CLINICAL ORTHOPAEDICS AND RELATED RESEARCH
Number 383, pp. 7–20

Upper Extremity Peripheral Nerve Anatomy

Current Concepts and Applications

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The nerve anatomy of the upper extremity is studied constantly through surgical findings, electrodiagnostic studies, and cadaveric dissections. Although it is recognized that the anatomy is not changing rapidly, knowledge of the anatomic relationships and their significance is increasing. The purpose of the current study is to provide a comprehensive analysis of the nerve anatomy of the upper extremity to include innervation patterns, critical landmarks, and clinical applications, with particular focus on recent contributions in the literature.

Orthopaedic surgery is applied anatomy. The surgeon's ability to diagnose and treat his or her patients is dependent on a fund of knowledge about anatomy. Although the anatomy of the upper extremity is fairly constant, knowledge of anatomy is increasing rapidly. An overview of the peripheral nerve anatomy of the upper extremity is presented, with an emphasis on the most recent studies published in the literature.

RADIAL NERVE

Anatomy

The radial nerve, including the radial nerve proper and the posterior interosseous nerve, innervates the muscles of the extensor surfaces of the brachium and forearm. The radial nerve arises from the posterior cord of the brachial plexus and receives contribution from the fifth through eighth cervical roots. Anterior to the subscapularis, the posterior cord divides into the axillary and the radial nerves. The axillary nerve enters the quadrangular space, which is bounded by the shoulder capsule and subscapularis tendon superiorly, by the teres major inferiorly, by the long head of the triceps medially, and by the neck of the humerus laterally.[5,42] The radial nerve commences its decent into the arm by passing anterior to the latissimus insertion and dives into the triceps to lie on the posterior surface of the humerus approximately 97 to 142 mm distal to the acromion.[24] It has been observed that the radial nerve lies on the surface of the medial head of the triceps, rather than the bony sur-

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The Chief, Bureau of Medicine and Surgery, Navy Department, Washington, DC, Clinical Investigation Program, sponsored this report # 84-16-1968-932 as required by HSETCINST 6000.41A.

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face of the humerus, and does not do so until it crosses to the lateral aspect of the humerus along the spiral groove.[24] The lower portion of the radial nerve crosses the midline at an average of 15 cm from the distal articular surface and pierces the lateral intermuscular septum at approximately 122 mm (range, 88–152 mm) from the lateral epicondyle.[24,39,62] The radial nerve is relatively safe during a posterior approach to the humerus (splitting the triceps). In the posterior approach, the radial nerve is located 13 to 15 cm proximal to the joint line.[24,40] For lateral approaches to the humerus, the radial nerve is located approximately 7.5 to 10 cm proximal to the lateral epicondyle[24,40] (Fig 1). Above the elbow, the radial nerve innervates the long, lateral, and medial heads of the triceps and the brachioradialis.[26,42] Although several textbooks describe the brachialis as having dual innervation from the radial and musculocutaneous nerve,[26,42] Abrams et al[2] reported that only 50% of specimens had this dual innervation.

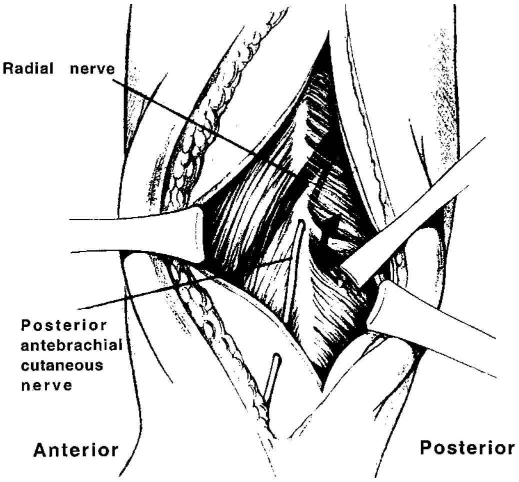

Fig 1. The position of the radial nerve piercing the intermuscular septum 7.5 to 10 cm proximal to the lateral intermuscular septum is shown. (Reprinted with permission from Mills WJ, Hanel DP, Smith DJ: Lateral approach to the humeral shaft: An alternative approach to fracture treatment. J Orthop Trauma 10:81–86, 1996.)

One to 3 cm distal to the lateral epicondyle and deep to the brachioradialis, the radial nerve splits into the superficial radial nerve and the posterior interosseous nerve.[38] The superficial radial nerve continues down the forearm along the lateral border of the brachioradialis and becomes subcutaneous at its middle ⅓, innervating the skin on the radial aspect of the forearm and the dorsal aspects of the radial three and one half digits[3] (Fig 2). The posterior interosseous nerve continues down the forearm diving into the supinator and then emerging to split into several branches that supply the extensors of the wrist and hand (Fig 3). The innervation pattern is important in determining levels of entrapment of the posterior interosseous nerve. The classic teaching is that the extensor carpi radialis longus, extensor carpi radialis brevis, brachioradialis (the mobile wad) and anconeus are innervated by the radial nerve proper before giving off the posterior interosseous nerve branch.[26,42] However, these findings have been challenged in several studies.[2,12] Branovacki et al[12] examined 60 arms from cadavers and observed the nerve to the extensor carpi radialis brevis originated from the posterior interosseous nerve in 45% of the specimens, at the bifurcation in 30%, and from the superficial branch of the radial nerve in 25%. Abrams et al[2] reported that 25% of the 20 arms from cadavers had extensor carpi radialis brevis innervation originating from the superficial branch of the radial nerve. Additionally they reported that 45% of the nerves to the extensor carpi radialis longus were branches from the posterior interosseous nerve.[2] Innervation of the common extensor origin at the level of the bifurcation of the posterior interosseous nerve is highly variable.

