Introduction

Magnetic resonance imaging (MRI) can demonstrate normal anatomy as well as pathology of the digital nerves of the hand and fingers with high spatial and contrast resolution. As such, MRI can play an important role in the clinical work-up of a patient with hand neuropathy, and it provides valuable information about the extent and severity of traumatic and nontraumatic nerve abnormalities. Traumatic abnormalities are the most common lesions that affect the digital nerves with acute injuries occurring more frequently than chronic injury. In fact, the digital nerves are the most commonly transected peripheral nerves. Prompt identification and operative repair are needed, typically within 3 days of occurrence of the digital nerve injury to reduce early complications such as increased repair difficulty and infection, and late complications such as loss of nerve function and neuroma formation. Less common lesions that affect the digital nerves include infectious, inflammatory, and vascular abnormalities; benign and malignant neurogenic neoplasms are rare.

MRI plays an increasingly central role in the assessment of peripheral nerve abnormalities. Previous investigations of digital nerve injury with ultrasound have been performed and enrolled a limited number of patients, were highly operator dependent, and predated the widespread availability of 3 T clinical MRI. In cases of injury, MRI offers a noninvasive method for differentiating severe injury from less severe injury. Additionally, MRI features identify patients with severe nerve injury earlier and provide morphologic detail that are not available with electrodiagnostic testing. In nontraumatic cases, MRI allows for a preoperative diagnosis, lesion morphology characterization, and the determination of lesion extent, that all assist in surgical planning. The purpose of this article is to review the normal anatomy of the distal nerves of the hand, and to illustrate the spectrum of pathology that may occur by MRI.

Normal Anatomy of the Nerves of the Wrist and Hand

The median, ulnar, and radial nerves innervate the hand, each with respective sensory and motor branches. Variant anatomy is common. Figures 1 and 2 diagrammatically summarize the relevant anatomy and Figure 3 depicts this anatomy with MRI.

Median Nerve

The median nerve originates from the medial and lateral cords of the brachial plexus (C5-T1). Beyond the transverse carpal ligament, the median nerve splits into a smaller lateral and larger medial portion (Fig 1). The lateral portion gives a short recurrent motor branch for the thenar muscles, and then it divides into 3 proper volar digital nerves; 2 of which supply either side of the thumb and a third innervates the radial side of the index finger after the first lumbricalis muscle (Fig 1). The medial portion divides into 2 common volar digital nerves (Fig 1). The first runs between the index and middle fingers, dividing into 2 proper digital nerves and innervating the second lumbricalis muscle. The second common volar digital nerve gives 2 proper digital nerves and runs between the middle and ring finger (Fig 1). Each proper digital nerve supplies the dorsal distal phalanx via a
dorsal branch that joins the dorsal digital nerve (from the superficial branch of the radial nerve, Fig 2). The proper digital nerve divides at the end of each digit into 2 branches; one of which supplies the pulp of the finger and the other supplies the nail bed (Fig 2).

Although the median nerve usually courses through the carpal tunnel as a single nerve and gives rise to the digital nerves distal to the transverse carpal ligament, bifurcation of the median nerve proximal to the transverse carpal ligament is a relatively common anatomical variation, present in 1%-3.3% of individuals undergoing carpal tunnel release surgery (incidentally noted in Fig 3).10-11 High bifurcation of the median nerve can be an isolated finding or it can be associated with a persistent median artery (Fig 4) or an accessory long finger flexor superficialis.11,14 The median artery, an embryologic remnant, is present in 1.2%-23% of the population.15

In addition, there are anatomical variations in the origin of the recurrent or motor branch of the median nerve that innervates the thenar eminence. These variants can be described as extraligamentous takeoff, subligamentous takeoff, or transligamentous takeoff. The extraligamentous takeoff is considered as normal anatomy and reported in 46%-90% of individuals.12 In the extraligamentous takeoff, the recurrent branch arises from the median nerve distal to the carpal ligament on the radial side. In the subligamentous takeoff, the recurrent branch arises within the carpal tunnel. In the transligamentous takeoff, the recurrent branch perforates through the carpal ligament. There is also a rare fourth variant where the recurrent branch ramifies anterior and ulnar in location and a rare fifth variant where the recurrent branch is superficial to the carpal tunnel. Knowledge of these variations is important when detecting and characterizing neurogenic pathology.

