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Clinical, electrodiagnostic and imaging features of true neurogenic thoracic outlet syndrome: Experience at a tertiary referral center☆

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ABSTRACT

Objective: True neurogenic thoracic outlet syndrome (TN-TOS) is an extremely rare neuromuscular disease. We report clinical, electrodiagnostic and radiologic features of patients with TN-TOS.
Methods: Retrospective chart review of patients satisfying criteria was done. Nerve conduction study (NCS) and needle electromyography (EMG) of upper extremity were reviewed. Brachial plexus MRI and computed tomography angiography (CTA) were also reviewed.
Results: Thirteen TN-TOS patients were identified. The most common neurologic signs were hypesthesia in the medial forearm or ulnar digits and weakness of the abductor pollicis brevis (APB) muscle. In NCS, medial antebrachial cutaneous (MABC) sensory nerve action potential amplitude was decreased in all tested patients. The APB muscle was most commonly involved in EMG. Among radiologic criteria, focal stenosis of subclavian artery in CTA was the most common finding.
Conclusion: We confirmed that TN-TOS is T1 predominant lower roots/trunk brachial plexopathy with clinical and electrodiagnostic features. Radiologic studies may be used to detect structural abnormalities.
Significance: As MABC NCS showed abnormal results in all tested patients, it should be added to electrodiagnostic study as screening method. If present, structural abnormalities might be confirmed with radiologic studies.

1. Introduction

Thoracic outlet syndrome (TOS) includes variable neurovascular symptoms and signs caused by compression of neurovascular bundle at a specific site in the thoracic outlet between the base of the neck and the axilla. TOS is divided into 3 categories depending on specifically compressed structures: arterial, venous and neurogenic TOS. Neurogenic TOS has been subclassified as true neurogenic TOS (TN-TOS) and disputed TOS [25].

TN-TOS is a well-documented neuromuscular disease. It is an extremely rare syndrome with an estimated prevalence of only 1 per 1,000,000 persons [7]. It is defined as chronic compressive C8, T1 nerve roots and/or lower trunk brachial plexopathy that usually results from compression by cervical rib or fibrous band arising elongated C7 transverse process [23]. Cervical rib or fibrous band connecting tip of the elongated C7 transverse process to first rib makes anterior primary ramus of T1 and, sometimes C8 spinal nerve root or lower trunk of brachial plexus overrides the cervical rib or fibrous band excessively with acute upward angulation. Because median innervated hand intrinsic muscles usually receive T1 dominant innervation and other hand

Abbreviations: ADM, abductor digiti minimi; APB, abductor pollicis brevis; CMAP, compound muscle action potential; CTA, computed tomography angiography; EIP, extensor indicis proprius; EMG, electromyography; FDI, first dorsal interossei; MRI, magnetic resonance imaging; MABC, medial antebrachial cutaneous; NCS, nerve conduction study; SCA, subclavian artery; SNAP, sensory nerve action potential; STIR, short tau inversion recovery; TN-TOS, true neurogenic thoracic outlet syndrome; TOS, thoracic outlet syndrome

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Table 1
Clinical features of patients with TN-TOS.

Patient	Sex	Age at presentation (years)	Age at onset of symptoms (years)	Duration of symptoms (months)	Side	Initial clinical presentations		
						Time sequence of symptoms	Sensory symptom	Motor symptom
1	F	43	42	12	R	S → M	Paresthesia in fourth, fifth fingers and medial side of forearm	**Insidious hand weakness**
2	F	48	47	12	R	M only	None	**Insidious hand weakness and atrophy**
3	F	50	41	108	R	S → M	**Hypesthesia in medial side of forearm**	Insidious hand weakness
4	F	43	42	12	L	S only	**Paresthesia in fourth, fifth fingers and medial side of forearm**	None
5	M	22	19	30	R	S only	**Paresthesia in medial side of forearm and arm**	None
6	F	21	20	12	R	S only	**Paresthesia in medial side of forearm and arm**	None
7	M	54	51	36	R	S = M	Paresthesia in all fingers and medial forearm	**Insidious hand weakness and atrophy**
8	F	29	27	24	R	S = M	Pain and numbness of arm	**Hand atrophy**
9	M	19	15	48	L	S only	**Paresthesia in medial side of forearm and arm**	None
10	F	32	28	48	L	S → M	**Paresthesia of whole arm**	Insidious hand weakness and atrophy
11	F	40	36	48	L	S = M	**Paresthesia of all fingers** **Pain in medial side of forearm**	Insidious hand weakness
12	F	70	66	48	R	S = M	Hypesthesia in fourth, fifth fingers and medial side of forearm	**Insidious hand weakness and atrophy**
13	F	53	13	480	R	M only	None	**Insidious hand weakness and atrophy**

Bold texts are chief complaints. TN-TOS, true neurogenic thoracic outlet syndrome; F, female; M, male; R, right; L, left; S, sensory; M, motor.

Table 2
Neurologic examination of patients with TN-TOS.