The order of innervation of the musculature (proximal to distal) is important in assessing entrapment syndromes of the radial nerve (Table 1). The most commonly accepted order of innervation (proximal to distal) is as follows: brachioradialis, extensor carpi radialis longus, extensor carpi radialis brevis, supinator, extensor digitorum communis, extensor carpi ulnaris, extensor digitorum minimus, ab-

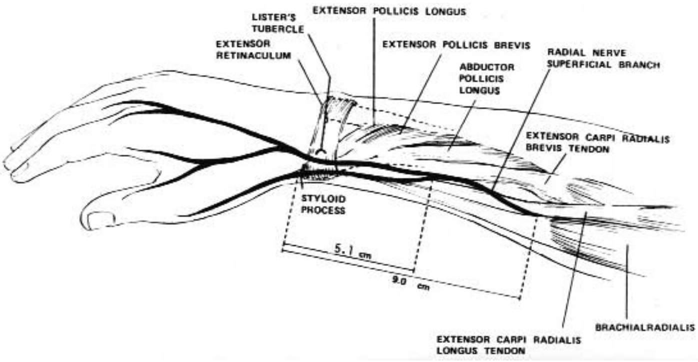

Fig 2. The usual position of the superficial branch of the radial nerve is shown. None of the branches are ulnar to Lister's Tubercle. (Reprinted with permission from Abrams RA, Brown RA, Botte MJ: The superficial branch of the radial nerve: An anatomic study with surgical implications. J Hand Surg 17A: 1037–1041, 1992.)

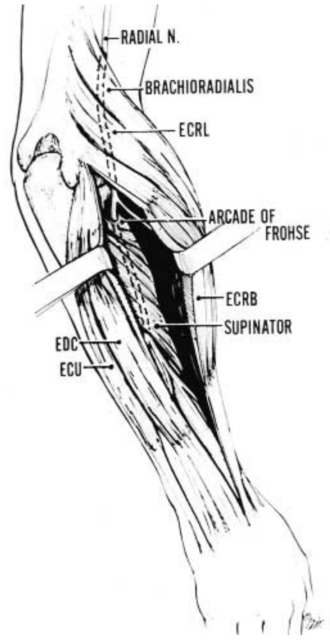

Fig 3. The position of the posterior interosseous nerve in the radial tunnel is shown. ECRL = Extensor Carpi Radialis Longus; ECRB = Extensor Carpi Radialis Brevis; EDC = Extensor Digitorum Communis; ECU = Extensor Carpi Ulnaris; N = nerve. (Reprinted with permission from Szabo RM: Entrapment and Compression Neuropathies. In Green DP, Hotchkiss RN, Pederson WC (eds). Green's Operative Hand Surgery. Ed 4. Philadelphia, Churchill Livingstone 1404–1447, 1999.)

ductor pollicis longus, extensor pollicis brevis, extensor pollicis longus, and extensor indicis proprious.[2,12,45] However, variability exists. Abrams et al[2] reported the extensor digitorum communis was innervated before the extensor carpi ulnaris in 60% of the arms and the most distally innervated muscle was the extensor indicis proprious in 75% and the extensor pollicis brevis in 25%. The terminal branch of the posterior interosseous nerve is a sensory branch to the dorsal wrist capsule and lies in the radial aspect of floor of the fourth dorsal compartment.

Clinical Applications of Radial Nerve Anatomy

Distal to its origin, the posterior interosseous nerve is prone to entrapment at several levels various structures. Classically posterior interosseous nerve entrapment is known as radial tunnel syndrome; however, this generic term fails to define the level of entrapment. The radial tunnel begins shortly after the bifurcation of the radial nerve (Fig 3). The posterior interosseous nerve passes deep to fibrous bands that are confluent with the brachialis, brachoradialis, extensor carpi radialis brevis and superficial head of the supinator, which forms the most proximal roof of the radial tunnel. These fibrous bands are the first structures that may compress the posterior interosseous nerve. Proximally, the floor of the tunnel consists of the capsule of the radiocapitellar joint. As the nerve travels distally,

TABLE 1. Motor Innervation by Nerve

Radial Nerve	Posterior Interosseous	Median Nerve	Anterior Interosseous	Ulnar Nerve
Brachioradialis	Supinator	Pronator teres	Flexor pollicis longus	Flexor carpi ulnaris
Extensor Carpi Radialis Longus	Abductor pollicis longus	Palmaris longus	Pronator quadratus	Flexor digitorum profundus (ring and small)
Extensor Carpi Radialis Brevis*	Extensor pollicis longus	Flexor carpi radialis	Flexor digitorum profundus (index and middle)	Adductor pollicis (deep head)***
Anconeus	Extensor pollicis brevis	Flexor pollicis brevis**		Opponens digiti minimi***
	Extensor indicis proprius	Abductor pollicis brevis**		Abductor digiti minimi***
	Extensor digitorium communis	Opponens pollicis**		Flexor digiti minimi brevis***
	Extensor digitorium minimus	Abductor pollicis (superficial head)**		Lumbricals 4,5***
		Lumbricals 2,3**		Interossei***

