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REVIEW

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An overview of neuromuscular ultrasound of important small nerves

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Abstract

Background Neuromuscular ultrasound has become an important tool in the diagnostic workup of nerve and muscle disorders. Scanning techniques, sonoanatomy, and sonographic appearance of the pathologies of the main upper and lower limb nerves have been extensively described in the literature. The nerve branches and small nerves have also been addressed but to a much lesser extent.

Main body of the abstract The aim of the article is to give an overview of neuromuscular ultrasound of important small nerves including nerve branches and other small nerves. The article provides a summary for machine settings and indications of ultrasound scanning of small nerves. It then discusses each nerve as regards the relevant anatomy, detailed scanning techniques, sonoanatomy, and common pathologies.

Conclusion This article represents a practical guide for scanning important nerve branches and small nerves which can facilitate sonographic assessment of pathologies of such challenging nerves.

Keywords Neuromuscular ultrasound, Nerve ultrasound, Nerve sonography, Small nerves, Nerve branches

Background

Neuromuscular ultrasound is currently considered an important diagnostic tool in the assessment of neuromuscular disorders [1–4]. Nerve ultrasound gives valuable structural information that complements the functional information obtained via electrodiagnostic studies [5–8]. The published literature focused on sonographic appearance, scanning techniques, and pathologies of the main limb nerves [9–13]. Several articles have also addressed some nerve branches and small nerves [14–19]. Although pathologies of the main and large peripheral nerves are more commonly encountered in clinical practice, pathologies of nerve branches and small nerves are not uncommon reasons for referral to the electromyography lab and neuromuscular ultrasound especially in traumatic settings. The scanning techniques and the identification of pathologies of such small nerves can be challenging especially for novice sonographers. Therefore, the aim of this article is to give an overview of the anatomy, scanning technique, sonoanatomy, and pathologies of the most important nerve branches and small nerves of the upper and lower limbs.

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Machine settings and principles of scanning

The principles of scanning of large nerve apply to scanning of nerve branches and small nerves. However, there are some differences. Linear probe with small footprint or hockey stick probe is the optimum tool for scanning small nerves. Small nerves are tiny, usually measuring 1–3 mm^2 in a cross-sectional area. Thus, their visualization requires the use of high frequency to obtain the best axial resolution. A probe with frequency of 18–20 MHz or higher is the optimum. A depth of 1–3 cm is usually sufficient to scan most of the small nerves because of their superficial position. Using one focal point is recommended with adjusting the focal position at the target nerve. The gain should be adjusted so that there is clear contrast between the nerves and the surrounding structures (usually in the range of 50–55%). The frequency, depth, and focal position are usually re-adjusted as one traces the nerves from one level to another along their courses.

The small nerves may acquire the same multifascicular or honeycomb pattern like the large nerves, but in many instances, the nerve branches and small nerves may appear as small round or oval hypoechoic or monofascicular structure. The nerve branches are usually identified by tracking them as they bifurcate from their parent nerves and commonly appear as train of fascicles like the dorsal ulnar cutaneous nerve and the posterior interosseus nerve. Using anatomical landmarks like blood vessels or bones can also facilitate the identification of small nerves. It is recommended to start scanning the small nerves in the axial view because it is easier to identify them in the short axis. Scanning the nerves in two perpendicular views is a rule in neuromuscular ultrasound. However, it may not be feasible to scan the small nerves in the two views given their small size.

Sonographic assessment of nerve branches and small nerves includes measurement of the nerve size, assessment of echotexture, vascularity, anatomic variants, and searching for extrinsic structural factors compressing the nerves. In traumatic nerve injuries, assessment of nerve continuity and looking for neuroma-in-continuity, nerve entrapment, or nerve encasement by scar tissue are important.

The cross-sectional area in the short axis is measured using the trace function of the ultrasound machine by tracing the nerve from just inside its hyperechoic rim. Nerve diameter can be measured using the distance function by extending the marks from just inside the hyperechoic border. Nerve echotexture changes can be assessed, but the loss of the honeycomb pattern that is usually seen in main nerve pathologies may not be evident in small nerve lesions because many small nerves may not acquire the typical honeycomb appearance of a nerve and appear as monofascicular structure.