Patient	Sensory deficit	Muscle atrophy			
		Motor power (MRC scale)	Thenar area	FDI	Forearm
1	Hypesthesia in medial forearm, digit 4,5	APB 4	+ +	0	0
2	None	APB 2, FDI 3, EIP 3, FPL 4, EDC 4	+ +	+ +	+
3	Hypesthesia in medial forearm, digit 5	APB 4, opposition weakness	0	0	0
4	Hypesthesia in digit 5	intact	0	0	0
5	Hypesthesia in medial upper arm, digit 5	APB, opposition mild weakness	+	0	0
6	Hypesthesia in medial forearm	intact	0	0	0
7	Hypesthesia in medial forearm, all digits	APB 1, FDI 2	+ +	+	0
8	Numbness of arm	Not described	+	0	0
9	Hypesthesia in medial arm, medial forearm, digit 4,5	APB 4	0	0	0
10	None	APB 2	+ +	0	0
11	None	intact	0	0	0
12	None	APB 3, FDP 2	+ +	+	0
13	Hypesthesia in medial forearm, digit 4,5	APB 0, FDI 3, FPL 4, FDP 4, EIP 4	+ +	+ +	0

TN-TOS, true neurogenic thoracic outlet syndrome; FDI, first dorsal interossei; ADM, abductor digiti minimi; MRC, medical research council; APB, abductor pollicis brevis; EIP, extensor Indicis proprius; FPL, flexor pollicis longus; EDC, extensor digitorum communis; + +, severe; +, mild; 0, none.

intrinsic muscles receive C8 dominant- or C8/T1 innervation [8], there is the typical finding called 'Gilliatt-Sumner hand'. In the same way, sensory deficit is most common on the medial side of forearm, followed by the medial side of hand. Electrodiagnostic study is useful in documenting TN-TOS, as the study can have typical 'median-motor, ulnar and medial antebrachial cutaneous (MABC)-sensory' abnormal pattern of TN-TOS caused by T1 dominant involvement of the disease [9,13,24]. It also helps differentiate TN-TOS from other mimicking diseases [1]. Plain radiographs are usually taken to confirm or exclude the presence of a cervical rib or elongated C7 transverse process. Nowadays, with the advance of imaging techniques, magnetic resonance imaging (MRI) can be used for TN-TOS patients to visualize and evaluate brachial plexus [1].

Diagnosing TN-TOS is clinically challenging. It is extremely rare and there is no gold standard of diagnosis of TN-TOS. Therefore, many patients undergo unnecessary surgical management just under the impression of TN-TOS without definite diagnosis. Because of its scarcity, there are scanty amount of literatures that describe neurologic, electrodiagnostic and radiologic findings of TN-TOS.

We report our experiences in clinical, electrodiagnostic, and radiologic findings of TN-TOS patients. There are three specific purposes of this study. The first was specific review of patients in the very early stage of TN-TOS with no motor symptom and sign. The second was to deduce whether the 'split hand index (APB/ADM ratio)', which is the ratio of compound muscle action potential (CMAP) amplitude of abductor pollicis brevis (APB) and abductor digiti minimi (ADM) muscles, can be used as a new diagnostic electrodiagnostic parameter because thenar, T1 myotome muscles are usually affected more severely than hypothenar, C8 myotome muscles in TN-TOS. The third study aim was to propose several imaging findings as additional supportive criteria for the diagnosis of TN-TOS since imaging studies that can show mechanical compression of the neural structures by cervical rib or fibrous band can be a gold standard for diagnosing TN-TOS, which is basically anatomic and structural disease.

2. Materials and methods

2.1. Subjects

We analyzed retrospectively databases of neuromuscular clinics and electromyography (EMG) laboratories of the Department of Physical Medicine and Rehabilitation and Department of Neurology in a tertiary university hospital between November 1994 and May 2017. Patients diagnosed with TOS or brachial plexopathy of the lower trunk were selected.

Since there is no gold standard for diagnosing TN-TOS, it is difficult to definitively decide who has TN-TOS. Studies have tended to include 'surgically confirmed' TN-TOS patients as the subjects [13,23,24]. In other studies, two especially [5,9], the diagnosis was based on previously described clinical and electrodiagnostic features. We regarded patients satisfying the following inclusion and exclusion criteria as TN-TOS among the initially selected cases.

2.1.1. Inclusion

The inclusion criteria were neurologic symptoms and signs suggesting lower roots/trunk brachial plexopathy (insidious onset pain/paresthesia in the medial side of forearm with or without digit 4 and 5, or obvious hypesthesia in the innervated area of the MABC nerve or ulnar nerve, or thenar hand muscle weakness or atrophy of unilateral upper extremity), along with cervical rib or elongated C7 transverse process in the cervical spine plain radiographs using prior criteria [2,18].