**Ulnar Nerve**

The ulnar nerve originates from the medial cord of the brachial plexus (C8-T1).9 At Guyon canal, the ulnar nerve either divides into 1 (bifurcation) or 2 superficial sensory branches (trifurcation). The superficial sensory branches supply the ring and small fingers (Fig 1). The deep motor branch supplies the muscles of the hypothenar eminence (Fig 1). Variations of the ulnar nerve at the level of the wrist and hand are rare. There are, however, case reports of an anomalous location of the ulnar nerve in the carpal tunnel.16-18

**Martin-Gruber and Marinacci Communications**

In addition to anomalous anatomical variations of the nerves of the hand and wrist, there can also be anomalous connections between the nerves such that communicating nerve fibers run between median and ulnar nerves. For example, the Martin-Gruber anastomosis represents varied median to ulnar innervation to the intrinsic hand musculature. The Marinacci communication is essentially the reverse ulnar to median Martin-Gruber anastomosis.19 There are no reports in the literature on the imaging of these variations.
Radial Nerve

The radial nerve arises from the posterior cord of the brachial plexus (C6-C8). The superficial branch of the radial nerve provides sensation to the radial aspect of the dorsal hand, the dorsal thumb, index finger, long finger, and the radial half of the ring finger proximal to the distal interphalangeal joint (Fig 2). The superficial sensory branch can be seen in the first dorsal compartment traversing the extensor tendons in the anatomical snuff box (Fig 2).

Dynamic Effects of Hand Position

Cadaveric studies have demonstrated dynamic positioning of the neurovascular bundles at the base of the phalanx with changes in hand position. In the neutral or extended positions, the neurovascular bundles were ventral to the flexor digitorum superficialis tendon. With flexed position, the neurovascular bundle moves dorsal to the flexor digitorum superficialis. This change in position of the neurovascular bundle with flexion suggests that there may be an increased risk of neurovascular injury with extended or neutral hand positions, as the neurovascular bundle becomes more superficial.

MRI Techniques

High-resolution MRI with a combination of 2 dimensional and 3 dimensional techniques can be performed as previously reported by Mitchell et al. The sequences should ideally be designed to offer a combination of high soft-tissue contrast along with high spatial resolution (through plane: $\approx 0.4-0.5$ mm for 2-dimensional imaging and $\approx 1.0-1.5$ mm isotropic resolution for 3-dimensional imaging; matrix: 256 $\times$ 256 or higher). Hence, spin echo imaging is often used. Spin echo imaging offers more optimal signal-to-noise ratio (SNR) than gradient echo techniques, although volumetric sequences are available with gradient echo that offer higher spatial resolution than spin echo techniques. Owing to the higher inherent SNR, high-field 3 T imaging is preferred for the imaging of digital nerves and imaging using a 1.5 T magnet system can be performed in the setting of instrumentation in the field of view.

Uniform fat suppression for fluid-sensitive images and removal of pulsation artifacts by optimal assignment of phase- and frequency-encoding directions is necessary. In addition, nerve-selective imaging with diffusion weighting (with a diffusion moment of $\approx 80-200$ s/mm$^2$) has been described, to suppress the adjacent vascular signal, as well as enhance the relative nerve signal within the neurovascular bundle. However, as diffusion gradients are added to imaging, the SNR is reduced and the image quality can be compromised. Disadvantages of adding a diffusion gradient to a sequence also include the possibility of susceptibility to local inhomogeneities, sensitivity to motion artifacts, and a failure of fat suppression.

Fig. 3. Sequential axial PD MRI demonstrating normal anatomy of the nerves of the hand. (A) Proximal to the carpal tunnel the ulnar (U) and median nerves and superficial sensory branch of the radial nerve (R) are identified. (B) At the level of the carpal tunnel the median nerve (M) is deep to the flexor retinaculum and the ulnar nerve (U) is identified at Guyon canal (anatomical variant bifid median nerve is present). (C) Distal to the carpal tunnel, the median nerve gives rise to 3 common digital nerves (CDN) and the ulnar nerve bifurcates into the deep (D) and superficial (S) branches. (D) Each CDN gives rise to 2 proper digital nerves (PDN) supplying the ulnar (U) and radial (R) aspect of digits 1-3. The ring and small finger PDN arise from the ulnar nerve superficial sensory branch. The vascular pedicle (V) is dorsal to the PDN. PD, proton density.

