REVIEW

High-resolution 3T MR neurography of radial neuropathy

Neurographie RM 3T haute resolution de la neuropathie radiale

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Summary  The radial nerve is a continuation of the posterior cord of the brachial plexus and one of the major nerves that provide motor and sensory innervations to the forearm. MR imaging evaluation of the radial nerve pathology has been described in scattered case reports. Current high-field MR scanners enable high resolution and high contrast imaging of the peripheral nerves. This article reviews the 3 Tesla magnetic resonance neurography imaging of radial nerve anatomy and various pathologies affecting it with relevant case examples.

Introduction
Radial neuropathy is relatively uncommon [1] and comes third in the order of frequency among all the neuropathies that involve the large mixed nerves of the body [2]. Diagnosis of radial neuropathy is often difficult due to the vague presenting symptoms and frequently inconclusive results of the electrodiagnostic studies [1,3]. High-resolution ultrasound (US) and magnetic resonance neurography (MRN) have proven to be useful tools in confirming the presence of neuropathy and defining the source, region and extent of the abnormality [4—6]. Although MRN is more expensive than US, it is less operator-dependent and can depict subtle abnormal signal intensity changes in the affected nerve and denervated muscles, thereby confirming neuropathy. This article provides an overview of radial nerve anatomy and a spectrum of pathologies on 3 Tesla (T) MRN imaging.

Anatomy of the radial nerve
Posterior cord of the brachial plexus, which has contributions from C5 to T1 nerves, gives rise to the radial nerve. The radial nerve courses posterior to the proximal segment of the axillary artery. In the arm, it courses around the posterior aspect of the humerus in the spiral groove from medial to lateral (Fig. 1), and pierces the lateral...
intermuscular septum (LIS) to traverse between the brachialis and brachioradialis muscles (Fig. 2) [7]. At the level of the elbow joint, it enters the radial tunnel that is approximately 5 cm long, extending from the capitellum to the lower border of the supinator muscle (Fig. 1) [8]. Here, the radial nerve terminates into its superficial and deep branches. The superficial sensory branch runs deep to the brachioradialis muscle and innervates the skin of the radial side of the dorsum of the hand. The deep motor branch, the posterior interosseous nerve, travels to the back of the forearm (Fig. 2) and descends on the interosseous membrane, anterior to the extensor pollicis longus to the back of the hand. The radial nerve innervates the triceps, anconeus and brachioradialis muscles. The extensor carpi radialis longus and brevis may be innervated by the radial or the interosseous nerve [3]. All the other muscles of the dorsolateral aspect of the forearm are supplied by the posterior interosseous nerve [7]. In approximately 80% of the cases, the brachialis has a dual innervation from the musculocutaneous and radial nerves and the radial nerve usually innervates the inferolateral portion of the muscle [9].

Figure 1  Anatomical diagram demonstrating the radial nerve and its sites of entrapment. Common sites of radial nerve entrapment are indicated by asterisks.

Figure 2  Normal Nerve. a: axial T2 SPAIR image at the level of the spiral groove shows normal intermediate signal of the radial nerve (large arrow). Notice the abnormal T2 hyperintensity and enlargement of the musculocutaneous nerve (small arrow) and denervation change (edema like T2 signal) in the surrounding biceps brachii muscle for comparison in this case of musculocutaneous neuropathy. b–d: sequential axial T2 SPAIR images from other healthy volunteers show normal course and appearance of the radial nerve (large arrows) in the arm (b), at the elbow (c) and, dividing at the lower part of the radial tunnel (d). The relative positions of median (small arrows) and ulnar nerve (arrowheads) have been also marked. Notice normal appearance of biceps muscle in the Fig 2b.
Etiopathogenesis

Radial neuropathy may be seen in isolation or in association with other peripheral neuropathies or brachial plexopathy. The etiopathogenesis encompasses two groups of causes, one being related to systemic etiologies, such as diabetes mellitus, collagen vascular disease, vasculitis, etc.; and the other to local-regional etiologies, such as brachial plexopathy, nerve injury or entrapment, peripheral nerve sheath tumors or other mass lesions in the vicinity of the nerve, bony fracture, thickened LIS, tight or thickened aponeurotic fascia of supinator muscle and diffuse peripheral nerve lesions. MRN has a role in the evaluation of the latter group entities.

