, which in turn may lead to nerve torsion, especially in nerve segments around joints or in nerves with a naturally tortuous course.

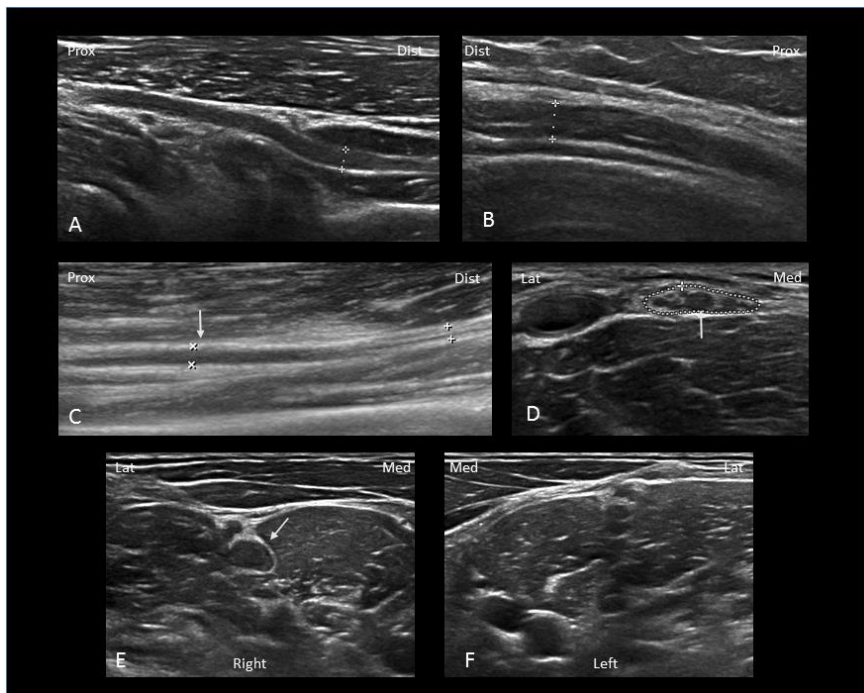


Fig. 1