Fig. 4. A 59-year-old woman with an incidentally noted persistent median artery (A). The patient had a history of carpal tunnel surgery with persistent median neuropathy. The median nerve (M) is enlarged and hyperintense on axial T2WI. T2WI, T2 weighted image.
**Expected Appearance of the Digital Nerves by MRI**

Typically, a digital nerve is expected to have intermediate signal on fluid-sensitive sequences. The isolated finding of minimal increase in the signal intensity of a peripheral nerve of interest as a sole abnormality is challenging to interpret. Increased nerve signal may reflect mild neuropathy but may also represent artifact related to technical factors such as failure of fat suppression. It is also important to be aware of the magic angle effect, a well-recognized artifact that results in increased signal in tendons as well as in nerves. In tendons, increasing the TE (> 40 ms) can overcome the magic angle artifact; however, in peripheral nerves, the high signal intensity related to magic angle artifact can persist at higher TEs (66 ms). It is important to keep these angle-specific signal alterations in mind when assessing peripheral nerve pathologic abnormalities.

Other primary nerve findings, such as changes in caliber and fascicular pattern, should be sought in addition to secondary findings of muscle denervation to support the diagnosis of neuropathy. In the absence of additional findings, high nerve signal that approaches adjacent vessels is more likely to be significant. Although there is no literature on the accuracy of MRI for the assessment of the digital nerves, there are limited data on MRI of neuropathy in the larger more proximal peripheral nerves of the upper extremity. For example, Jarvik et al prospectively assessed median nerve signal intensity and found MRI 91% sensitive for detecting carpal tunnel syndrome but less than 40% specific. Bäumer et al performed a similar investigation of the ulnar nerve at the elbow with MRI with higher specificity of 85% and sensitivity of 83%. Literature on the accuracy, sensitivity, and specificity of MRI for detecting nerve abnormalities exists in the lower extremities with similar sensitivities and specificities. However, there is no large-scale study investigating the accuracy of MRI for correlating peripheral nerve injury severity to surgical and histological classifications.

**Traumatic Abnormalities of the Digital Nerves**

**Classification of Nerve Injury**

Seddon et al first classified the severity of peripheral nerve injury into grade I-III (neurapraxia, axonotmesis, and neurotmesis), which was later expanded into 5 classes by Sunderland. Although an in-depth discussion of peripheral nerve injury classification is beyond this article’s scope, it is important to classify digital nerve injuries because higher grade injuries are associated with worse clinical outcomes. MRI can differentiate patients with severe injury (ie, transection or avulsion with grade V injury) that require operative intervention from patients with mild injury (neurapraxia or grade I injuries). It can take 2-3 weeks for findings to become apparent on electrodiagnostic tests, such as electromyelography, studies that have traditionally been considered the reference test for peripheral nerve injury. With recent advancements in nerve specific MRI, nerve signal changes can be seen 4 days after injury, allowing for an earlier and noninvasive identification of patients with peripheral nerve injury. MRI can provide information about nerve morphology and any associated soft tissue abnormalities that can be valuable for surgical planning, otherwise not available with electrodiagnostic testing.

Early identification of patients with high grade nerve injury is associated with improved clinical outcomes. The classification scheme of Mitchell et al describes the different MRI features of neurapraxia, axonotmesis, and neurotmesis. However, stringent MRI characteristics have not been defined for the different grades of axonotmesis. Importantly, by MRI, the presence of muscle denervation changes rules out neurapraxia and requires further exploration for the possibility of axonotmesis or neurotmesis, especially useful for the assessment of the more proximal nerves of the hand with motor branches. Note that the proper digital nerves are purely sensory nerves and disorders of the proper digital nerves are not associated with muscle denervation changes.

**Clinical Presentation of Digital Nerve Injury**

Although rare (0.3%-3% of hand injuries), injury to the digital nerves of the hand is associated with significant disability, and it commonly causes patients to be absent from work with a median absence of almost 2 months. Patients with digital nerve injury experience significant losses in hand dexterity, which increases their potential to have burns or lacerations. Injury most commonly occurs in males with a median age of 30 years, and happens at work, typically due to a penetrating injury from a knife or glass. The prognosis of patients with digital nerve injury is better in younger patients, with full recovery expected in children. Patients older than 40 years or with severe injuries or nerve avulsion have a worse prognosis.

The primary treatment of patients with suspected digital nerve injury is operative microvascular repair. Patients are classified at surgery, either as having complete nerve transection, or if the nerve is visually continuous at surgical exploration, as having “traumatic neurapraxia.” Patients with intact nerves at exploration represent approximately 12% of patients with digital nerve injury, and all such patients have been reported to have sensory recovery in 6 months of observation. This clinical classification of traumatic...
neurapraxia includes grade I–IV injury (Sunderland classification), a very wide range of nerve pathologies. Therefore, MRI offers the opportunity to further refine this clinical classification by differentiating patients with neurapraxia (Sunderland I) before surgery, and it may lead to potentially avoiding surgery.