2.1.2. Exclusion

The exclusion of other neuromuscular disorders is mandatory since a variety of diseases can show clinically similar features with TN-TOS. Therefore, in the most cases, TN-TOS is a diagnosis of exclusion [10]. We excluded patients with any of the following: history of traumatic injury of brachial plexus, fracture or fibrous dysplasia of first rib, neoplastic brachial plexopathy, radiation therapy-induced brachial plexopathy, or sternotomy-related brachial plexopathy based on clinical information; sensory impairment or paresthesia restricted to the median nerve supplied area, especially 1st, 2nd, and 3rd digits; evidence of carpal tunnel syndrome, high median neuropathy (including pronator teres syndrome), ulnar neuropathy, motor neuron disease, juvenile benign focal amyotrophy and lower cervical/upper thoracic radiculopathy in electrodiagnostic study; and evidence of definite root compression due to cervical herniated intervertebral disc, cervical spondylotic myelopathy, syringomyelia, or any other cervical spinal cord lesion in cervical spine MRI.

2.2. Evaluations

Sensory NCS was done in bilateral median and ulnar nerves with the antidromic [6] or orthodromic method [19]. MABC nerve was studied bilaterally with the antidromic method [20]. Median and ulnar motor NCS was also done on both sides, recorded in APB and ADM respectively. Age-stratified reference values derived from our electrodiagnostic laboratories were used for absolute criteria for amplitude abnormality. Relative reduction was defined as amplitude < 50% of the value recorded from the contralateral, asymptomatic side. Split hand index (APB/ADM ratio) was calculated by dividing median CMAP

Table 3
Nerve conduction study results.

Patient	Sensory nerve conduction study							Motor nerve conduction study							
	Median nerve amplitude(μV)			Ulnar nerve amplitude(μV)			MABCN amplitude(μV)			Median nerve amplitude(mV)			Ulnar nerve amplitude(mV)			Split hand index (APB/ADM ratio)	
	Affected	Unaffected	Ratio	Affected	Unaffected	Ratio	Affected	Unaffected	Ratio	Affected	Unaffected	Ratio	Affected	Unaffected	Ratio	Affected	Unaffected
1	40.0	44.9	0.89	18.4	28.1	0.66	NT	NT		**3.1**	14.7	**0.21**	15.4	16.5	0.94	**0.20**	0.89
2	23.6	20.6	1.15	15.3	26.5	0.58	**4.3**	17.0	**0.25**	**2.4**	7.7	**0.31**	**5.5**	9.1	0.60	**0.44**	0.85
3	47.1	73.8	0.64	29.3	62.2	**0.47**	**5.0**	21.7	**0.23**	**5.3**	14.3	**0.37**	**7.0**	10.4	0.67	0.76	1.38
4	55.7	49.7	1.12	34.1	47.8	0.71	**8.2**	20.2	**0.41**	9.7	9.0	1.08	9.7	9.4	1.03	1.00	0.96
5	50.1	50.0	1.00	**12.0**	31.3	**0.38**	**NR**	12.4	**0.00**	**1.8**	13.8	**0.13**	12.8	14.4	0.89	**0.14**	0.96
6	29.1	NT		24.1	NT		**4.6**	13.5	**0.34**	**8.1**	NT		10.3	NT		0.79	
7	21.3	22.6	0.94	**4.4**	15.3	**0.29**	**NR**	15.2	**0.00**	**2.7**	12.2	**0.22**	**5.3**	11.4	**0.46**	**0.51**	1.07
8	31.6	44.7	0.71	**10.8**	60.5	**0.18**	**NR**	39.2	**0.00**	**4.8**	13.2	**0.36**	**6.0**	9.9	0.61	0.80	1.34
9	77.2	78.4	0.98	**11.2**	41.2	**0.27**	**2.5**	10.7	**0.23**	**7.2**	12.5	0.58	**7.7**	10.8	0.71	0.94	1.16
10	82.0	73.0	1.12	**15.2**	60.0	**0.25**	**NR**	11.2	**0.00**	**2.3**	12.0	**0.19**	**6.3**	10.0	0.63	0.37	1.20
11	36.2	42.2	0.86	33.6	34.1	0.99	**7.1**	13.3	0.53	10.8	8.7	1.24	11.8	10.9	1.08	0.92	0.80
12	42.7	53.3	0.80	**13.7**	29.4	**0.47**	**1.9**	13.3	**0.14**	**1.6**	18.8	**0.09**	15.9	15.6	1.02	**0.10**	1.21
13	37.5	40.5	0.93	23.7	33.1	0.72	15.1	31.3	**0.48**	**0.4**	11.8	**0.03**	**3.8**	7.5	0.51	**0.11**	1.57

Bold values are abnormal. MABCN, medial antebrachial cutaneous nerve; APB, abductor pollicis brevis; ADM, abductor digiti minimi; NT, not tested; NR, no response.

amplitude by ulnar CMAP amplitude. It is regarded as abnormal when the ratio is ≤ 0.6 as proposed in a study conducted with amyotrophic lateral sclerosis patients [11].

With the advance of brachial plexus MRI techniques, it has been reported that following structures can be visualized and analyzed, if present: brachial plexus, scalene anterior and medius muscles, cervical rib or elongated C7 transverse process, and even fibrous band between cervical rib or elongated C7 transverse process and first thoracic rib compressing brachial plexus [1,4,12]. Secondary changes of brachial plexus from compression, such as swelling or signal change may also be detected [14]. In this study, we reviewed following two imaging findings with a skilled radiologist (Y.C.Y.) who specialized in musculoskeletal MRI: the presence of upwardly pushed C8, T1 anterior primary rami or lower trunk in oblique coronal images, and the presence of increased signal intensity of those neural structures sparing the upper plexus in sagittal short tau inversion recovery (STIR) or T2-weighted images.