Clinical findings

Radial nerve compression or injury at the level of the brachial plexus, axilla or the proximal arm causes denervation changes of all muscles innervated by the radial nerve. Radial neuropathy at the level of the spiral groove relatively preserves the triceps function (elbow extension) [10], but interferes with the rest of the functions as mentioned above. Pain, paresthesia and/or sensory deficit in the radial nerve distribution may be observed in radial neuropathy at any of these levels [11]. Compression of the radial nerve in the radial tunnel may result in two different syndromes, namely the radial tunnel syndrome and posterior interosseous nerve (PIN) syndrome. Radial tunnel syndrome occurs in subjects performing repeated supination and pronation or forceful extension movement of the forearm [12]. Posterior interosseous nerve syndrome usually results from trauma, mass lesions and inflammation [3]. Radial tunnel syndrome predominantly presents with pain, paresthesia and numbness in the radial distribution of the wrist and hand [11], whereas posterior interosseous nerve syndrome predominantly presents with weakness of the extensor muscles of the digits [1,10]. On physical exam, positive Tinel sign may aid in localization of the anatomic site of injury/compression. In spiral groove syndrome, positive Tinel sign is noted at the site of the groove at the junction of upper 2/3 and lower 1/3 of the arm. However, in the radial tunnel syndrome, it is usually positive over the radial side of the forearm [10,13]. Compression of the superficial radial nerve results in Wartenberg syndrome. This often happens at the site where the nerve pierces the deep fascia to become subcutaneous between the tendons of the extensor carpi radialis longus and brachioradialis. It results from athletic activities with repeated supination and pronation of the forearm, as well as, from direct trauma to the arm [11].

Magnetic resonance neurography imaging evaluation of radial neuropathy

The protocol used for MRN of the upper extremity in author’s institution has been outlined in Table 1. Depending upon the field of view, a 4–8 channel flex coil or a dedicated elbow coil is commonly employed for imaging of the radial nerve on a 3-T magnet. Axial T1 weighted and axial T2 spectral adiabatic inversion recovery (SPAIR) imaging techniques tailored to the site of abnormality are used for primary interpretation of nerve size and signal characteristics. The SPAIR sequence is a frequently applied sequence on 3 T MRN imaging [14,15]. It uses varying flip angles and is thereby, more specific absorption rate (SAR) favorable than the short tau inversion recovery (STIR) sequence. It also provides better fat saturation than frequency selective fat suppressed spin echo image, while maintaining higher signal to noise ratio (SNR) than the STIR image [16,17]. The radial nerve demonstrates isointense signal intensity to the muscle on all imaging sequences, as opposed to the ulnar nerve, which may have an artifactual mild increased T2 signal intensity (SI) even in asymptomatic subjects (Fig. 2). A coronal proton density sequence is used to exclude space-occupying lesions along the length of the nerve and to detect any major internal derangement of the elbow joint. Isotropic 3D (dimensional) sequences, such as SPAIR SPACE (sample perfection with application optimized contrasts using varying flip angle evolutions, Siemens, Erlangen, Germany) and 3D DW-PSIF are used as problem solving techniques as they allow isotropic multiplanar reconstructions and maximum intensity projections. SPACE is a spin-echo 3D sequence with higher SNR than the 3D gradient echotype sequence, which can be acquired in acceptable time period of 5–6 minutes.