MRI Appearance of Digital Nerve Traumatic Injuries

MRI can assist in the triage of patients with suspected nerve injury toward surgery by identifying nerve transection (with lack of nerve continuity). Less severe intermediate and high grade nerve injuries (axonotmesis) can be identified by the T2 or short tau inversion recovery (STIR) hyperintensity signal intensity of the nerves and muscles that are innervated. These nerve injuries may also have loss of the normal fascicular architecture on T1 weighted images. Abnormal T2 or short tau inversion recovery (STIR) hyperintensity signal in the adjacent muscles implies higher grade nerve injury (Sunderland grade II–IV), although injury to purely sensory nerves such as the proper digital nerves does not have associated skeletal muscle denervation. As seen in Figure 5, nerve enlargement implies higher grade injury (Sunderland grade III–IV) and is typically referred to as neuroma-in-continuity.

Neuroma formation occurs in patients due to abnormal nerve regeneration following injury and is more common in patients with delayed operative repair. Other factors associated with neuroma formation are chronic irritation, pressure, stretch, and improper repair of a prior neuroma. Abnormal nerve regeneration is believed to be caused by damage to the perineurium that normally acts as a barrier to regenerating axons. Damage to the perineurium incites disorganized axonal growth into the epineural tissues in a process called fascicular escape along with fibroblast, Schwann cell, and blood vessel proliferation ultimately resulting in neuroma formation.

Perineural fibrosis is the ingrowth of fibrous tissue adjacent to the digital nerves. Patients with chronic nerve injury or prior nerve repair are at increased risk of perineural fibrosis. The frequent presence of a sesamoid bone at the first metacarpophalangeal joint predisposes patients to this condition. It has been suggested that the presence or absence of enhancement after administration of intravenous contrast material could be used to distinguish perineural fibrosis from neuroma in Bowler’s thumb. The role of contrast material in detection or characterization of traumatic neuropathy, however, remains to be clearly defined.

Finally, MRI is useful for identifying soft tissue derangement adjacent to nerves. For example, MRI allows for the detection of tendon injury that is often present in association with nerve injury.

Infection of the Digital Nerves

Primary infection of the digital nerves is rare and is most commonly due to spread of an adjacent soft tissue infection as
seen in Figure 7. Direct infection of the digital nerves can be seen in patients with leprosy and digital neuropathy can be the presenting symptom in patients with pure neural leprosy.37 Mycobacterium leprae bacteria damage the Schwann cell basement membrane via a host immune response, causing peripheral nerve inflammation.37 Nerve dysfunction is caused by nerve swelling against an inflexible perineurium and fibrous tunnels (such as the carpal tunnel).37 In one case report, pure neural leprosy presented with multiple digital nerve abscesses.38 There are numerous closed synovial and subfascial spaces within the hand. Many of these spaces communicate and can lead to proximal and extracompartimental spread of infection with resultant neural compromise.39 There are rare case reports of a horseshoe abscess between the first and fifth flexor tendons presenting with dense anesthesia in the median nerve distribution owing to proximal spread of infection into the carpal tunnel via the radial and ulnar bursae.40

Fig. 8. A 57-year-old woman with eosinophilic fasciitis extending from the distal forearm into the carpal tunnel. Axial STIR (A) shows diffuse flexor and extensor compartment tenosynovitis proximal to the carpal tunnel. At the level of carpal tunnel, axial T2 weighted images (B) show hyperintensity of the median nerve with mild surrounding fascial edema. Sagittal STIR (C) shows the extent of the fascial inflammation in the distal forearm. STIR, short tau inversion recovery.

Inflammation and the Digital Nerves

Patients with connective tissue diseases such as rheumatoid arthritis (RA), systemic lupus erythematosus, Sjogren syndrome (SS), and systemic sclerosis can have an associated peripheral neuropathy. The proposed mechanism for neuropathy is secondary to a systemic vasculitis.41 Patients with RA can have peripheral neuropathy in approximately 10% of cases, which can overlap with symptoms of arthritis and be difficult to distinguish clinically.41,42 Peripheral neuropathy in patients with RA has been associated with anti–cyclic citrullinated peptide antibody positivity in one case series.42 Peripheral neuropathy in Lupus in recent studies has been seen in approximately 6% of patients, although older reports have suggested up to 50% of patients were affected.43 The incidence of peripheral neuropathy is similarly debated in the literature in SS with reports ranging from 2%-60%.44,45 The timing of neuropathy onset is also debated in SS with some reports suggesting neuropathy may precede sicca symptoms onset and the diagnosis of SS.44,45 Peripheral neuropathy in systemic sclerosis is very rare and seen in < 1% of patients.44 Figure 8 shows a rare case of median nerve inflammation at the carpal tunnel from eosinophilic fasciitis.