Computed tomography angiography (CTA) of the upper extremity is also useful to evaluate compression of neurovascular bundle, especially in the dynamic study with arm elevation [21]. Since focal stenosis of subclavian artery (SCA) or high-mounted SCA over the cervical rib or elongated C7 transverse process could indirectly suggest upward compression or distortion of neural structures that run along with the SCA, we reviewed two image findings on CTA reconstruction image using volume rendering with a skilled radiologist (Y.H.C.) specialized in CTA. The first finding was the presence of focal stenosis of SCA The second finding was the presence of high-mounted SCA over the cervical rib or elongated C7 transverse process.

3. Results

Patients considered to have TOS clinically or suspected to have brachial plexopathy of the lower trunk in electrodiagnostic study were identified. Among them, 54 were selected after excluding patients with brachial plexopathy from other etiologies. Of these patients, 21 satisfied the inclusion criteria. Among them, 1 patient was excluded because fracture and callus formation of the first rib was thought to be a causative structure. Four patients were excluded from electrodiagnostic study (2 patients with ulnar neuropathy, 1 with radiculopathy and 1 with motor neuron disease). Another 3 patients were excluded because of absence of cervical spine MRI study. Finally, 13 TN-TOS patients were identified.

3.1. Clinical features

All 13 patients had unilateral symptoms and/or signs although cervical rib or elongated C7 transverse process were identified at both sides in all patients (Table 1). The patients were 19–70 years of age (mean, 40.3 years). Ten (77%) were women. On initial visits, 4 patients (31%) had sensory symptoms only, 7 patients (54%) had both sensory and motor symptoms and 2 patients (15%) complained only of motor symptoms. Chief complaints were paresthesia or tingling in 6 patients (46%), weakness or atrophy in 6 patients (46%), and hypesthesia in 1 patient (8%). One of patients who visited with only motor symptom (patient 2) had previous history of transient paresthesia of medial side of forearm 9 years before the presentation. Vascular symptoms, such as loss of distal pulses, coolness and discoloration, were absent in all patients. The duration of symptoms before diagnosis ranged from 12 to 480 months (mean, 70.6 months).

3.2. Neurologic examination

On neurologic examination, 9 patients (69%) showed sensory deficit in medial forearm or ulnar digits (Table 2). Nine patients (69%) revealed weakness of any muscles of hand. All patients with muscle weakness showed APB muscle weakness, followed by first dorsal

Table 4
Needle electromyography results.

Patient	D	BB	BR	TB	FCR	EDC	EIP	FCU	FDI	ADM	FPL	APB	PSP
1	○	○	○	○	○			◐	◐			●	○
2				○		◐	●	●	●	◐	●	●	○
3		○		○	○		○	○	●	◐		●	○
4	○	○		○	○			○	○	○		○	○
5	○	○		○	○		◐	●	●			●	○
6		○			○			○	○			◐	○
7	○	○		○	○	◐	◐	◐	●		○	●	○
8	○	○			○		●	○	●			●	○
9	○	○		○	○	○	◐	○	◐			◐	○
10						○	○	○	◐	◐	●	◐	○
11	○	○		○	○			○	○			○	○
12							◐		○			●	○
13	○	○			○	○	○	◐	◐	◐	◐	◐	○

D; deltoid, BB; biceps brachii, BR; brachioradialis, TB; triceps brachii, FCR; flexor carpi radialis, FCU; flexor carpi ulnaris, EDC; extensor digitorum communis, EIP; extensor indicis proprius, FDI; first dorsal interossei, ADM; abductor digiti minimi, FPL; flexor pollicis longus, APB; abductor pollicis brevis, PSP; paraspinalis, ●; denervation potentials (fibrillation potential or positive sharp wave) with neuropathic recruitment changes, ◐; neuropathic recruitment changes only ○; normal.

Table 5
Imaging study results.

Patient	Brachial plexus magnetic resonance imaging		Computed tomography angiography	
	Upwardly pushed neural structures in oblique coronal images	Increased signal intensity of C8,T1 anterior primary rami or lower trunk	Focal stenosis of SCA	High-mounted SCA
1	NT	NT	NT	NT
2	Positive	Positive, C8 root	Positive	Positive
3	Negative	Negative	Positive	Positive
4	Positive	Negative	Positive	Negative
5	Negative	Positive, C8, T1 root	Positive	Negative
6	Negative	Negative	Positive	Negative
7	Negative	Positive, lower trunk	Positive	Positive
8	NT	NT	NT	NT
9	Negative	Unknown[a]	Positive	Positive
10	Negative	Positive, lower trunk	Negative	Negative
11	NT	NT	Negative	Negative
12	Negative	Positive, C8 root	Negative	Negative
13	NT	NT	NT	NT

NT; not tested.
[a] Sagittal short tau inversion recovery (STIR) or T2-weighted mages were not available., SCA; subclavian artery.

interossei (FDI) muscle. Atrophy of intrinsic hand or forearm muscles, especially in thenar area was present in 8 patients (62%).

