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A Decade of Imaging Patients with Traumatic Brachial Plexopathy: What have We Learned?

Vaishali Upadhyaya[1] Divya Narain Upadhyaya[2] Abhijat Mishra[2]

[1] Department of Radiology, Vivekanada Polyclinic and Institute of Medical Sciences, Ramkrishna Mission Sewashram, Lucknow, Uttar Pradesh, India
[2] Department of Plastic and Reconstructive Surgery, King George's Medical University, Lucknow, Uttar Pradesh, India

Address for correspondence Divya Narain Upadhyaya, MS, MCh, FACS, B-2/128, Sector–F, Janakipuram, Lucknow 226021, Uttar Pradesh, India (e-mail: dnu1@hotmail.com).

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Abstract

Aim In this paper, the authors share their experience of imaging patients with traumatic brachial plexopathy by magnetic resonance neurography (MRN) spanning over a period of nearly 10 years.

Setting and Design This was a single-institution, prospective, observational study conducted between August 2012 and March 2022.

Materials and Methods Children and adults presenting to the plastic surgery outpatient department with features of traumatic brachial plexopathy were included in the study. The MRN study was performed in a 1.5T scanner (Magnetom Essenza, Siemens, Erlangen, Germany). The area scanned extended from C3 level to T3 level.

Statistical Analysis Descriptive statistics (percentages, mean, median, and mode).

Results A total of 134 patients ($n = 134$) were included in the study. The age of our patients ranged from 6 months to 65 years. The mean age was 24.95 ± 12.10 years, with a median of 23 years. All patients had unilateral injury, and the right side was more commonly involved. Road traffic accident was the most common mode of injury, and blunt crush-avulsion was the most common mechanism of injury. Involvement of shoulder, elbow, and hand together (panplexopathy) was the most common clinical presentation.

Conclusion This study of patients with traumatic brachial plexopathy imaged by MRN, spanning nearly a decade, has led to several interesting observations. The majority of these injuries occur in young men from urban areas who usually present with panplexopathy. The most common mode of injury is road traffic accident, and blunt crush-avulsion is the most common mechanism of injury.

Keywords
- brachial plexus
- injuries
- magnetic resonance imaging
- magnetic resonance neurography
- neurography

Introduction

The increased incidence of brachial plexopathy following trauma in recent times has caused a proportionate increase in magnetic resonance neurography (MRN) examinations for evaluation of the brachial plexus. MRN is the modality of choice for imaging the brachial plexus as it provides comprehensive assessment of the plexus from the spinal cord

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until the terminal branches in the axilla.[1–5] In this paper, the authors share their experience of imaging patients with traumatic brachial plexopathy by MRN, spanning over a period of nearly 10 years. It will enable the readers to learn about planning the imaging of such patients and get familiar with the spectrum of imaging findings in traumatic brachial plexopathy.

Anatomy of the Brachial Plexus

The brachial plexus is a complex network of nerves, which originate from the spinal cord, pass through the spaces of the thoracic outlet, and finally terminate in the axilla as terminal branches. It provides motor and sensory innervations to the shoulder girdle and the upper extremity. Ventral and dorsal rootlets that emerge from the spinal cord join to form ventral and dorsal roots, which carry motor and sensory fibers, respectively. The dorsal root incorporates a dorsal root ganglion at the level of the intervertebral foramen, within which lie the cell bodies of the sensory fibers. The cell bodies of the motor fibers, in contrast, lie in the anterior horn cells of the spinal cord. The ventral and dorsal roots join to form the spinal nerve, which subsequently splits into ventral and dorsal rami. The ventral rami of C5, C6, C7, C8, and T1 spinal nerves contribute to forming the brachial plexus while the dorsal rami innervate the paraspinal muscles. A “pre-fixed” plexus is one which receives additional innervation from the ventral ramus of C4, and a “post-fixed” plexus is one which receives additional innervation from the ventral ramus of T2.[6–8]

The extra-spinal roots, along with the subclavian artery, pass through the interscalene triangle, and coalesce to form the trunks as they exit the neck. The upper trunk is formed by the union of C5 and C6 roots, middle trunk by the C7 root, and the lower trunk is formed by the union of C8 and T1 roots. Subsequently, behind the clavicle and at about the lateral border of first rib, each trunk divides into an anterior and a posterior division. As they pass inferolaterally, these divisions then join to form the cords. The anterior divisions of the upper and middle trunks unite to form the lateral cord, while the anterior division of the lower trunk carries on as the medial cord. The posterior cord is formed by the union of posterior divisions of all the trunks. The nomenclature of the cords is indicative of their relationship to the axillary artery. The cords pass deep to the pectoralis minor muscle and divide into their terminal branches in the axilla. The ulnar nerve, medial root of median nerve, and medial cutaneous nerves of arm and forearm are branches of the medial cord. Branches of the lateral cord include the lateral root of median nerve and musculocutaneous nerve. The radial and axillary nerves are branches of the posterior cord[6–8](►**Fig. 1**).

Materials and Methods

This was a single-institution, prospective, observational study conducted between August 2012 and March 2022.