The digital nerves may rarely be involved in patients with Dupuytren disease. In Dupuytren disease, involvement is usually superficial with fibromatosis nodules confined to the palmar fascia. If fibromatosis involves the spiral cord in the digits, digital nerve impingement can occur as the palmar digital nerves are compressed against the relatively inelastic transverse metacarpal ligament.46

Vascular Abnormalities and the Digital Nerves

Digital nerve entrapment due to a vascular etiology such as a malformation, hemangioma, or arterial aneurysm is rare. More commonly, extrinsic digital nerve compression is due to an adjacent mass.47-49 There are a few case reports in the literature describing extrinsic compression caused by specific positions such as finger grips from laparoscopic surgery, heavy plastic bags hanging from the fingers, use of a walking stick, and certain hand positions in cheerleading.50-53 Vascular malformations have only been reported as a cause of digital nerve entrapment in 2 case reports previously in the literature.97-98 Figure 9 shows a hand venous malformation with digital nerve encasement.

Fig. 9. An 8-year-old girl with left hand venous malformation. Axial T1WI (A) and axial T2WI (B) show an extensive T2 hyperintense venous malformation encasing the neurovascular bundle of the index and ring finger (arrow). Coronal maximum intensity projection T2 (C) and subtraction fat-suppressed T1 weighted postcontrast images (D) show the proximal to distal (arrow) extent of the venous malformation. T1WI, T1 weighted image; T2WI, T2 weighted image.
Neoplasm of the Digital Nerves

Extrinsic compression of a digital nerve is often due to a mass, most commonly a ganglion cyst; giant cell tumors, lipomas, intraneural cysts, metastasis, and pacinian corpuscle hyperplasia are less frequent. Additionally, local muscle hypertrophy can be a cause of extrinsic compression. Figure 10 shows a case of digital nerve encasement caused by a giant cell tumor of the tendon sheath.

Benign Digital Nerve Neoplasms

Benign lesions of the digital nerves include schwannomas, neurofibromas, fibrolipomatous hamartomas, and glomus tumors. Schwannomas, the most common peripheral nerve tumor of the hand, are often slow growing, usually solitary, and are painless until symptoms of nerve compression appear. Neurofibromas have also been reported to involve the digital nerves, though less...
frequently than schwannomas.\textsuperscript{58,59} Multiple schwannomas can be seen in patients with schwannomatosis or neurofibromatosis type 2, whereas multiple neurofibromas can be seen in patients with neurofibromatosis type 1. The treatment of a solitary benign peripheral nerve sheath tumor is microsurgical resection and recurrence rates are very low with adequate surgical dissection.\textsuperscript{56} Figure 11 shows a case of neurofibromatosis type 2 affecting the digital nerves. Fibrolipomatous hamartomas are rare benign tumors of unknown etiology that most commonly affect the median nerve; however, there are case reports of involvement of the digital nerves and an association with macrodactyly.\textsuperscript{60,61} Glomus tumors can also affect the digital nerves; but are also rare with few case reports in the surgical literature.\textsuperscript{62-66} Figure 12 shows a case of a glomus tumor with digital nerve encasement.

\textbf{Malignant Nerve Lesions}

Malignant peripheral nerve tumors arising in the digital nerves are extremely rare. There are only 3 case reports in the literature of a malignant peripheral nerve sheath tumor arising in a digital nerve and other more common diagnoses should first be considered.\textsuperscript{67-69} Figure 13 shows a case of cutaneous squamous cell carcinoma with extensive digital nerve encasement.

\textbf{Conclusion}

MRI aids the clinical assessment of patients with digital nerve lesions by offering an accurate assessment of the extent and severity of nerve injury, and is helpful for the characterization of various benign and malignant pathologies affecting the nerves. Changes in nerve morphology and signal intensity are observed with the high spatial and contrast resolution of MRI, helping to classify abnormalities of the digital nerves. Importantly, MRI is useful for identifying patients for surgical intervention, thereby preventing late complications of nerve injury.

\textbf{References}