*Controversial; **Recurrent Motor Branch of the Median Nerve; ***Deep Motor Branch of Ulnar Nerve.

the floor is made of the deep head of the supinator muscle until the posterior interosseous nerve dives into the substance of this muscle. As the posterior interosseous nerve continues through the tunnel and reaches the level of the radial neck, the roof is made of recurrent vessels of the radial artery (Leash of Henry). The Leash of Henry is the second structure that may entrap the nerve. The posterior interosseous nerve then encounters the extensor carpi radialis brevis and gives off a branch to it (if the innervation comes from the posterior interosseous nerve). The extensor carpi radialis brevis may compress the nerve at this location. The posterior interosseous nerve passes beneath the sharp proximal edge of the supinator (Arcade of Frohse), which is the final location where it may be compressed. The posterior interosseous nerve finally transits through the supinator, on exiting its branches rapidly divide to innervate the forearm in the variable pattern previously described.[30,45]

Although radial tunnel syndrome and posterior interosseous nerve entrapment often are used interchangeably, they should be considered two separate entities. The symptoms of radial tunnel syndrome are mostly pain and often are confused with lateral epicondylitis. The pain associated with radial tunnel syndrome can be differentiated from lateral epicondylitis by location, because the pain associated with lateral epicondylitis is located at the epicondyle versus 6 to 7 cm distal over the belly of the brachioradalis in radial tunnel syndrome. Also, pain associated with radial tunnel syndrome often is provoked by resisted supination and repetitive forearm pronation or wrist flexion. However, because the posterior interosseous nerve is primarily a motor nerve, weakness is the hallmark of its entrapment. The posterior interosseous nerve gives off branches to the extensor digitorum communis, abductor pollicis longus, extensor digitorum minimus, extensor indicis proprius, extensor pollicis longus and extensor pollicis brevis distal to where it exits the supinator. Therefore, the presence of motor weakness with extension of the fingers or thumb with pain at the lateral aspect of the elbow should raise suspicion of posterior interosseous nerve entrapment. The mobile wad will be spared, because its innervation is proximal to the radial tunnel, allowing for full strength of extension of the wrist. The nerve to the supinator often comes off before the posterior interosseous nerve passing beneath the arcade of Frohse and into the supinator, thus the classic posterior interosseous nerve entrapment (or supinator syndrome), often will spare the supinator.[17,30,45–47]

As discussed previously, the terminal branches of the posterior interosseous nerve supply sensory innervation to the dorsal wrist capsule. Berger[6] was able to exploit this very consistent anatomic relationship to treat patients with chronic wrist pain with a neurectomy at a level 3 to 4 cm proximal to the distal radioulnar joint. In 22 of 24 patients treated with combined anterior and posterior interosseous neurectomies through a dorsal longitudinal approach, complete pain relief was observed at followup after 1 year. Objective improvement also was documented with a minimum increase in the patients' grip strengths of 10%.[6]

The superficial branch of the radial nerve is notorious for producing pain when injured. Abrams et al[1] examined 20 cadavers and found the superficial branch of the radial nerve most commonly (50% of the specimens) originated at the lateral epicondyle, or within 2.1 cm of it (Fig 2). They observed the superficial branch of the radial nerve coursed beneath the brachioradialis and emerged between the brachioradialis and the extensor carpi radialis longus and was subcutaneous at an average of 9 cm proximal to the radial styloid (range, 7–10.8 cm). The superficial branch of the radial nerve began to branch at an average of 5 cm proximal to the radial styloid (range, 3.2–7.1 cm). None of the 20 specimens had branches ulnar to Lister's tubercle.[1] Auerbach et al[3] dissected 20 arms from cadavers and found similar branching landmarks of the superficial branch of the radial nerve. However, Auerbach et al[3] observed three to 10 branches distally opposed to the two to three branches observed by Abrams et al. Auerbach et al also reported that branches in 12 of the 20 specimens were directly over the location for the three to four arthroscopic portal and 16 of 20 specimens had branches directly over the radial styloid, which placed it at risk during a de Quervain's release.[3] Because of numerous branching patterns in this area, the superficial branch of the radial nerve is highly susceptible to injury from placement of pins, wires, or external fixation pins. As such, most surgeons recommend at least a limited open approach in this area to avoid injury to this nerve.[25,28,55]

In 1932, Wartenberg[65] first described entrapment of the superficial branch of the radial nerve in five patients as entrapment of the superficial branch of the radial nerve between the brachioradialis and extensor carpi radialis longus. Its symptoms usually are numbness and dysesthesias over the dorsal and lateral aspect of the hand; however, it also can manifest as a tender area to palpation. Braidwood[10] documented 12 patients with superficial branch of the radial nerve entrapment who all had a positive Tinel's sign at the radial styloid. However, his series included three patients who had previous de Quervain's releases, which may have represented neuromas rather than an entrapment.[10] The classic description of superficial branch of the radial nerve entrapment is that of compression between the fascia of the brachioradialis and extensor carpi radialis longus in the pronated wrist.[57] The key factor involved in entrapment of the superficial branch of the radial nerve is the point at which it emerges beneath the brachioradialis. In 143 patients treated for entrapment of the superficial branch of the radial nerve, Turkof et al,[61] observed that seven patients had a split brachioradialis tendon. In these seven patients, the superficial branch of the radial nerve emerged from between the two slips of tendon rather than the fascia of the brachioradialis and extensor carpi radialis longus, placing it in a position vulnerable to compression.[61] Wartenberg's syndrome is a poorly understood condition, which often is misdiagnosed as de Quervain's syndrome, and is understood easier by the anatomic relationship and innervation pattern.