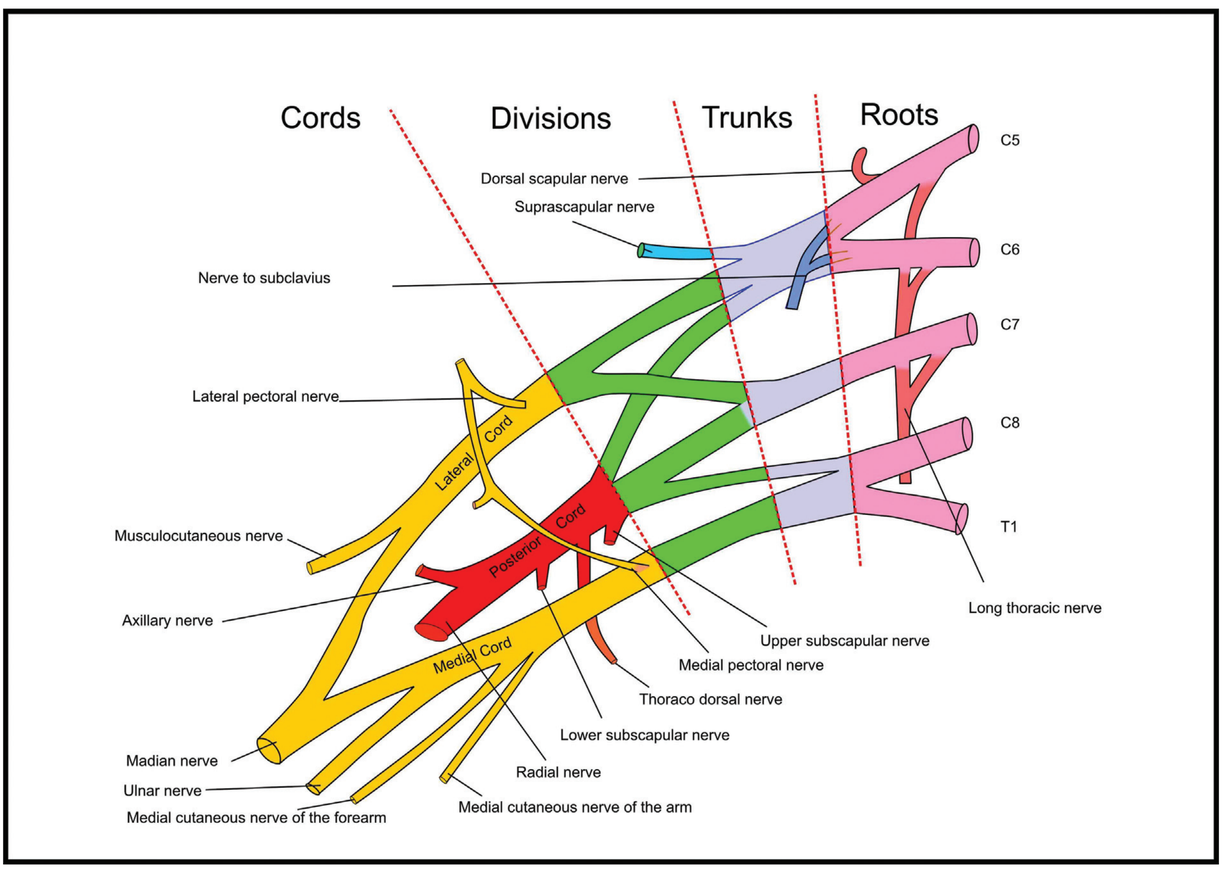

Fig. 1 Schematic diagram of the normal brachial plexus.

Consent was obtained from the patients for use of their anonymized data for research purposes. Institutional ethical clearance was waived off as no identifying features were present in the dataset used.

Children and adults presenting to the plastic surgery outpatient department with features of traumatic brachial plexopathy were included in the study. Exclusion criteria consisted of patients in whom MRI was contraindicated, those with severe claustrophobia, and those who did not give consent for participation in the study.

Patients were scanned at least 4 weeks after the trauma to give time for the posttraumatic edema and hemorrhage to subside. They were requested to lie still for the duration of the scan to avoid motion artifacts and avoid repetition of sequences. In some cases, sedation was administered by the anesthesiologist on call for the duration of the scan after informed consent.

MRN Protocol

The MRN study was performed in a 1.5 T scanner (Magnetom Essenza, Siemens, Erlangen, Germany).

Patients were instructed to lie supine in the scanner with arms by their sides. Both the cervical and body coils were used. The area scanned extended from C3 level to T3 level. The MRN protocol (►**Table 1**) included T1W and T2W fat-saturated sequences in axial plane, T1W and 3D STIR (short-tau inversion recovery) SPACE (sampling perfection with application-optimized contrasts using varying flip angle evolutions) sequences in coronal plane, STIR sequence in sagittal plane covering the affected brachial plexus, and sagittal T2W SPACE sequence focused on the cervical spine. No intravenous contrast was given to these patients, except in one case where there was a clinical suspicion of vascular injury.

T1-weighted images in axial and coronal planes help to evaluate the anatomy of the plexus as well as adjacent structures such as muscles, vessels, and bones. The perineural fat planes are well-delineated. T2-weighted images in the axial plane help to localize and characterize the injury. The coronal 3D STIR SPACE sequence gives an overview of the entire plexus, identifies the injury and its extent, and enables comparison with the opposite side. These images can be reconstructed in multiple planes for optimal assessment of the injury. Sagittal STIR sequence can assess the cross-section of the plexus and its relationship with subclavian and axillary vessels. Sagittal T2-weighted SPACE images focused on the cervical spine enable assessment of spinal cord lesions and intradural roots.[1,3]

Data Set

The demographic, clinical, and MRN findings were recorded as per a predefined proforma. The data that were recorded included age, sex, occupation, place of residence, laterality, time since injury, mode, and mechanism and level of injury.

The MRN findings were assessed by a radiologist (V.U.) with more than 18 years of experience in reading MR scans. Findings were evaluated at the level of the spinal cord, intraspinal roots, extraspinal roots, trunks, cords, and terminal branches. Additional findings included adjacent osseous and vascular injuries, and changes in adjacent muscles. However, we did not include changes in posterior paraspinal muscles as part of our observations.

Image Analysis

A normal nerve has a round or ovoid shape with smooth margins and does not show any sudden deviation in its course. It appears isointense to muscle in T1-weighted images and mildly hyperintense in T2-weighted fat-saturated and STIR images. In the absence of any scarring, perineural fat appears uniformly hyperintense in T1-weighted images. The plexus should be evaluated in a systematic manner, starting from the spinal cord, then the intraspinal roots, extraspinal roots, trunks, cords and finally the terminal branches in the axilla. The spinal cord and intraspinal roots are best seen in the sagittal T2 SPACE sequence and its reconstructed axial sections (►**Fig. 2**) The post-ganglionic plexus requires a multiplanar combination of T1-weighted, T2-weighted, and 3D STIR SPACE sequences (►**Fig. 3**). Changes in adjacent muscles, vessels, and osseous structures also have to be noted for a comprehensive evaluation of the injury and its extent.

On MR images, T2 hyperintense signal in the spinal cord was suggestive of edema or myelomalacia while T2 hypointense signal suggested hemorrhage. The intraspinal roots

Table 1 MRN protocol at the author's institution

Sequence	FOV (mm)	Slice thickness (mm)	Slice gap (mm)	TR (msec)	TE (msec)	Acquisition Duration (min)	Voxel Size (mm)
Axial T1W	190 × 320	3.0	0.9	597	15	3:59	1.2 × 1.0 × 3.0
Axial T2W FS	188 × 320	3.0	0.9	3860	102	3:15	1.3 × 1.0 × 3.0
Coronal T1W	263 × 350	3.0	0.6	460	12	3:18	1.1 × 0.8 × 3.0
Coronal 3D STIR SPACE	300 × 300	1.2	–	3800	207	7:38	1.3 × 1.2 × 1.2
Sagittal STIR (Affected Side)	240 × 240	3.0	0.3	5210	19	6:52	1.2 × 0.9 × 3.0
Sagittal 3D T2 SPACE	250 × 250	0.75	–	1500	226	6:51	0.8 × 0.8 × 0.8

Abbreviations: FOV, field of View; FS, fat saturated; MRN, magnetic resonance neurography; SPACE, sampling perfection with application optimized contrasts using varying flip-angle evolutions; STIR, short tau inversion recovery; T1W, T1-weighted; T2W, T2-weighted; TE, time of echo; TR, repetition time.