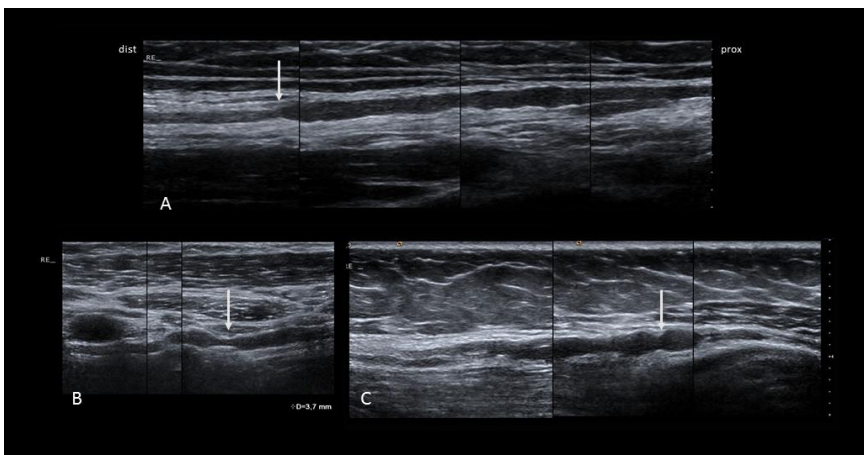


Fig. 2

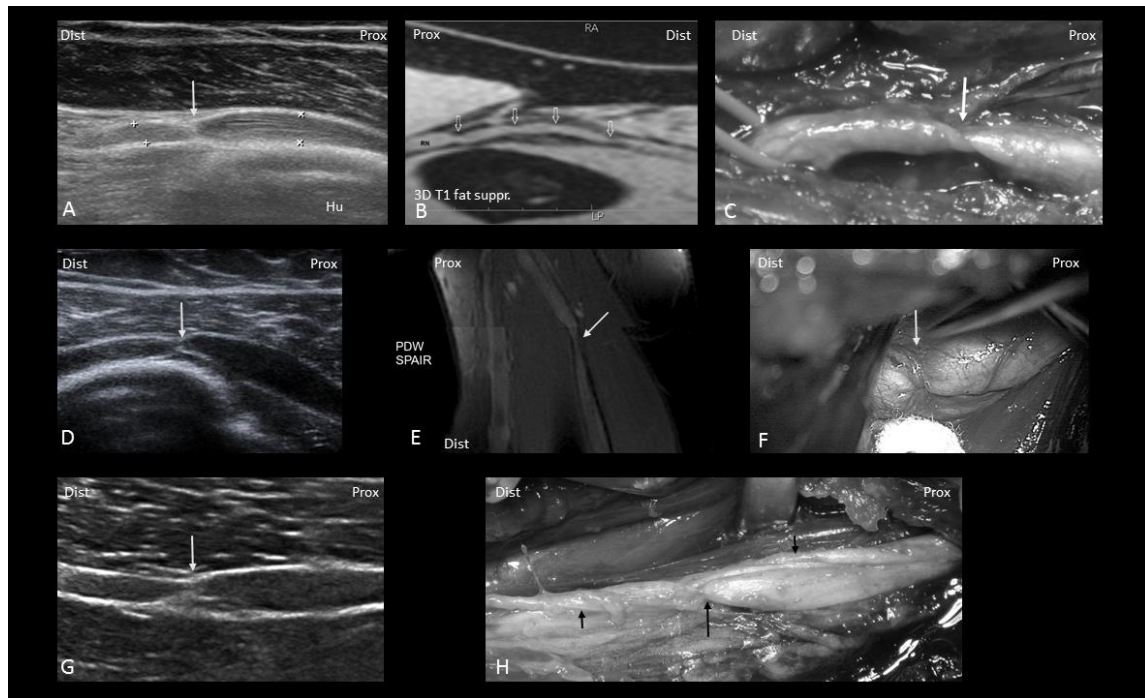


Fig. 3

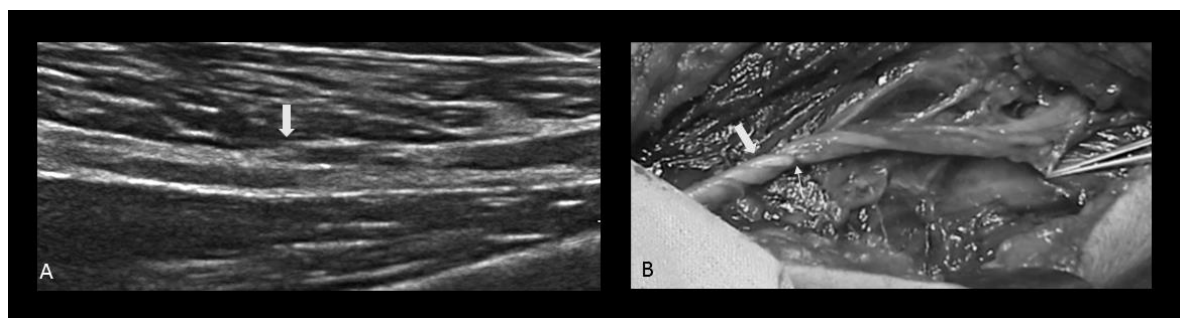


Fig. 4

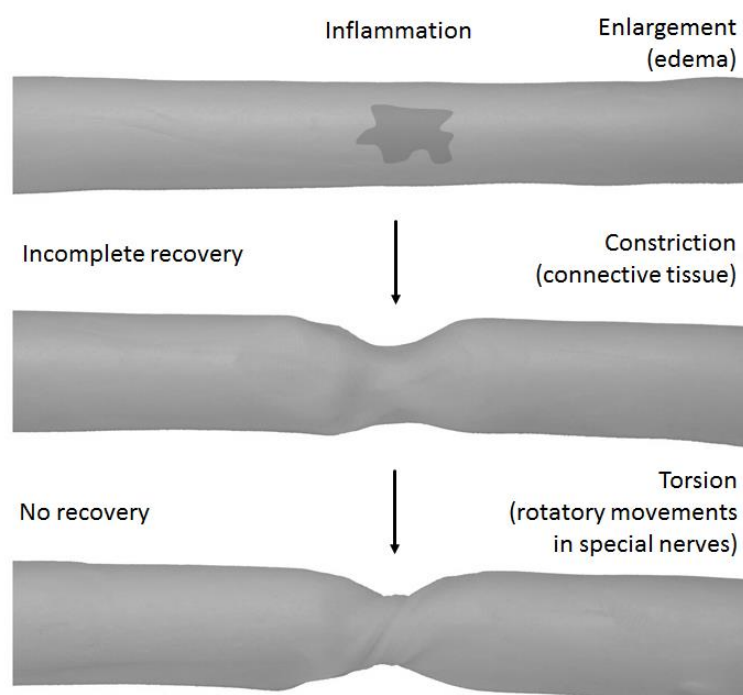


Fig. 5.