MEDIAN NERVE

Anatomy

The medial and lateral cords of the brachial plexus emerge from beneath the pectoralis minor's attachment to the coracoid process of the scapula and split. The more lateral branch of the lateral cord is the musculocutaneous nerve, which has contributions from C5–C7. The musculocutaneous nerve dives into the coracobrachialis at approximately 5 to 8 cm distal to the coracoid and travels between the biceps and brachialis, innervating the coracobrachialis, long and short heads of the biceps, and half of the brachialis. The musculocutaneous nerve terminates as the lateral antebrachial cutaneous nerve of the forearm providing sensation of the lateral volar surface of the forearm. The median nerve has contributions from essentially the entire brachial plexus (C5-T1), and is formed by portions of the lateral and medial cord.[5,26,42]

The median nerve does not provide motor or sensory innervation until it reaches the elbow. Motor branches most commonly are found at the level of the elbow flexion crease, however, branches have been seen as far as 4 cm proximal to the elbow.[18] The median nerve courses down the arm within the lateral intermuscular septum, deep to the short head of the biceps and lateral to the brachial artery. At the midbrachium, it crosses to the medial side of the brachial artery and descends to the antecubital fossa. In the antecubital fossa, the median nerve lies deep to the bicipital aponeurosis, medial to the antecubital vein, and medial to the brachial artery, making it the most medial structure encountered with the exception of the common origin of the flexor and pronator tendons (Fig 4). Although the median nerve is anterior to the trochlea and superficial to the brachialis, it occasionally can be found medial to the trochlea, such that it lies anterior to the medial epicondyle.[49] This is of clinical importance in elbow dislocations. In theory, the nerve would be at greater risk of entrapment within the joint and in surgical fixation of medial epicondyle fractures.

Distal to the elbow, the median nerve courses down the forearm deep to the flexor digitorum superficialis and superficial to the flexor digitorum profundus. In the distal ⅓ of the forearm, the median nerve emerges from beneath the flexor digitorum superficialis to lie medial to the flexor carpi radialis and lateral to the palmaris longus, before entering the carpal tunnel. The most consistent order of branches off the median nerve is the pronator teres, flexor carpi radialis, flexor digitorum superficialis, palmaris longus, anterior interosseous nerve, and terminal or recurrent branches to flexor digitorum superficialis and palmaris longus (Table 1). The innervation to the pronator teres is proximal to the elbow, whereas the remaining muscles are innervated distal to the elbow.[23] The median nerve gives a palmar cutaneous branch that provides sensation to thenar skin of the palm, and is most commonly branches 4 to 5 cm proximal to the wrist, lying on the ulnar side of the flexor carpi radialis (Fig 5). The palmar cutaneous branch

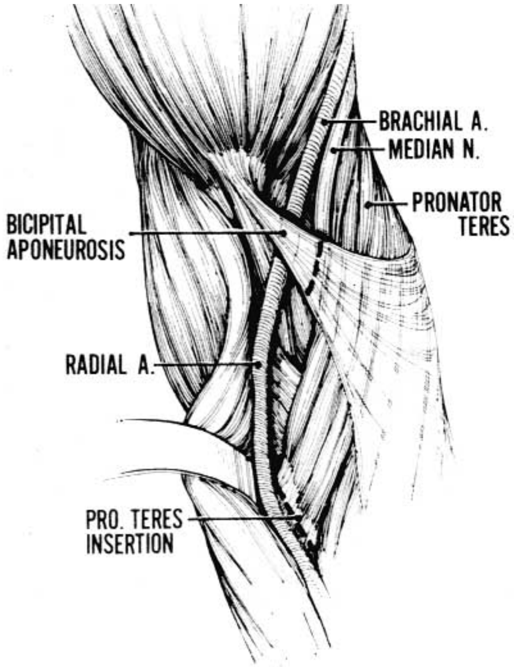

Fig 4. The median nerve in the antecubital fossa, the most medial structure in this region is shown. A = artery; N = nerve; Pro = Pronator. (Reprinted with permission from Szabo RM: Entrapment and Compression Neuropathies. In Green DP, Hotchkiss RN, Pederson WC (eds). Green's Operative Hand Surgery. Ed 4. Philadelphia, Churchill Livingstone 1404–1447, 1999.)

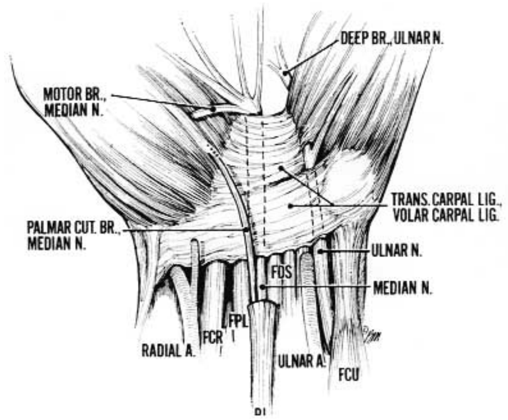

Fig 5. The median nerve and palmar cutaneous nerves at the wrist are shown. A = artery; BR = branch; FCR = Flexor Carpi Radialis; FPL = Flexor Pollicis Longus; FDS = Flexor Digitorum Superficialis; FCU = Flexor Carpi Ulnaris; N = nerve. (Reprinted with permission from Szabo RM: Entrapment and Compression Neuropathies. In Green DP, Hotchkiss RN, Pederson WC (eds). Green's Operative Hand Surgery. Ed 4. Philadelphia, Churchill Livingstone 1404–1447, 1999.)