Three patients (patients 4, 6 and 11) who showed no abnormalities of motor system in neurologic examination were regarded to be in the very early stage of TN-TOS. An average duration of symptoms for these 3 patients (24.0 months) was shorter than that of other 10 patients (84.6 months).

3.3. Electrodiagnostic findings

On sensory NCS, median SNAP amplitude was normal in all patients (Table 3). The ulnar SNAP amplitude was decreased in 6 of 13 patients (46%) with absolute value criteria, and 7 of 12 patients (58%) with relative value criteria (1 patient had NCSs in only symptomatic side). Sensory NCS of MABC nerve was performed in 12 patients and its amplitude was decreased in 11 of 12 patients (92%) with both absolute and relative criteria, and could not be obtained in 4 patients.

On median motor NCS recorded in APB, CMAP amplitude was decreased in 11 of 13 patients (85%) with absolute value criteria and in 9 of 12 patients (75%) with relative value criteria (Table 3). The ulnar CMAP amplitude recorded in ADM decreased in 7 of 13 patients (54%) with absolute value criteria and in 1 of 12 patients (8%) with relative value criteria. The split hand index (APB/ADM ratio) of affected hand decreased in 6 of 13 patients (46%).

On needle EMG (Table 4), all but 2 patients showed some abnormalities in APB muscle (11 of 13 patients, 85%), followed by FDI muscle (9 of 13 patients, 69%) and extensor indicis proprius (EIP) muscle (6 of 9 patients, 67%). Deltoid, biceps brachii, brachioradialis, triceps brachii, flexor carpi radialis, and cervical/thoracic paraspinal muscles were normal in all cases in which they were examined.

When reviewing the results of electrodiagnostic study for 3 patients who were in the very early stage of TN-TOS (patients 4, 6 and 11), the decrease in SNAP amplitude in MABC NCS was noticed for all 3 patients, and was the sole abnormal finding for patient 4 and 11. For patient 6, in addition to that finding, the amplitude of median CMAP decreased with absolute criteria, and neuropathic potential was detected at APB muscle in needle EMG.

3.4. Radiologic findings

Brachial plexus MRI was done in 9 patients (Table 5). Upwardly pushed neural structures within thoracic outlet were found in 2 of 9 patients (22%). The findings were detected in multi-point Dixon in-phase sequence in patient 2, and STIR sequence in patient 4 (Fig. 1, A-C). Increased signal intensity of C8, T1 anterior primary rami or lower trunk of brachial plexus in sagittal STIR sequence was detected in 5 of 8 patients (63%). In patient 2 and 12, C8 anterior primary ramus is presumed to be a main lesion considering signal intensity. Despite high signal intensity was revealed in both C8 and T1 root in patient 5, signal intensity was higher in C8 root than T1. In Patient 7 and 10, high signal intensity was mainly found in lower trunk, not in root level (Fig. 1, D). We could hardly identify T1 nerve root 1-2 cm distal to the neural foramen, although it could be identified immediately adjacent to the neural foramen.

CTA with arm hyperabduction position was done in 10 patients (Table 5). Gross focal stenosis in affected side SCA was found in 7 of 10 patients (70%) (Fig. 2, A). High-mounted SCA in the reconstruction images was revealed in 4 of 10 patients (40%) (Fig. 2, B).

3.5. Operative status and follow-up results

Seven patients underwent surgical exploration, 3 patients refused surgical managements and 3 other patients in the very early stage of TN-TOS (patients 4, 6 and 11) were not recommended for surgery (Table 6). Patients were followed for 3–163 months (mean, 37.0 months). All except 1 patient who underwent surgery subjectively reported somewhat improvement of their sensory and/or motor symptoms. However, patient 5 reported worsening of hypesthesia after