**Table 1  3 T MR Neurography examination protocol for the evaluation of radial neuropathy.**

<table>
<thead>
<tr>
<th>MR sequence</th>
<th>FOV</th>
<th>Base resolution</th>
<th>Slice thickness</th>
<th>TR/TE/TF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial T1</td>
<td>22</td>
<td>448</td>
<td>3</td>
<td>657/11/5</td>
</tr>
<tr>
<td>Axial T2 SPAIR TSE</td>
<td>22</td>
<td>448</td>
<td>3</td>
<td>4500/84/15</td>
</tr>
<tr>
<td>Sagittal PD SPAIR</td>
<td>38</td>
<td>704</td>
<td>6</td>
<td>4880/40/13</td>
</tr>
<tr>
<td>3D SPAIR Space</td>
<td>30</td>
<td>384</td>
<td>0.8</td>
<td>1020/91/119</td>
</tr>
<tr>
<td>3D DW PSIF</td>
<td>38</td>
<td>384</td>
<td>0.9</td>
<td>10/5/7</td>
</tr>
</tbody>
</table>

MR: magnetic resonance; TSE: turbo spin echo; SPAIR: spectral adiabatic inversion recovery; 3D DW-PSIF: three-dimensional diffusion-weighted reversed fast imaging with steady state precession (fat suppressed sequence with a diffusion moment-b value of 80–90 s/mm²); TF: Turbo factor; PD: Proton density.

Space is a single slab three-dimensional sequence with variable excitation pulse (sampling perfection with application optimized contrasts using variable flip angle evolutions, Siemens, Erlangen, Germany). Field of view (FOV) is presented in cm, slice thickness in mm, and TR/TE in ms.
and provides sub 1 mm in-plane resolution. 3D DW-PSIF also creates nerve selective images with vascular suppression due to its steady state nature and a low diffusion moment (Fig. 3). It is an isotropic steady state sequence (0.9 mm in-plane resolution) with low diffusion moment (b value=80 mm/s²), which suppresses the signal from the flowing protons, creating nerve specific images. The normal nerves show isointense SI on this sequence and the abnormal nerves show increased SI similar to T2 SPAIR sequence, while the SI of the adjacent hyperintense vessels is nulled. It is primarily for anatomic imaging with application of a low diffusion moment to keep enough SNR in the image. Use of higher b values (1000 mm/s²) for functional imaging, such as diffusion tensor imaging and tractography is currently in feasibility stages. The authors do not use intravenous contrast for entrapment and traumatic neuropathies in their practice. But, contrast enhanced scans are useful for characterization and better delineation of pathology in cases of inflammations, diffuse polyneuropathies and suspected mass lesions.

### Entrapment neuropathy

Common sites of radial nerve entrapment include areas of spiral groove and the radial tunnel; with the latter being more commonly observed (Fig. 1). At the spiral groove, the nerve may be entrapped by thickened lateral intermuscular septum (>2 mm) or prominent/tight tendinous arch of the lateral head of the triceps muscle [18]. The nerve may also get compressed at this level against the humerus in the classic syndrome of Saturday night palsy, where the patient, sometimes intoxicated with alcohol, sleeps on the outstretched arm or dangles the arm on the back of a chair for prolonged hours (Fig. 3) [19].
Within the radial tunnel, the radial nerve and/or its branches, most commonly the posterior interosseous nerve, may be compressed at any of the following locations: (1) the radiocapitellar joint by fibrous bands; (2) the tendinous edge of the extensor carpi radialis brevis muscle; (3) the radial recurrent artery and branches (leash of Henry); (4) the arcade of Frohse, representing the proximal tendinous edge of the supinator muscle [20], which is the most common of all (1); and (5) the distal end of the supinator muscle by a fibrous band (Fig. 1) [3,21]. On MRN, the neuropathy is demonstrated as focal or diffuse enlargement of the nerve, as well as increased T2 hyperintensity approaching the signal intensity of the adjacent vessels (Fig. 3). The highest degree of T2 hyperintensity is noted in the vicinity of the entrap-
Figure 5  Locoregional Space occupying lesion. Axial T2 fat saturated image in a 16-year-old boy presenting with shoulder and arm pain. Notice abnormal T2 hyperintensity of the encased radial nerve (arrow) by a biopsy proven osteosarcoma.

ment site with distal gradual normalization of the SI. This abnormal SI is related to various hypothesized mechanisms, e.g. proximal axoplasmic flow blockade, venous congestion and distal Wallerian degeneration changes. MRN can differentiate compressive from adhesive lesions. Radial nerve course deviations due to the adjacent mass lesions may also be noted. In our experience, focal twist in the nerve course due to fibrous bands or thickened intermuscular septum is best demonstrated on images reconstructed along the long

axis of the nerve (Fig. 3c). Although electrodiagnostic studies may confirm the presence of neuropathy, cross-sectional imaging is essential to detect the underlying cause of entrapment. Regional muscle denervation changes on MRN also serve as important secondary findings confirming neuropathy.