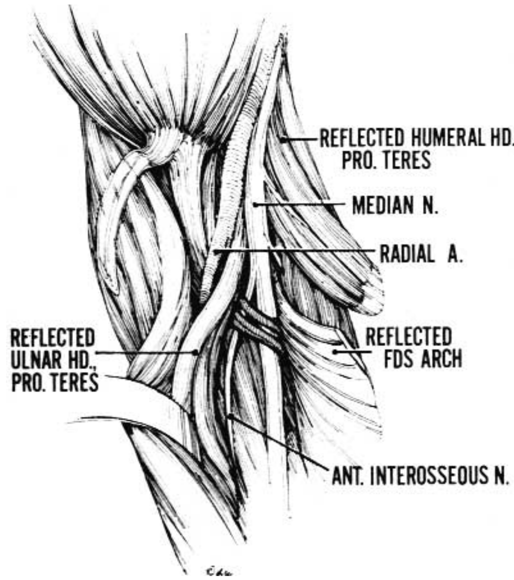

Fig 6. The median nerve giving off the anterior interosseous nerve at the elbow is shown. HD = Head; Pro = Pronator; FDS = Flexor Digitorum Superficialis; Ant = Anterior; N = nerve. (Reprinted with permission from Szabo RM: Entrapment and Compression Neuropathies. In Green DP, Hotchkiss RN, Pederson WC (eds). Green's Operative Hand Surgery. Ed 4. Philadelphia, Churchill Livingstone 1404–1447, 1999.)

divides into a radial branch that supplies the skin at the base of the thenar eminence and an ulnar branch that supplies part of the palm.[5,18,26,42,64] The ulnar branch of the palmar cutaneous branch often is found to penetrate the transverse carpal ligament before innervating the skin of the palm. Therefore, radial placement of the incision for a carpal tunnel release places this nerve at risk.[59]

The pronator teres has of two heads of origin, a humeral head which is part of the common origin of the flexor and pronator tendons of the medial epicondyle and an ulnar head that originates distal to the coronoid process of the ulna. At the level of the junction of the two heads of the pronator teres, the median nerve gives off the anterior interosseous nerve (Fig 6). The anterior interosseous nerve quickly dives deep to the flexor and pronator mass and travels with the anterior interosseous artery (a branch of the ulnar artery) to travel on the volar surface of the interosseous membrane. Along its course, the anterior interosseous nerve innervates the flexor pollicus longus, pronator quadratus, and the flexor digitorum profundus to the index and middle finger before terminating as the sensory fibers to the volar capsule of the carpus.[6,18,26,42]

The proximal wrist flexion crease identifies the proximal edge of the carpal tunnel, which extends to the midpalm and ends at the base of the third metacarpal. The boundaries of the carpal tunnel are formed by the carpal bones (the floor), the hook of the hamate (ulnar wall), the trapezium (radial wall), and the transverse carpal ligament (the roof). Ten structures, nine tendons (four flexor digitorum superficialis, four flexor digitorum profundus and flexor pollicus longus), and the median nerve traverse the carpal tunnel. Within the carpal tunnel, the median nerve divides into three terminal branches. The lateral branches supply the thumb and radial side of the index finger and the terminal branches of the medial division supply the middle finger and radial aspect of the ring finger. The lateral-most division gives off the terminal motor innervation of the median nerve, the recurrent motor branch, that innervates the abductor pollicis brevis, flexor pollicis brevis, opponens pollicis, and the lateral two lumbricals before to dividing into its terminal sensory branches[33] (Fig 5). The recurrent motor branch is of particular interest because it has been observed to have a variable location of origin.[43] Papathanassiou[43] described three variations, the most common of which had the nerve originating beyond the carpal tunnel (46%), within the tunnel but traversing to the thenar eminance distal to the tunnel (31%), and finally, one that originated within the tunnel and pierced the transverse carpal ligament (23%). Recently, Kozin[32] studied 100 cadavers and found that the recurrent motor branch in only 7% was interligamentous (Type I); moreover, he reported that 93% were distal to the transverse carpal ligament, 74% had passed through separate obliquely oriented fascia that originated on the transverse carpal ligament (Type II), and 19% did not pass through the obliquely oriented fascia (Type III). Stancic et al[56] reported eight variations of the take off of the recurrent branch. The most interesting was the presence of an accessory branch in 21% of specimens that arose at the proximal and distal ends of the carpal tunnel. These authors emphasized that branches of the median nerve must be visualized during a carpal tunnel release.[56]