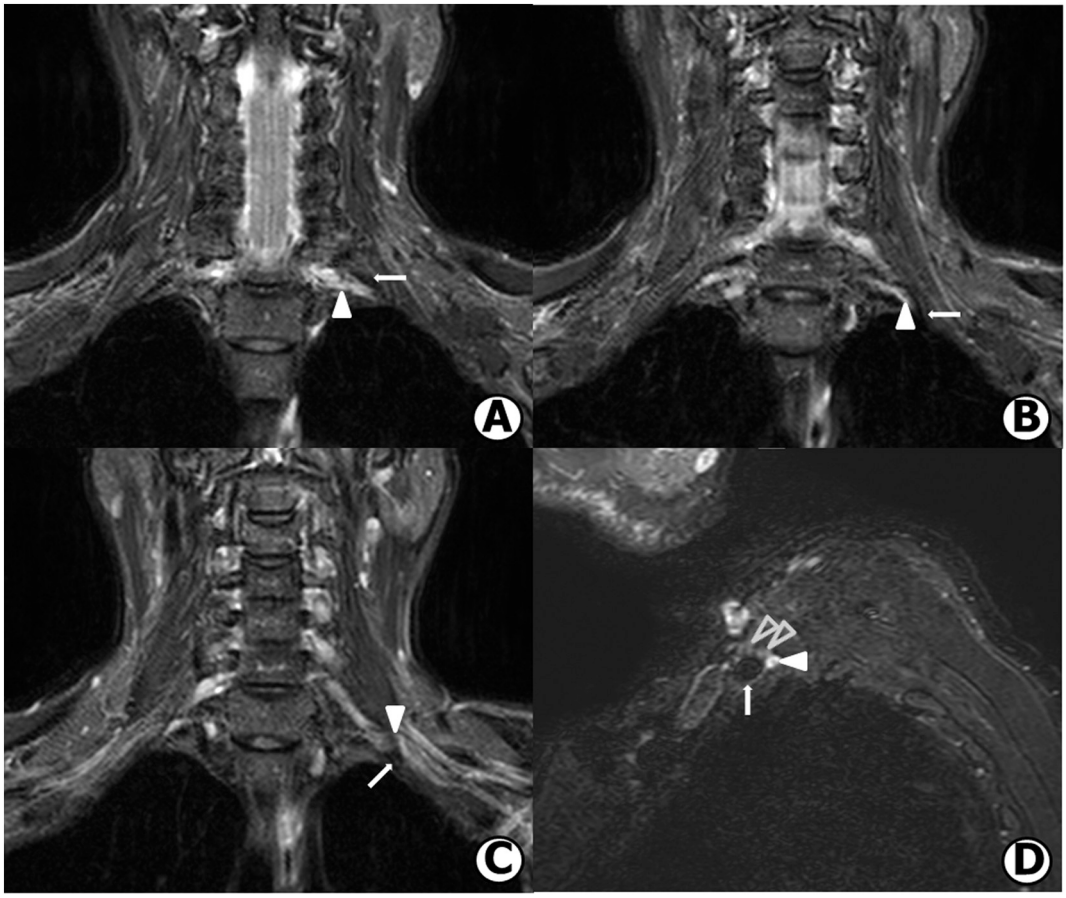

Fig. 1. Brachial plexus MRI of patient 4 (A-C) and patient 7 (D). A-C. Contiguous Coronal STIR images (A is hindmost and C is foremost) show spatial relationship of C8 anterior primary ramus (*arrowheads*) and the cervical rib (*arrows*). C. C8 anterior primary ramus is pushed upward by the tip of cervical rib along its course. D. Sagittal STIR image shows increased signal intensity of the inferior trunk (*arrowhead*) of brachial plexus, compared to superior and middle trunk (*voided arrowheads*). The brachial plexus is running together with SCA (*arrow*).

the operation. Three patients who refused the surgery denied any aggravation of symptoms, albeit the durations of follow-up were relatively short. In the last follow-up, motor system involvement was not revealed yet in all 3 patients with the very early stage of TN-TOS.

4. Discussion

We confirmed that TN-TOS is very rare disease again. There were only 13 among 100,915 patients who visited our EMG laboratories in a tertiary hospital for over 20 years.

It is known that the presenting symptom of TN-TOS is usually muscle atrophy or weakness, rather than sensory disturbances, even though mild tingling or paresthesia can be present for a long time before the presentation [7,15,26]. However, in our study, more than half of the patients reported sensory symptoms as chief complaints. Furthermore, 31% of the patients had no motor symptoms complaints at first visit. It may be that, contrary to the traditional view, patients could present to a neuromuscular physician with sensory symptoms before the onset of motor symptoms. Moreover, 3 patients (patients 4, 6 and 11) showed no weakness or atrophy in neurologic examination. We regarded them as being in the very early stage of TN-TOS. It is also notable that these patients showed relatively short duration of symptoms before presentation.

If present, weakness and muscle atrophy were prominent in T1/median nerve innervated thenar muscles. Also, no case showed weakness or atrophy sparing APB. These findings confirmed the predominance of T1 involvement of TN-TOS. In advanced cases, weakness or atrophy was found in C8 as well as C8/T1 myotome muscles (e.g., FDI, EIP and extensor digitorum communis muscle).

In an electrodiagnostic study, decrease of SNAP amplitude of MABC nerve was the most sensitive marker in NCS. This finding arises from anatomical fact that the nerve fibers consisting the MABC nerve mainly derive from the T1 root. The results echo previous studies [22,24]. The decrease of SNAP amplitude of MABC nerve was the only abnormal finding in two patients (patient 4 and 11). There were no evidences of motor system involvement on neurologic examination in those patients. In another study [22], all 16 patients with pain or paresthesia of unilateral arm without motor deficit or atrophy showed abnormality in MABC NCS. The authors of that study suggested that MABC NCS can be used to detect mild lower trunk brachial plexus lesion. In line with that suggestion, it is reasonable to suggest that our two patients are in very early stage of TN-TOS.

The split hand index (APB/ADM ratio) does not have additional diagnostic value, contrary to our expectation, because all patients with decreased ratio showed reduced median CMAP amplitude. As ulnar CMAP amplitude is frequently reduced in TN-TOS, the ratio seems to not be overly decreased. However, if the patient within diagnostic evaluation shows a decreased split hand index (APB/ADM ratio), TN-TOS should be suspected as a possibility.