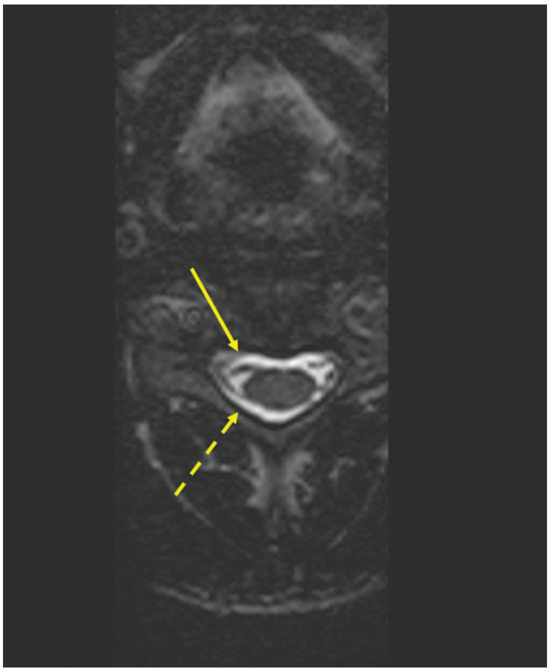

Fig. 2 Axial reconstruction of T2W SPACE image showing normal preganglionic ventral (solid yellow arrow) and dorsal (dashed yellow arrow) rootlets.

were considered avulsed if there was discontinuity in the ventral or dorsal roots or both. An extradural fluid collection showing signal intensity similar to cerebrospinal fluid (CSF), which extended from the spinal canal into the neural foramen was suggestive of pseudomeningocele. If roots were intact and only pseudomeningocoele was visualized, it was considered due to root sheath laceration. Nerve thickening and hyperintense signal in fluid-sensitive sequences with interspersed hypointense foci was suggestive of scarring. In rupture or transection, there was loss of nerve continuity. A well-defined nodular lesion in a nerve along its course or at its ends was interpreted as neuroma.

All the data generated as above were entered in an MS excel spreadsheet and analyzed.

Results

Two hundred four patients ($n = 204$) were referred to the MRI unit of the Department of Radiology for an MRN study of the brachial plexus. However, seventy ($n = 70$) of these patients had to be excluded due to reasons including contraindications to MRI, severe claustrophobia, and those who did not give consent. In the last 2 years of the study, unfortunately, very few patients were referred for MRN of the brachial plexus due to the prevalent COVID-19 pandemic. Finally, 134 patients ($n = 134$) were included in the study.

Demographic Data

The age of our patients ranged from 6 months to 65 years. The mean age was 24.95 ± 12.10 years, with a median of 23 years. More than 75% patients were less than 30 years old. There was a dominance of male patients ($n = 122$, 91%) and the male to female ratio was 10.17:1 Most patients were self-employed ($n = 45$, 33.6%) as shopkeepers, tailors, or farmers, followed by students ($n = 43$, 32.1%). There were 14 (10.4%) patients who were aged ≤ 10 years and in whom occupation was not noted. Majority of the patients ($n = 86$, 64.2%) were from urban areas, with only 48 patients (35.8%) from rural areas. The demographic data are summarized in ►**Table 2**.

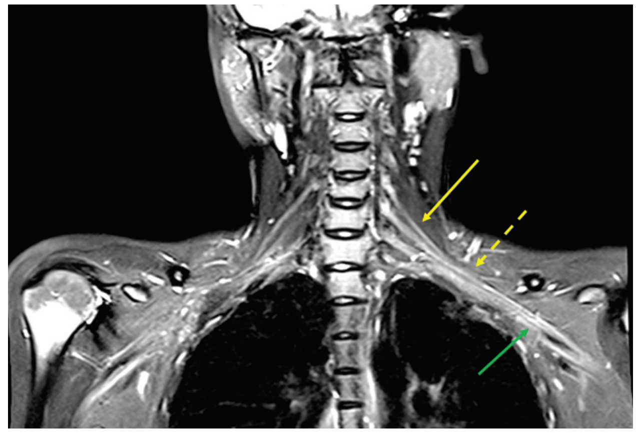

Fig. 3 Coronal 3D STIR MIP image in a healthy volunteer showing normal extraspinal roots (solid yellow arrow), trunks (dashed yellow arrow), and cords (solid green arrow).

Plexal Injuries

Laterality

All patients had unilateral injury, and right side was more commonly involved ($n = 82$, 61.2%) than the left side ($n = 52$, 38.8%).

Time to Presentation

Most patients ($n = 62$; 46.3%) had a history of trauma within the last 1 to 3 months followed by those with history of

Table 2 Demographic profile of patients with traumatic brachial plexopathy

SN	Demographic details	Statistic
1.	Mean age ± SD (range) in years	24.96 ± 12.10 (0.5–65.0)
	Median age [IQR] years	23 [18–30]
2.	Sex	
	Male	122 (91%)
	Female	12 (9%)
3.	Occupation	
	Employed	25 (18.7%)
	Self-employed	45 (33.6%)
	Unemployed	7 (5.2%)
	Student	43 (32.1%)
	Child ≤10 years	14 (10.4%)
4.	Place of residence	
	Rural	48 (35.8%)
	Urban	86 (64.2%)

trauma 3 to 6 months ago ($n = 38$; 28.4%), between 6 to 12 months ($n = 16$; 11.9%), less than 1 month ago ($n = 10$; 7.5%), and more than 12 months ago ($n = 8$; 6%), respectively.

Mode of Injury

Road traffic accident was the most common mode of injury ($n = 98$; 73.1%) followed by fall from a height ($n = 8$; 6%), heavy machine-related injury, and gunshot injury ($n = 4$; 3%). There were 2 (1.5%) cases each in whom mode of injury was fall of heavy object over shoulder, injury sustained while engaging in sports, occupational injuries, non-penetrating assault, fall over sharp object, and animal-related injury. There was one (0.7%) patient, a 2-year-old child who was injured when his hand got stuck accidentally in a thresher machine.