Clinical Applications of the Median Nerve

The median nerve may become entrapped proximally or distally. There are two proximal entrapment syndromes, the pronator syndrome and the anterior interosseous syndrome, which have similar symptoms making them difficult to differentiate. The pronator syndrome occurs when the median nerve proper is compressed at the level of the elbow, and may be compressed by four different structures; the proximal ligamentous attachment of the humeral head of the pronator teres (ligament of Struthers), lacertus fibrosis, muscle belly of the pronator, or the proximal edge of the flexor digitorum superficialis. The ligament of Struthers is seen 5 cm proximal to the medial epicondyle and is a fibrous band that interconnects a bony spur on the distal humerus to the medial epicondyle (Fig 7). The symptoms of pronator syndrome include pain in the proximal volar forearm that may be associated with weakness, and numbness of the radial digits. Provocative maneuvers can localize the level of entrapment. Symptoms reproduced by resisted elbow flexion suggest compression at the ligament of Struthers. Conversely, symptoms initiated by flexion against a pronated wrist or resisted supination in a flexed elbow would suggest compression at the lacertus fibrosis. Finally, symptoms brought on by resisted pronation with the forearm stabilized on a table implicates the proximal edge of the flexor digitorum superficialis. Patients with

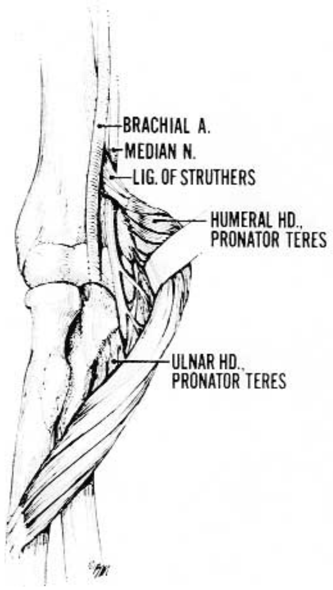

Fig 7. The ligament of Struthers and it relationship to the median nerve is shown. A = artery; HD = Head; Lig = Ligament. (Reprinted with permission from Szabo RM: Entrapment and Compression Neuropathies. In Green DP, Hotchkiss RN, Pederson WC (eds). Green's Operative Hand Surgery. Ed 4. Philadelphia, Churchill Livingstone 1404–1447, 1999.)

compression of the anterior interosseous nerve also may present with pain at the volar elbow and forearm. However, the differentiating feature is the lack of sensory symptoms in the fingers. Although there may be weakness of the flexor pollicus longus and flexor digitorum profundus to the index finger with anterior interosseous nerve compression, the thenar muscles should be spared and electrodiagnostic studies may be helpful in differentiating these syndromes.[18,21,22,27]

No discussion of median nerve entrapment would be complete without mentioning carpal tunnel syndrome. The significance of this diagnosis is evidenced by the approximately 500,000 decompressions performed per year in patients in the United States.[64] Symptoms of carpal tunnel syndrome manifest as numbness and dysesthesias in the radial three and one half digits of the hand and in the most severe cases it progresses to weakness in the thenar musculature. Kozin et al[33] showed the significance of the thenar intrinsics to grip strength through selective blocks of the median nerve at the level of the wrist and found that grip strength decreased 32% and pinch decreased 60% after blockade. Although a complete discussion of carpal tunnel syndrome and the psychosocial aspects of its diagnosis are beyond the scope of the current study, the anatomic relationships of the recurrent motor and palmar cutaneous branches are worthy of mention. It cannot be overemphasized that a radial incision places the palmar cutaneous branch at risk of injury and may cause a painful neuroma; however, an ulnarly placed incision places the ulnar nerve at risk in Guyon's Canal. The surgeon also should be mindful of the recurrent motor branch, the anatomy of which is variable. The general location of the recurrent motor branch often can be localized by the intersection of Kaplan's Cardinal Line (a parallel line drawn on the superior boarder of the abducted thumb) and a line drawn distal to proximal from the second web space.[64]

ULNAR NERVE

Anatomy

After the medial cord of the brachial plexus gives off is contribution to the median nerve, the terminal branch continues into the axilla as the ulnar nerve with contributions from the eight cervical and first thoracic, with occasional contributions from C7. The ulnar nerve courses with the axillary artery and vein, and lies deep to the pectoralis minor. As the ulnar nerve passes through the axilla into the brachium, it lies superficial to the subscapularis, teres major, and the latissumus dorsi's tendinous attachment to the proximal humerus. The ulnar nerve is deep to the pectoralis major and courses medial to the brachial artery emerging from beneath the pectoralis major, medial to the coracobrachialis and anterior to the long head of the triceps. At the level of the distal attachment of the coracobrachialis to the humerus (average 10 cm proximal to the medial epicondyle),[14] the ulnar nerve pierces the medial intermuscular septum to enter the posterior compartment of the brachium. Here it lies on the anterior border of the medial head of the triceps (Fig 8).

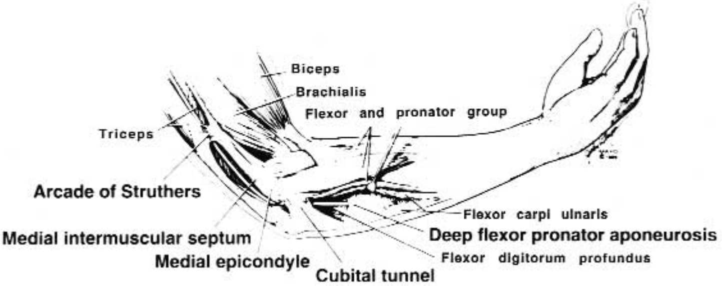

Fig 8. The locations of ulnar nerve entrapment are shown. (Reprinted with permission from the Mayo Foundation and Amadio PC: Anatomic basis for a technique of ulnar nerve transposition. Surg Radiol Anat 8:155–161, 1986.)