Figure 6  Benign peripheral nerve sheath tumor. Coronal STIR image in a 72-year-old man with chronic intermittent left arm pain. EMG study shows the presence of bilateral median neuropathies at the wrists and patchy brachial plexopathy. MR image shows an incidental benign peripheral nerve sheath tumor (schwannoma) arising from the radial nerve. Notice the classic target sign (small arrow) and tail sign related to minimal enlarged of the proximal radial nerve (larger arrow).

Figure 7  Schwannomatosis. Twenty-two-year-old man diagnosed with schwannomatosis (INI1 mutation) in adolescence with both central and peripheral tumors as well as both the central and peripheral symptoms. Coronal STIR image shows the peripheral nerve sheath tumor with classic target and tail signs related to proximal and distal radial nerve enlargement in the right arm (large arrow). Also, notice additional tumors in keeping with history of schwannomatosis (small arrows).

Figure 8  Diffuse neuropathy in neurofibromatosis type I (NF-I). Axial STIR image in a 41-year-old man, previously diagnosed with NF-I presenting with right elbow pain. Notice enlarged and abnormally T2 hyperintense radial (large arrow), median (small arrow) and ulnar (arrowhead) nerves with preserved fascicular appearance. No focal mass was detected in these diffusely enlarged nerves.
**Traumatic neuropathy**

Trauma is the most common cause of radial nerve injury at the level of the arm [11,12]. Common examples include displaced humeral bone fractures, improper use of axillary crutches, prolonged use of tourniquet at the upper arm, lateral or posterior intramuscular injections to the arm [3], and open surgery for reduction of humeral fractures [22]. Approximately 12% of humeral fractures result in radial neuropathy. This incidence is higher in fractures of the midshaft and significantly higher in open fractures [23,24]. Direct trauma can also affect the interosseous and superficial branches of the radial nerve.

In general, trauma can result in mild (neuropaxia—stretch injury), moderate (axonotmesis—partial or complete discontinuity of axons) or severe (neurotmesis—partial or complete discontinuity of nerve) nerve injuries [16,17].

Progress in the degree of nerve abnormality, often results in increased T2 signal abnormality and neuroma formation. Mild-moderate nerve abnormalities (Fig. 4) on MRN should be distinguished from focal neuromas and nerve discontinuity of severe nerve injury, which frequently require surgery. Electrodiagnostic studies cannot distinguish nerve in continuity from discontinuity and MRN is useful for preoperative planning.