Mechanism of Injury

Blunt crush-avulsion was the most common mechanism of injury ($n = 112$; 83.6%), followed by pure traction injuries ($n = 14$; 10.4%), and penetrating injuries ($n = 8$; 6%), respectively.

Motor Deficit

Involvement of shoulder, elbow, and hand together (pan-plexopathy) was the most common clinical presentation ($n = 88$; 65.7%) followed by the involvement of the shoulder with elbow ($n = 25$; 18.7%). A total of 8 (6%) patients had only shoulder involvement, 6 (4.5%) had only hand weakness, 5 (3.7%) had both elbow and hand involvement, and 2 (1.5%) had only elbow involvement. These details are summarized in ►**Table 3**.

Table 3 Clinical features of patients with traumatic brachial plexopathy

SN	Clinical features	Number of patients	Percentage of patients
1.	Laterality		
	Unilateral	134	100
	Left	52	38.8
	Right	82	61.2
	Bilateral	–	–
2.	Time since injury		
	< 1 month	10	7.5
	1–3 months	62	46.3
	3–6 months	38	28.4
	6–12 months	16	11.9
	> 12 months	8	6.0
3.	Mode of injury		
	Vehicular accident	98	73.1
	Fall from height	8	6.0
	Fall of heavy object	2	1.5
	Sport injury	2	1.5
	Machine injury	4	3.0
	Other occupational injury	2	1.5
	Nonpenetrating assault	2	1.5
	Fall over sharp object	2	1.5
	Gunshot injury	4	3.0
	Animal related injury	2	1.5
	Birth palsy	7	5.2
	Miscellaneous	1	0.7
6.	Mechanism of injury		
	Blunt crush avulsion	112	83.6
	Penetrating injury	8	6.0
	Pure traction injury	14	10.4
7.	Level of injury		
	Shoulder	8	6.0
	Elbow	2	1.5
	Hand	6	4.5
	Shoulder and elbow	25	18.7
	Elbow and hand	5	3.7
	Shoulder, elbow and hand	88	65.7

Spinal Cord and Plexal Injuries

Spinal cord injuries were seen in 9 (6.7%) cases, of which 5 (3.7%) had edema and 4 (3%) had myelomalacia (►**Fig. 4**). Intraspinal root injuries with root avulsion were seen in 33 patients (24.62%) and root sheath laceration were seen in 30 patients (22.38%) (►**Fig. 5**). These injuries overall were most frequent at C7 level ($n = 51$, 38.1%) followed by C8 level ($n = 38$, 28.4%).

Extraspinal root injuries in the form of edema, rupture, scarring, and neuroma formation were seen mostly at C6 ($n = 101$, 75.4%) and C5 ($n = 96$, 71.6%) levels. These were followed by injuries at C7 ($n = 84$, (62.7%), C8 ($n = 60$, 44.8%), and T1 ($n = 51$, 38.1%) levels. Amongst the trunks, the upper trunk was most commonly injured ($n = 112$, 83.6%) and both the middle and lower trunks showed a similar percentage of injury ($n = 101$, 75.4%). Amongst the cords, the posterior cord sustained injury most often ($n = 90$, 67.2%), followed by the lateral cord ($n = 86$, 64.2%), and the medial cord was least often injured ($n = 81$, 60.5%) (►**Figs. 6–10**).

Scarring was the commonest pattern of injury at the level of the extraspinal roots, trunks, and cords. The trunks were most often scarred ($n = 109$, 81.34%), followed by the extra-spinal roots ($n = 107$, 79.85%) and cords ($n = 92$, 68.65%). Terminal branch injuries were seen in only 15 patients (11.1%), most of which ($n = 13$, 9.7%) were due to scarring. The number and percentage of these injuries is presented in ►**Table 4**.

Extra-Plexal Injuries

Fractures

Fractures associated with brachial plexus injuries were seen in 49 patients (36.56%). Fractures of the clavicle without

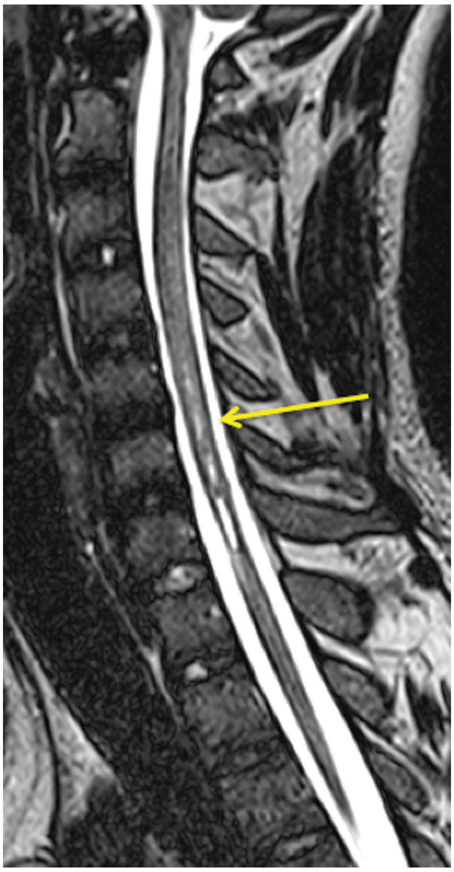

Fig. 4 Sagittal T2W image of a 22-year-old male with left-sided brachial plexus injury 6 months back showing T2 hyperintense signal in the cord (yellow arrow) due to myelomalacia.

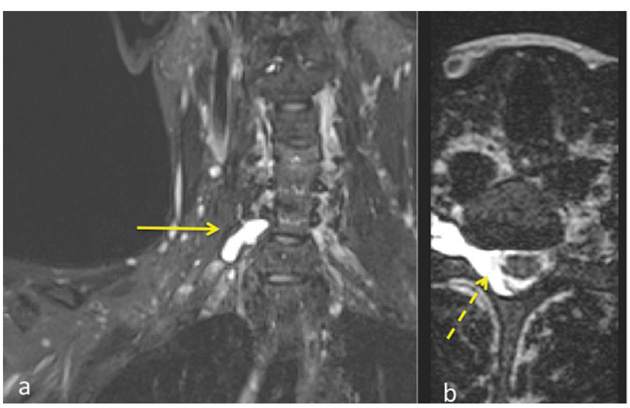

Fig. 5 Coronal 3D STIR SPACE image (**a**) and axial T2W fat saturated image (**b**) of a 24-year-old male with right-sided brachial plexus injury 5 months ago showing pseudomeningocele at right C7 level (solid yellow arrow) and avulsed roots (dashed yellow arrow).

extrinsic compression over the plexus were seen in 20 (14.9%) patients, whereas those causing extrinsic plexus compression were seen in 3 (2.2%) patients (►**Fig. 11**). Fractures of the rib, scapula, humerus, and vertebra were seen in 4 (3%), 14 (10.4%), 9 (6.7%), and 15 (1.2%) patients (►**Fig. 12**).