On needle EMG, among muscles that are examined more than two third of patients, there were abnormalities in order of T1 innervated muscle (i.e., APB), C8/T1 innervated muscle (i.e., FDI), and C8 innervated muscles (i.e. EIP, flexor carpi ulnaris). This finding also identified T1 predominance of TN-TOS again.

In radiological evaluation, focal stenosis of SCA in CTA was the most common finding, as detected in 70% of evaluated patients.

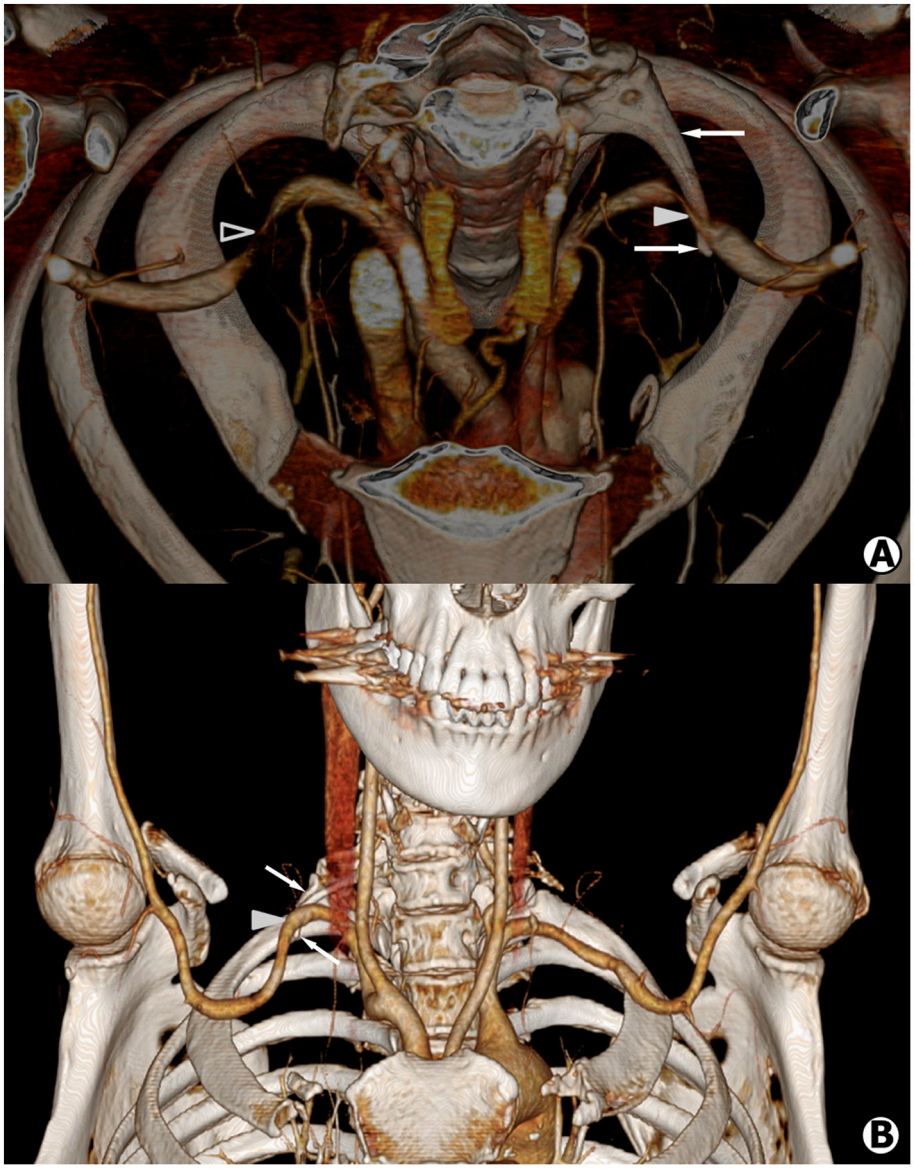

Fig. 2. CTA of patient 4 (A) and patient 2 (B) reconstructed using volume rendering. A. When viewed from above, narrowing of the SCA of affected side (*arrowhead*) is identified when it passes over the cervical rib (*arrows*). Note that the SCA of asymptomatic side is also narrowed (*voided arrowhead*). B. When viewed from front, high-mounted SCA (*arrowhead*) running over the tip of cervical rib (*arrows*) is observed. Note more acute angulation in course of SCA than contralateral side.

Interpretation should be made with caution, since there are some cases showing SCA stenosis in CTA conducted under arm hyperabduction position in the general population [17]. Also, we are not aware of any studies that analyze the cut-off value for the degree of stenosis. Further study to verify the cut-off value is needed to increase the accuracy of the diagnosis.

Upwardly pushed neural structures in brachial plexus MRI were found only in 2 of 9 patients. In both patients, the cervical ribs were the causative structures that push the neural structures. A 'fibrous band' was not detected in any patient. Identification of the fibrous band in imaging studies has only been described in case reports and remains unreliable [3]. Even though increased signal intensity of lower plexus (C8, T1 nerve roots or lower trunk) was found in 5 patients, high signal was mainly found in the C8 root, rather than T1. It was difficult to visualize and identify the T1 anterior primary ramus in brachial plexus MRI. In other articles reviewing MRI findings of neurogenic TOS, increased signal or kinking of C8 root or lower trunk, rather than T1 root, was mainly addressed ([1,14,16].