A thick fascial band that connects the medial head of the triceps to the intermuscular septum crosses the ulnar nerve at approximately 8 cm proximal to the medial epicondyle (the arcade of Struthers). Found in approximately 70% of the population, the arcade of Struthers is more common than the ligament of Struthers (median nerve entrapment) which is found in 1% of the population.[60] The ulnar nerve moves into a position that is posterior to the medial humeral condyle, wrapping around the medial epicondyle at the level of the elbow. As the nerve passes posterior to the epicondyle, it is encased within a fibrous sheath (Osborne's ligament) laterally, and the head of the flexor carpi ulnaris posteromedially. Together, these two structures form the cubital tunnel. The first branch of the ulnar nerve provides sensory innervation to the elbow capsule.[5,26,29,42,48]

As the ulnar nerve exists the cubital tunnel, it courses between the two heads of the flexor carpi ulnaris and enters the anterior compartment of the forearm (Fig 8). Shortly after exiting the cubital tunnel, the ulnar nerve gives off motor branches to the flexor carpi ulnaris. It then lies on the anterior surface of the flexor digitorum profundus. At approximately 5 cm distal to the medial epicondyle, the ulnar nerve gives off branches to the ulnar aspect of the flexor digitorum profundus providing innervation to the long flexors of the ring and small fingers. Recently, Bhadra et al[7] studied 20 forearms from cadavers and found the flexor digitorum profundus to the long finger had dual innervation from the ulnar nerve and the anterior interosseous nerve in 75%. In the middle of the forearm, at approximately 12 cm distal to the medial epicondyle,[14] the ulnar nerve becomes superficial and meets with the ulnar artery as it travels toward the wrist. Before the flexor carpi ulnaris becomes tendinous, the ulnar nerve divides. The more superficial of the two branches courses dorsally toward the distal ulna and dorsum of the hand and becomes the dorsal sensory branch of the ulnar nerve. Botte et al[8] dissected 20 specimens and showed the dorsal sensory branch originated 8.3 cm proximal to the pisiform and 6.4 cm proximal to the ulnar head. The dorsal sensory branch of the ulnar nerve emerged from beneath the flexor carpi ulnaris approximately 5 cm proximal to the pisiform and became subcutaneous with an average of five branches observed (range, 3–9 branches) that supplied the dorsal ulnar side of the hand.[8] Lourie et al[37] found similar values, however, they observed the presence of a branch to the distal radioulnar joint and the overlying skin in 20 of 24 specimens, indicating a broad sensory innervation of the dorsoulnar wrist from the ulnar nerve that may be at risk when approaching the distal ulna. An inconsistent palmar contribution of the ulnar nerve to the palm, the palmar cutaneous branch of the ulnar nerve (Nerve of Henle) arises proximally, approximately 5 to 11 cm distal to the medial epicondyle and carries innervation to the hypothenar skin and sympathetic fibers to the ulnar artery. Recently, Balogh et al[4] were only able to show its presence in 58% of the 30 specimens they dissected.

Near the wrist the ulnar nerve rises superficial to the flexor retinaculum and lies under the tendon of the flexor carpi ulnaris before its attachment to the pisiform (Fig 9). The ulnar nerve then turns radial to the pisiform to lie in a fibrous tunnel known as Guyon's Canal (Space or Tunnel) whose floor is made mostly of the transverse carpal ligament, but also the flexor digitorum profundus, pisohamate and pisometacarpal ligaments, and the opponents digiti minimi. The roof of the canal is the palmar carpal ligament and the palmaris brevis, and distally passes ulnar to the hook of the hamate.[9] Within the canal, the ulnar nerve divides into motor and sensory branches. The superficial branch first gives off motor fibers to palmaris brevis and divides to innervate the ulnar side of the palm and ring finger, and the entire small finger. The deep branch provides innervation to the adductor pollicis, opponens digiti minimi, abductor digiti minimi, flexor digiti minimi brevis, flexor pollicis brevis (deep head), the interossei and the lumbricals to the ring and small fingers[5,9,13,15,26,34] (Table 1).

Several variations in the position of the ul-

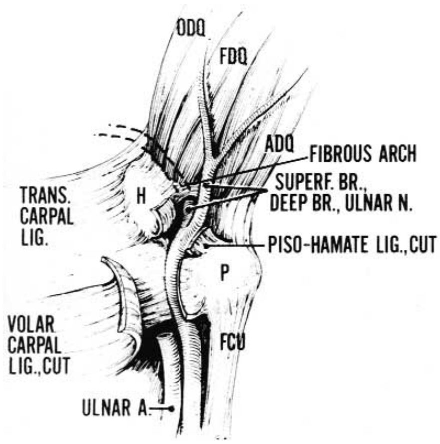

Fig 9. The ulnar nerve in Guyon's Canal is shown. (Reprinted with permission from Szabo RM: Entrapment and Compression Neuropathies. In Green DP, Hotchkiss RN, Pederson WC (eds). Green's Operative Hand Surgery. (Green's Operative Hand Surgery. Ed 4. Philadelphia, Churchill Livingstone 1404–1447, 1999.) ADQ = Abductor Digiti Quinti; A = artery; BR = branch; FDQ = Flexor Digiti Quinti; FCU = Flexor Carpi Ulnaris; Lig = ligament; OPQ = Opponens Digiti Quinti.