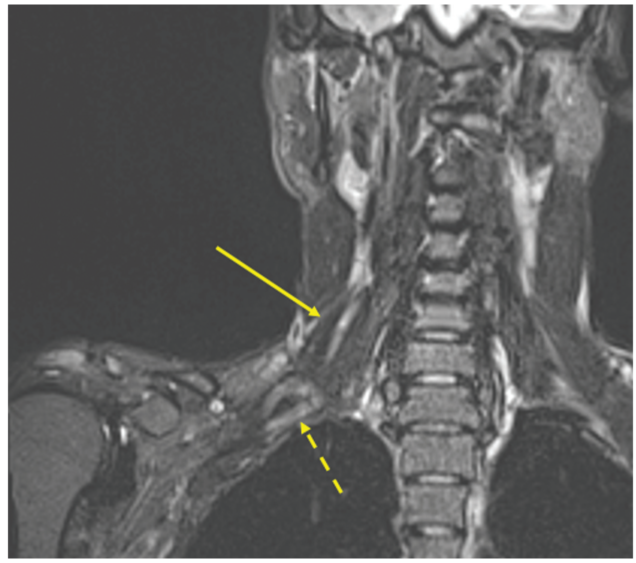

Fig. 6 Coronal 3D STIR SPACE image of a 20-year-old male patient with right-sided brachial plexus injury 3 months ago showing mild thickening with heterogeneously hyperintense signal suggestive of scarring in the C5 extra-spinal root (solid yellow arrow) and upper and middle trunks (dashed yellow arrow) with deformity of upper trunk.

Fig. 7 Coronal 3D STIR SPACE image of a 48-year-old male patient with left-sided brachial plexus injury 1.5 months ago showing hyperintense signal with clumping and mild contour deformity in the extraspinal roots, trunks, and cords (yellow arrow) suggestive of scarring.

Vascular Injuries

Vascular injuries with thrombosis in the subclavian artery, axillary artery, and axillary vein were seen in 1 (0.7%), 2 (1.5%), and 1 (0.7%) cases(►**Fig. 13**).

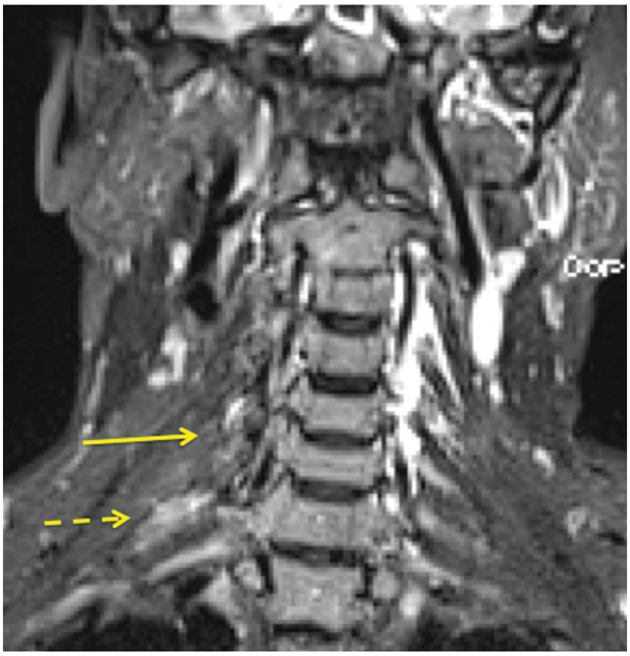

Fig. 8 Coronal 3D STIR SPACE image of a 38-year-old male patient with right-sided brachial plexus injury 8 months ago showing ruptured C5 and C6 extraspinal roots (solid yellow arrow) and scarred C7 extraspinal root (dashed yellow arrow).

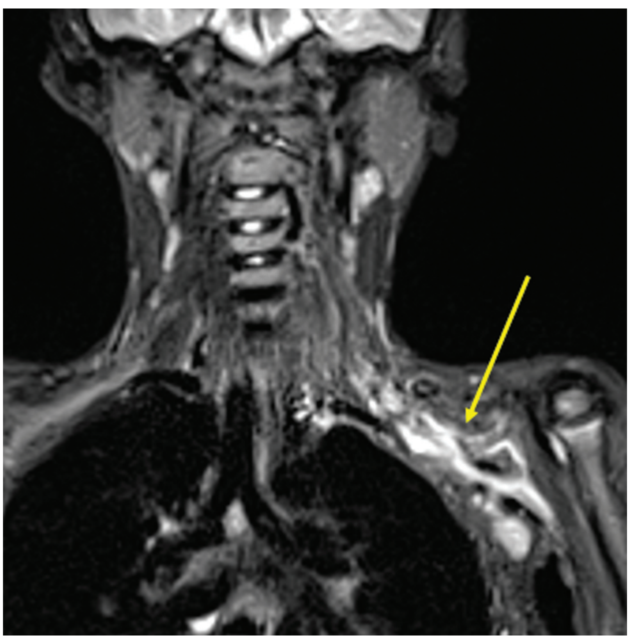

Fig. 9 Coronal 3D STIR SPACE image of an 8-year-old-boy with traction injury 3 weeks ago showing edema with deformed contour in the infra-clavicular plexus (yellow arrow).

Muscle Changes

Muscle denervation changes in supraspinatus, infraspinatus, and subscapularis were seen in 37 (27.6%), 41 (30.6%), and 39 (29.1%) cases, respectively. Most muscle changes were in the form of edema-like signal intensity (►**Fig. 14**). No changes in bulk or signal intensity were seen in other adjacent muscles. These findings are enlisted in ►**Table 5**.

Fig. 10 Coronal 3D STIR SPACE image of a 20-year-old male patient with left-sided brachial plexus injury 4 months ago showing small nodular hyperintense lesions in the left C6 extra-spinal root, suggestive of neuromas-in-continuity (yellow arrow).