Patient 4 is noteworthy. As TN-TOS is neuropathy caused by chronic compression of lower trunk of brachial plexus by certain anatomical structures such as cervical rib or fibrous band, structural abnormalities might precede a functional or clinical manifestation. In the same vein, even though she was in the very early and mild stage of the disease in clinical and electrodiagnostic evaluations, structural abnormalities were found both in brachial plexus MRI and CTA (Fig. 1, A-C and 2, A). As highlighted by this case, imaging studies have ancillary role in diagnosing early stage TN-TOS before the typical clinical and electrodiagnostic features are emerged [4]. However, physicians should keep in mind that radiologic studies cannot diagnose TN-TOS without clinical and electrodiagnostic corroboration. Moreover, imaging studies are useful only in a few cases with definite abnormalities because of their low sensitivity and lack of established criteria. Imaging sensitivity will increase with advances in imaging quality or methods. Also, with more cases and case-control studies, it is required to more objectify and quantify the presently suggested criteria.

Although follow-up periods were not long enough, there were postoperative improvements of sensory symptoms. However, motor weakness was not improved in objective manual muscle strength test in all

Table 6
Operative findings and follow-up results.

Patient	Operative status	Operative findings	Follow-up periods (months)	Last follow-up result	
				Sensory symptom/sign	Motor symptom/sign
1	Done	Fibrous band→fibrous band resection and cervical rib removal	163	Numbness disappeard	Unchanged
2	Done	Cervical rib → cervical rib removal	5	Paresthesia improved	Unchanged
3	Done	First rib complete removal	97	Paresthesia, numbness improved	Motor weakness improved subjectively
4	Not recommended	N/A	85	Paresthesia aggravated	Unchanged
5	Done	First rib complete removal	15	Pain slightly reduced Hypesthesia aggravated	Unchanged
6	Not recommended	N/A	78	Unchanged	Unchanged
7	Refused	N/A	9	Unchanged	Motor weakness improved subjectively Muscle atrophy unchanged
8	Refused	N/A	3	Unchanged	Unchanged
9	Done	Lower brachial plexus swelling → cervical rib, first rib removal	3	Paresthesia improved	Unchanged
10	Done	Anterior and middle scalenectomy	7	Paresthesia improved	Motor weakness improved subjectively Muscle atrophy unchanged
11	Not recommended	N/A	0	Not available	Not available
12	Done	Fibrous band in the anterior scalene muscle → anterior scalenectomy	3	Paresthesia improved	Motor weakness improved subjectively
13	Refused	N/A	13	Unchanged	Unchanged

N/A; not applicable.

patients undergone surgery. This finding is consistent with prior data [9]. Because improvement of muscle strength is negligible with surgery when patients have serious muscle weakness and muscle atrophy, it is important to diagnose TN-TOS before the occurrence of muscle weakness. Three patients in the very early stage of TN-TOS showed no motor symptoms or signs at the last follow-up. We are considering recommending surgery immediately when the motor system involvement is developed in the future to prevent permanent disabilities.

This study has limitations that are inherent to a retrospective study. First, diagnostic evaluations are not fully covered in all patients. Some patients in relatively old times didn't conduct part of diagnostic evaluations such as MABC NCS, brachial plexus MRI and CTA. Protocol, slice thickness and included sequences in imaging studies varied. In addition, needle EMG exams were conducted by different clinicians. To determine the accuracy and usefulness of the diagnostic modalities discussed above, a prospective study using homogenous protocol with control group is needed. However, because TN-TOS is an extremely rare disease, conducting a prospectively designed study is almost impossible. We are not aware of any prospective studies in the field of TN-TOS. Another limitation is the fact that we set the inclusion and exclusion criteria under our discretion. Excluding other similar diseases is necessary since TN-TOS has no definite diagnostic criteria. Nowadays, many patients are suffering from unnecessary operations just under the impression of TN-TOS without a definite diagnosis. Therefore, we tried to be very strict when we formulated the exclusion criteria putting our priority on diagnostic specificity over sensitivity.

5. Conclusions

We confirmed that TN-TOS is T1 predominant lower roots/trunk brachial plexopathy with the following findings: APB dominant motor weakness, thenar area dominant muscle atrophy, high sensitivity of MABC NCS and high prevalence of abnormalities in APB with needle EMG. Radiologic studies may be used to detect structural abnormalities of TN-TOS.

Our results suggest the high possibility that patients present to us with only sensory symptoms without weakness or atrophy. Because muscle weakness or atrophy in TN-TOS is usually not reversible after the operation, it is important to diagnose in early stage with no or mild weakness to prevent permanent disability from muscle weakness. As MABC NCS showed abnormal results in all tested patients, it should be added to electrodiagnostic study as screening method. If an anatomical lesion is present, structural abnormalities might be confirmed with radiologic studies such as brachial plexus MRI and CTA.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jns.2019.07.024.

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