**Tumors and tumor-like lesions**

Neoplasms, such as peripheral nerve sheath tumors (PNST) and lymphoma, as well as tumor-like conditions such as amyloidosis and perineurioma, can result in radial neuropathy apart from encasement or displacement by locoregional neoplastic space occupying lesions (Fig. 5) [25–27]. PNSTs are divided into benign peripheral nerve sheath tumors...
(BPNSTs), which are more common, and malignant peripheral nerve sheath tumors (MPNSTs). These tumors may occur sporadically or in association with neurocutaneous syndromes. The most common subtypes of BPNST are schwannomas and neurofibromas. Schwannomas are more common in the third to sixth decades of life. They mostly present as solitary tumors and may be seen as an incidental finding (Fig. 6). Multiple schwannomas of the radial nerve and other peripheral nerves usually occur in association with neurocutaneous syndromes (Fig. 7) [28,29]. Neurofibromas, however, occur at a younger age. Solitary neurofibromas involve the subcutaneous nerves and show no preference for a particular region of the body [30]. MPNSTs are more common in the third to sixth decade of life. These tumors comprise 10% of soft-tissue sarcomas. They are more common and occur at an earlier age in patients with neurofibromatosis. In these patients, as compared to the general population, tumors tend to be larger and of higher grade. MPNSTs are more likely to involve the major nerves, such as the brachial or sacral plexus and are usually located in the deeper soft tissues [31]. Currently, MR is the best imaging method for the diagnosis of PNSTs, with MRN showing a potential for better depiction of fascicular continuity or neural origin of the mass lesion. It not only differentiates the normal from abnormal nerves, but it also can depict the focal mass lesion, its relationship to the nerve and its fascicles, the extension to the surrounding bony and soft tissues as well as, diffusely thickened nerves (Fig. 8) [30]. Benign lesions typically appear as ovoid, round or fusiform masses with well-defined margins. On T2-weighted images, they demonstrate low signal intensity in the central portion and high signal intensity in the periphery, a sign referred to as “target sign” (Fig. 6) or a “fascicular sign”, as multiple rings with lower signal at the center. A tail sign depicting the proximity or abnormality of the adjacent nerve may be evident (Fig. 7). A “split fat sign” which can be seen on longitudinal T1-weighted images, when the well-defined tumor is surrounded by a layer of fat. These lesions may show variable or homogeneous enhancement on post-contrast imaging. MRN imaging can also demonstrate even mild degrees of atrophy in the innervated muscles. Presence of a mass lesion close to a nerve and atrophy of the regional muscles are suggestive of neural origin of the tumor. However, these signs may also be variably seen in MPNSTs. Malignancy is highly suspected when there are clinical findings of new onset pain/neurologic deficits and upon the presence of two or more of the following MR findings: ill-defined/invasive margins, peritumoral edema, largest diameter over 5 cm and heterogenous signal intensity on T1 and T2-weighted images [32,33].

Both T-cell and B-cell lymphomas have been reported to involve peripheral nerves and may cause peripheral neuropathy. There are scattered reports of involvement of the radial nerve with the resultant neuropathy and MR imaging has proven to be of value in the evaluation of these case (Fig. 9) [34—36]. Other neoplastic or non-neoplastic mass lesions, which originate from the tissues adjacent to the radial nerve, e.g. soft tissue sarcoma, lipoma, ganglion cyst, enlarged lymph nodes and aneurysm, can also cause radial neuropathy [37—44]. The high contrast and spatial resolution of MRN can help in the differentiation of PNSTs from other mass lesions, which are in proximity to the nerve. The PNSTs usually show an abnormal fascicular continuity with the mass lesion, which is not appreciated with extrinsic lesions. MRN studies in cases of suspected mass lesions should be performed with intravenous contrast for better delineation and characterization of the pathology.

**Miscellaneous conditions**

Brachial plexopathy may secondarily cause radial neuropathy. It may occur as a result of degenerative cervical spondylotic changes, trauma [45], primary and secondary neoplastic disorders, radiation, brachial neuritis, chronic inflammatory demyelinating polyneuropathy and multifocal motor neuropathy [46,47].

The radial nerve may also be involved in infectious or inflammatory conditions, especially autoimmune disorders.

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**Figure 10** Inflammatory neuropathy. Forty-one-year-old woman with left humeral pain and left wrist drop and no detectable radial nerve conduction at the spiral groove, clinically suspicious for brachial versus radial neuritis. Coronal MIP reconstruction image from 3D STIR SPACE sequence (a) shows normal symmetrical brachial plexuses. Axial T2 SPACE image (b) shows diffusely abnormal arm nerves, with most abnormality of the radial nerve (long arrow) and milder abnormality of the ulnar (arrowhead) and median nerves (small arrow) with preserved fascicular appearance in this case of autoimmune neuritis.
High-resolution 3T MR neurography of radial neuropathy

By defining the source, region and extent of the disorder, MRN provides useful additional information and should be considered in the diagnostic protocol of patients with suspected radial neuropathy.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

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