nar nerve at the wrist have been described. Dodds et al[15] studied 57 wrists and in all but one wrist, the ulnar artery was medial to the ulnar nerve within Guyon's Canal. One specimen had a high division of the ulnar nerve that rejoined the nerve before entering the canal. Although Dodd et al found several muscular anomalies, they concluded that the neural anatomy was very consistent at Guyon's Canal.[15] Konig et al[31] reported a similar finding in a study 23 wrists. They found that in all but two wrists, both components pass through the canal. In two cases where it did not pass through the canal, the sensory branch came off the dorsal ulnar nerve. In 10 wrists there was a superficial anastomosis between the median and ulnar nerves in the palm. Konig et al[31] also showed a fairly consistent anatomy within the canal, but also observed thick fibrous bands at the distal extent of the canal that may cause entrapment of the nerve. Rogers et al[50] reported on seven of 77 dissections in which they observed an aberrant loop of the deep branch that separated before exiting the canal, with the two branches exiting on either side of the hook of the hamate, only to rejoin in the palm. LeGeyt and Ghobadi[35] described a patient who had an ulnar nerve and artery 6 mm radial to the hook of the hamate during an emergent carpal tunnel release for compartment syndrome, showing that despite a fairly consistent location for the contents of Guyon's Canal, care must be taken to identify anatomic anomalies when operating in this area.

Finally, there are two well described connections between the median and ulna nerves that should be mentioned: the Martin-Gruber or proximal anastomosis,[11,36,54,63] and the Riche-Cannieu anastomosis.[16,19,51,52] The Riche-Cannieu anastomosis occurs distally as a communication between the palmar cutaneous branches of the median and ulnar nerves. The Martin-Gruber anastomosis is the better described phenomenon occurring in 10.5% to 25%[11] of the population. The Martin-Gruber anastomosis is an anastomotic connection between the median and ulnar nerve in the forearm. Taams[58] studied 112 forearms from cadavers and found that 23% (13 arms) had the internervous connection. None of the specimens had an ulnar to median connection and all the connections came from the anterior interosseous nerve branch of the flexor digitorum profundus.[58] Shu et al[54] found Martin-Gruber anastomosis in 17 of 72 forearms and described four types: Type I, anterior interosseous nerve to the ulnar; Type II, median to the ulnar; Type III, branches to flexor digitorum profundus and to the ulnar; and Type IV, a combination of Types I, II, and III. The significance of these findings is the crossover contributions from the median nerve that may lead to an underestimation of an injury to the ulnar nerve clinically and electrodiagnostically.

Clinical Applications of the Ulnar Nerve

The ulnar nerve can become entrapped in five anatomic locations along its course down the upper extremity; the medial intermuscular septum, Arcade of Struthers, the cubital tunnel, the fascia of the flexor carpi ulnaris, and Guyon's Canal. The most common location of compression is the cubital tunnel. Initially symptoms of ulnar neuropathy present as medial forearm pain that progresses to numbness and dysesthesia along the ulnar aspect of the wrist and ring and small fingers. Two-point discrimination may be increased in the ring and small fingers. As the condition progresses, wasting occurs in the flexor carpi ulnaris if the lesion is proximal, and wasting of the hypothenar musculature and wasting of the interspace of the thumb and index finger occur as the adductor pollicis atrophies. A useful test was described by Froment.[20] The patient is asked to grasp a piece of paper between his or her thumb and radial border of the index metacarpal. If the patient has weakness in the adductor, he or she will attempt to hold on to the paper by recruiting the flexor pollicis longus, innervated by the anterior interosseous nerve. Many patients complain of reproduction of their symptoms at night or with elbow flexion; as the elbow is hyperflexed, the ulnar nerve is stretched against a rigid medial epicondyle. In five fresh cadavers Schuind et al[53] showed that from full extension to full flexion the cubital tunnel lengthened 45%, placing the ulnar nerve on stretch. Patel et al[44] used magnetic resonance imaging to evaluate elbows in varying degrees of flexion and found not only was the nerve stretched in flexion, but there appeared to be fat surrounding the nerve where it is against the medial epicondyle.

Within Guyon's canal there are three locations where the nerve may be entrapped: Zones I, II, and III. Zone I is proximal in the canal, before the division of the deep and superficial nerve. A patient with a Zone I entrapment will have motor weakness of all intrinsics, and numbness in the ulnar ring and entire small finger. Zone II is at the distal radial aspect after the superficial and deep branches of the ulnar nerve have divided. In Zone II entrapment, the superficial branch is spared and there is no loss of sensation in the ring and small fingers, but the intrinsics are weak, with the exception of some of the hypothenar muscles, particularly the palmaris brevis. Zone III also is distal, but the compression occurs more medially in the canal, compressing the superficial branch and presents as numbness in the ring and small fingers.[9,41]

There are several anatomic relationships that are fairly consistent, whereas others are more variable. In the current study, the authors have attempted to provide an overview of the nerve anatomy of the upper extremity, while emphasizing the most recent additions to the literature. As the field of orthopaedic surgery is in essence the science of applied anatomy, the prowess of the surgeon lies in his understanding of anatomy. In that sense, the quote from Sir Francis Bacon is quite fitting—"Knowledge is power."

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