Discussion

This study of patients with traumatic brachial plexopathy imaged by MRN, spanning nearly a decade, has led to several interesting observations. We included patients with all forms of trauma to the brachial plexus, even those with birth brachial plexus palsy. Hence, the age of our patients ranged from 6 months to 65 years.

The median age of patients was 23 years, and more than three-fourths of these patients were less than 30 years of age. Our findings are similar to other epidemiological studies performed on patients with traumatic brachial plexopathy. In a study by Jain et al, the majority of patients (45.72%) were in the third decade of life and the average age of patients was 24 years.[9] The average age of patients was 28.4 years in a study by Faglioni et al and 26 years in another study by Cho et al.[10,11] This is very unfortunate as these are the most productive years of life and loss of function of the affected upper limb can result in difficulty in performing basic daily activities, poor employment prospects, and psychological sequelae.

Men greatly outnumber women in this study, and are injured about 10 times more. A meta- analysis by Kaiser et al in adult patients with severe brachial plexus injuries had also found a male to female ratio of 13.3:1.[12] Most patients in this study were working in their own set-ups (33.6%) such as shops, or were tailors, or farmers. Unfortunately, this injury

Table 4 Number and percentage of patients with intraspinal and extraspinal injuries

SN	Level of injury	Number of patients	Percentage of patients
1.	Spinal cord	9	6.7
2.	Intraspinal roots		
a)	C5	14	10.4
b)	C6	29	21.6
c)	C7	51	38.1
d)	C8	38	28.4
e)	T1	16	11.9
3.	Extraspinal roots		
a)	C5	96	71.6
b)	C6	101	75.4
c)	C7	84	62.7
d)	C8	60	44.8
e)	T1	51	38.1
4.	Trunks		
a)	Upper trunk	112	83.6
b)	Middle trunk	101	75.4
c)	Lower trunk	101	75.4
5.	Cords		
a)	Medial cord	81	60.5
b)	Posterior cord	90	67.2
c)	Lateral cord	86	64.2
6.	Terminal branches	15	11.1

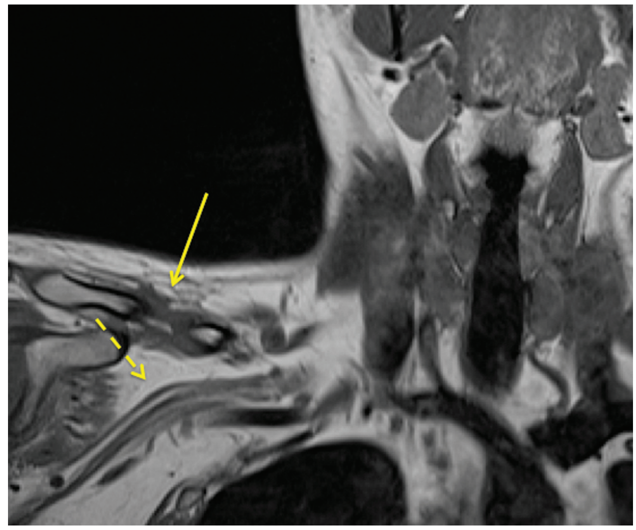

Fig. 11 Coronal T1W image of a 32-year-old male patient with right-sided brachial plexus injury 6 months ago showing a nonunited fracture in the right clavicle (solid yellow arrow), which is not causing extrinsic compression over the right brachial plexus (dashed yellow arrow).

Fig. 12 Sagittal T2W image of the same patient as ►**Fig. 8** showing multiple vertebral compression fractures.

had disastrous consequences for them, affecting their ability to sustain their livelihood. More patients were from urban areas (64.2%) as compared with rural areas (35.8%) which could be due to easier availability of motorcycles in cities, better roads enabling people to drive at higher speeds, and increased vehicular traffic on roads making accidents more likely.

All our patients had unilateral injury to the brachial plexus, and the right side (61.2%) was more commonly involved as compared with the left (38.8%). Faglioni et al, in contrast, found more patients with left-sided plexopathy in their study (54.1%) while Cho et al and Jain et al found more patients with right-sided plexopathy, seen in 57% and 60.97% patients, respectively.[9–11]

Majority of our patients ($n = 62$, 46.3%) presented for imaging between 1 and 3 months following trauma whereas the least number of patients ($n = 8$, 6%) were those whose injury was more than a year old. This has a definitive impact on patient management as timely intervention can decrease the degree of functional loss and facilitate early recovery. Cho et al noted that their patients presented within 3 days to 15 months after the injury and the majority of patients (25%) presented within the first month.[11]

Most patients in the present series ($n = 98$, 73.1%) sustained brachial plexus injury due to vehicular accidents. This may be due to people driving two-wheelers especially motorcycles at high speeds, poor compliance of traffic rules, and use of mobile phones while driving. This study also revealed a variety of other causes of traumatic plexopathy such as fall from height, fall of heavy object over the shoulder, fall over a sharp object, injury occurring during sporting activity such as cricket, working with animals in rural areas,

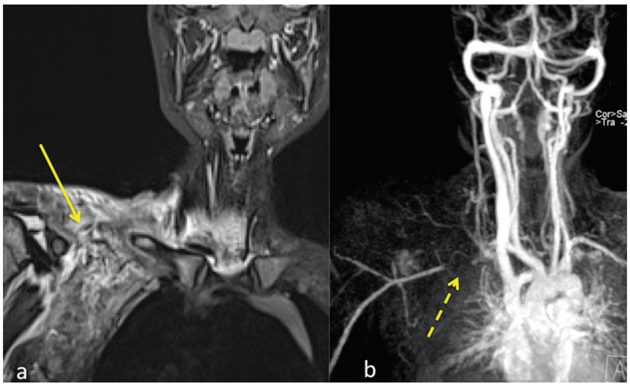

Fig. 13 Coronal 3D STIR SPACE image (**a**) and contrast-enhanced angiography image (**b**) of an 8-year-old girl who was injured in a road traffic accident 10 days ago showing right clavicular fracture and extensive edema in the region of right brachial plexus (solid yellow arrow) along with thrombus in the right subclavian artery (dashed yellow arrow).

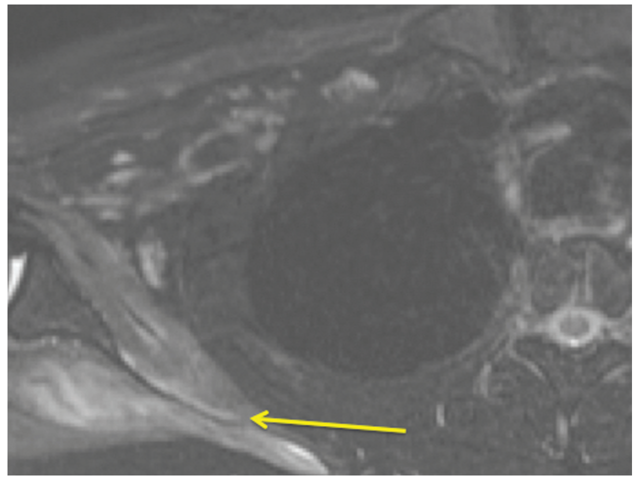

Fig. 14 Axial T2W fat-saturated image of patient with right sided brachial plexus injury showing edema-like signal intensity in the right infraspinatus and subscapularis muscles (yellow arrow).

injury while operating heavy machines and other occupational injuries, gunshot injury, nonpenetrating assault, and birth palsy. There was one case in which a 2-year-old child in a village had accidentally put his hand in a thresher machine.

In their study, Jain et al found that 94.4% of cases were due to road traffic accidents and 90.24% of these involved two wheelers. Other causes including industrial accidents, fall

Table 5 Number and percentage of patients with extraplexal injuries

S. No.	Extraplexal injuries	Number of patients	Percentage of patients
1.	Fractures		
a)	Fracture clavicle not causing extrinsic plexal compression	20	14.9
b)	Fracture clavicle causing extrinsic compression over the plexus	3	2.2
c)	Fracture rib	4	3.0
d)	Fracture scapula	14	10.4
e)	Fracture humerus	9	6.7
f)	Fracture vertebra	15	11.2
2.	Vascular injuries (thrombosis)		
a)	Subclavian artery	1	0.7
b)	Subclavian vein	–	–
c)	Axillary artery	2	1.5
d)	Axillary vein	1	0.7
3.	Muscle changes		
a)	Supraspinatus	37	27.6
b)	Infraspinatus	41	30.6
c)	Subscapularis	39	29.1

from height and fall of heavy object over the shoulder comprised just 5.59% of cases.[9] Faglioni et al attributed 79% of their cases of traumatic plexopathy to motorcycle accidents. Other causes such as car accidents, firearm injuries, and fall from height were only responsible for 2 to 4% of cases.[10] Cho et al found that road traffic accidents were responsible for brachial plexus injury in majority of their patients and 75% of these were motorcycle accidents.[11] Kaiser et al in their meta-analysis reported a pooled prevalence of 67% of motorcycle accidents causing closed injuries of the brachial plexus. Car accidents had a prevalence of 14% and other miscellaneous causes such as sports related injuries, occupational injuries, fall of a heavy object on the shoulder region had a prevalence of 10%.[12]

As far as the mechanism involved in these injuries is concerned, we found that blunt crush-avulsion of the plexus was seen in 83.6% of cases ($n = 112$), while penetrating injuries comprised only 6% ($n = 8$) and pure traction injury was seen in only 10.4% of cases ($n = 14$).

Panplexopathy with involvement of shoulder, elbow, and hand was seen in the majority of patients in this study ($n = 88$, 65.7%). There were 18.7% patients($n = 25$) with involvement of shoulder and elbow only, and the least number of patients ($n = 2$, 1.5%) were those who had only elbow involvement. Jain et al reported panplexopathy in 48.02% of their patients which comprised the majority of their cases.[9]

In MRN findings, spinal cord injuries were seen in 6.7% of cases ($n = 9$). These were due to edema in 3.7% cases ($n = 5$) and due to myelomalacia in 3% cases ($n = 4$). In patients with preganglionic plexal injuries, intramedullary altered signal intensity was seen in ~20% cases which may be due to hemorrhage, edema, or myelomalacia.[13] In our study, because imaging was done at least 4 weeks after the trauma, it is possible that mild degree of edema or hemorrhage would have resolved by the time the scan was done.

Intraspinal root injuries in the form of root avulsions and root sheath lacerations with pseudomeningocele were seen mostly at C7 level ($n = 51$, 38.1%). These were followed in decreasing order by injuries at C8 ($n = 38$, 28.4%), C6 ($n = 29$, 21.6%), T1 ($n = 16$, 11.9%), and C5 ($n = 14$, 10.4%) levels. A study in children with nonobstetric traumatic brachial plexopathy had shown root avulsions in 44% of patients, and most of these were seen at C7 (32.2%) and C6 (29.0%) levels.[4] Jain et al reported at least one root avulsion in 89% patients with traumatic plexopathy and 59% of these were at C7, C8, and T1 levels.[9] Narakas, in his landmark study, which included more than one thousand patients of traumatic brachial plexopathy gave the "7 times 70%" rule, according to which, 70% of patients were injured in road traffic accidents, 70% of these were driving motorcycles, 70% had combined injuries of which 70% lesions were supraclavicular, at least one root was avulsed in 70% of these cases and of these C7, C8, and, T1 roots were involved in 70% cases and chronic pain was noted in 70% of these patients with avulsions.[14]

There are central and peripheral mechanisms of root avulsions. After a major cervical injury, the roots get avulsed centrally when the spinal cord moves in a transverse or longitudinal direction resulting in shear forces and bending of the cord. When severe traction injury occurs, this damages the fibrous supporting structures around the roots and leads to peripheral root avulsion. The C5 and C6 roots have fascial vertebral attachments, which are strong and hence these roots get avulsed less often as compared with C7, C8, and T1 roots.[15]

Pseudomeningoceles are extradural CSF collections, which occur with root avulsion or root sheath laceration and they extend from the spinal canal into the neural foramina. These occur when roots get avulsed as the connective tissues of the nerve sheath merge with the arachnoid and dura mater. In ~23% of cases, roots can get avulsed without pseudomeningoceles, and conversely, pseudomeningoceles can be present in the absence of root avulsions in ~24% of the patients . Hence, their absence does not exclude root avulsion. Sometimes, pseudomeningoceles can extend beyond the neural foramina into the paravertebral soft tissues as well.[6,16]

The part of the brachial plexus distal to the dorsal root ganglion constitutes the post-ganglionic plexus. The post-ganglionic plexus is much more amenable to surgery as compared with the pre-ganglionic plexus. Most patients with severe trauma have a combination of both pre-ganglionic and post-ganglionic injuries, while patients with milder trauma have injuries confined to the post-ganglionic plexus with a better prognosis. MRN is the best imaging modality to visualize different injury patterns in the post-ganglionic part of the plexus including edema, scarring, rupture, or transection and neuromas. In post-traumatic edema, the nerves show hyperintense signal in fluid-sensitive sequences. When scarring occurs, the nerves can be thickened and clumped with distorted contour and show heterogeneous signal intensity. There is nerve discontinuity in cases of rupture. A neuroma is seen as a nodular soft tissue mass lesion along the nerve or at its ends.[4] A meta-analysis of adult post-ganglionic injuries by Leigheb et al revealed that MRI had a pooled sensitivity of 90% and pooled specificity of 90% for these injuries.[17]

Among the extra-spinal roots, most injuries were seen at C6 level (75.4%) and C5 level (71.6%). The upper trunk was more frequently injured (83.6%) when compared with the middle and lower trunks. Posterior cord injuries (67.2%) were more common than those in the medial and lateral cords. Scarring was the most common injury pattern at all these levels. According to Moran et al, brachial plexus injury in adults is more common in the supraclavicular plexus with involvement of roots and trunks as compared with the infraclavicular plexus with involvement of cords and terminal branches. Traction injury that occurs when the head and neck move in a direction opposite to that of the shoulder injures the C5 and C6 roots and superior trunk of the plexus. Traction injury that occurs when the arm is forcefully abducted overhead injures the C8, T1 roots, and inferior trunk of the plexus.[15] The supraclavicular plexus is more frequently injured in birth brachial plexus palsy also.[18]

Nerve injuries can be graded as per the Seddon and Sunderland classifications. Sir Herbert Seddon classified injuries into neuropraxia, axonotmesis, and neurotmesis. Neuropraxia is the mildest form of injury in which there is no structural damage and only a conduction block occurs, which resolves in around 3 weeks. MRN images show a mildly enlarged nerve with hyperintense signal in T2 images. In axonotmesis, there is axonal rupture but endoneurium, perineurium, and epineurium are spared. MRN findings include an enlarged nerve with T2 hyperintense signal and enlarged or disrupted fascicles. In neurotmesis, there is complete rupture of the nerve. If imaging is done early, MRN can show a disrupted nerve with a collection at the site of injury. Later, fibrosis and scarring occur at the injury site, which appear as T2 hypointensity, or a neuroma can be seen as a small nodular soft tissue signal lesion along the nerve or at its end.

Sunderland further classified nerve injuries into five types based on the degree of connective tissue involvement. Type I is similar to neuropraxia and Type II is similar to axonotmesis. In Types III and IV, there is disruption of the endoneurium and perineurium, respectively, which results in mild and moderate fibrosis. Type V is similar to neurotmesis in which the entire nerve with all connective tissue layers is disrupted. A sixth type was added by Mackinnon, which is a combination of Type II to Type V injuries. Until Type III, conservative management can be considered but Type IV to Type VI are high-grade injuries, which require surgical intervention.[3,6,19,20]

Some of the patients in this series had associated fractures in adjacent bones including the clavicle, ribs, scapula, humerus, and vertebrae. The clavicle was the most frequently fractured bone and clavicular fractures were seen in 14.9% of cases. This was followed by scapular fractures that were seen in 10.4% of cases. Jain et al reported fractures in 32% of their patients with traumatic plexopathy and these included 10% patients with clavicular fractures.[9] Fractures can cause extrinsic compression of the plexus due to hematomas and displaced bone fragments. Callus associated with clavicular fracture can also compress the adjacent plexus resulting in neuropathy.[21]

Only 3% of patients had associated vascular injuries, which included thrombosis in the subclavian and axillary vessels. The reason for this could be that most vascular injuries would have been managed as an emergency before the patient was referred for brachial plexus imaging. Vessels can be injured directly when there is penetrating trauma, or by displaced fracture fragments. Mild vascular injury can lead to the formation of pseudoaneurysms and these too can cause extrinsic compression over the plexus. In such cases, symptoms of plexopathy may appear days to weeks after the actual trauma.[22]

Associated muscle changes were seen in ∼30% of cases in this study due to muscle denervation. These were in the form of edema-like signal intensity in the supraspinatus, infraspinatus, and subscapularis muscles. This does not represent true edema but occurs due to fluid shift from the intracellular to the extracellular compartment.[20] Such changes were seen at imaging as the majority of our patients presented within the first 3 months after injury. Acutely denervated muscles can show abnormal enhancement in ∼24 hours after the injury. They appear hyperintense in fluid-sensitive sequences. Later on, in the chronic phase, muscles show fatty changes with T1 hyperintense signal, and decreased bulk.[23,24] Because the dorsal rami of the nerves, which form the brachial plexus, innervate the posterior paraspinal muscles, these can show similar changes in cases of preganglionic injury. However, assessment of the changes in paraspinal muscles was not a part of our observations for this study.

The findings of MRN have a significant impact on the management of patients with brachial plexus injuries as they facilitate surgical planning and prognostication of these patients by the treating surgeon. The type of injury (preganglionic, post-ganglionic, or mixed), its level (single or multi-level), extent and any associated perineural injuries can be determined. Patients who have pre-ganglionic intraspinal root avulsions or a combination of pre-ganglionic and post-ganglionic nerve ruptures or multilevel injuries are treated by distal nerve transfers, such as spinal accessory to suprascapular nerve transfer. Patients with postganglionic scarring without nerve rupture are treated by neurolysis. Patients with postganglionic nerve rupture at a single level undergo neck exploration with primary nerve repair or cable grafting. Those patients with postganglionic neuroma with distal nerve deficit are treated by neuroma excision and cable grafting. In case of neuroma with symptoms of nerve entrapment, fascicular neurolysis is done.

The imaging findings of this study were not correlated with either electrophysiological, or operative findings, which remain a limitation of the present study.

Conclusion

The authors shared their experience of imaging patients with traumatic brachial plexopathy by MRN. Majority of these injuries occur in young men from urban areas who usually present with panplexopathy. The most common mode of injury is road traffic accident, and blunt crush-avulsion is the most common mechanism of injury. Spinal cord injury in the form of edema and myelomalacia was seen in 6.7% of cases. Amongst the intra-spinal roots, C7 was most often injured (38.1%), in the form of avulsion or root sheath laceration. C6 extra-spinal root (75.4%), upper trunk (83.6%), and posterior cord (67.2%) were most commonly involved in postganglionic injuries in the form of scarring. Most common associated osseous injury was a fractured clavicle (14.9%). Associated muscle changes with edema-like signal intensity was noted in the supraspinatus, infraspinatus, and subscapularis muscles in ∼30% of patients. Only a few patients (3%) had associated vascular injury that included thrombosis in the subclavian and axillary vessles.

Conflict of Interest
None declared.

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