General indications of neuromuscular ultrasound of nerve branches and small nerves

The main indications of sonographic assessment of nerve branches and small nerves include suspected entrapment neuropathies and traumatic nerve injuries. Nerve mapping prior to surgical excision of soft tissue masses or prior to vascular surgeries involving the nearby blood vessels is also an indication.

The role of ultrasound in suspected local entrapment of nerve branches and small nerves is to localize the entrapment sites because electrodiagnostic studies usually fail to localize the entrapment of small nerves. For example, posterior interosseus nerve (PIN) entrapment usually lead to diffuse axonal pattern in nerve conduction studies and axonal changes in the PIN-innervated muscles. However, ultrasound can accurately determine the entrapment site being at the arcade of Froshe, inside the supinator tunnel, or at the tunnel exit. Ultrasound can also detect soft tissue masses that may compress the nerves like ganglion cysts, or intramuscular masses.

In traumatic nerve injury, ultrasound allows the assessment of nerve continuity and gives valuable information to the surgeon with respect to the length of nerve gap, the levels of nerve stumps, whether there is stump neuroma or not. Ultrasound can also detect neuroma-in-continuity, nerve encasement by scar tissue, or nerve compromise by fractures, metal plates, or screws. These findings are important to detect because they may interfere with the reinnervation process in cases of partial axonal injures.

Further, ultrasound can be used to map the nerves along their courses prior to soft tissue or vascular surgeries to identify the relation of the primary pathology to the nerve and avoid their iatrogenic injury. Moreover, ultrasound can be used to guide nerve conduction studies of small nerves like the sural and the lateral femoral cutaneous nerves [20, 21].

Important branches of the main upper limb nerves

Palmar cutaneous branch of the median nerve

Anatomy The palmar cutaneous nerve (PCN) is the last collateral branch originating from the median nerve trunk at the distal forearm. It typically originates from the lateral aspect of the median nerve [22]. The level of origin of PCN from the median nerve varies in the cadaveric studies ranging from 4–8 cm proximal to the distal wrist crease or the biaxial line (a line from the radial to the ulnar styloid processes) [23]. The PCN descends alongside the median nerve or may diverge away from the nerve as it approaches the deep brachial fascia. It does not pass under the flexor retinaculum, but it pierces it to run superficial to the carpal tunnel where it lies on the medial side of the flexor carpi radialis (FCR) tendon [22, 23]. It terminates by giving lateral and medial branches. The lateral branches supply the thenar skin and connect with the lateral cutaneous nerve of the forearm, while the medial branches supply the central palmar skin and connect with the palmar cutaneous branch of the ulnar nerve [24].

Anatomic variants: Rarely, the nerve may originate from the medial aspect of the median nerve [25] and may pierce the FCR tendon sheath and runs within it [23]. Moreover, two separate PCN may originate from the median nerve [26], and the nerve may be absent in minority of individuals [27].

Scanning technique *Patient's position*: Sitting with the wrist and hand resting on the examination table/bed with the forearm supinated, wrist extended, and palm up. Supporting the wrist with a pillow may facilitate proper wrist positioning.

Scanning window: from distal third of the forearm to the wrist.

Landmarks: the main trunk of the median nerve, the flexor retinaculum (or the deep brachial fascia), and the flexor carpi radialis tendon.

Tracing and sonoanatomy: To capture the PCN in the axial view as it originates from the median nerve, it is better to start at the mid-forearm where one can easily identify the main trunk of the median nerve lying in the fascial plane that separates the superficial flexor digitorum superficialis from the deep flexor digitorum profundus. Next, the median nerve is traced distally and visually tracked on the screen looking for a tiny single round hypoechoic fascicle leaving the lateral aspect of the median nerve at the distal third of the forearm (Fig. 1A). This tiny fascicle represents the palmar cutaneous branch of the median nerve. Back and forth tracing may facilitate the identification of the PCN as it originates from the median nerve. The branch is then followed distally and can be seen coursing first underneath the deep brachial fascia (Fig. 1B) then pierces it (Fig. 1C) to run in

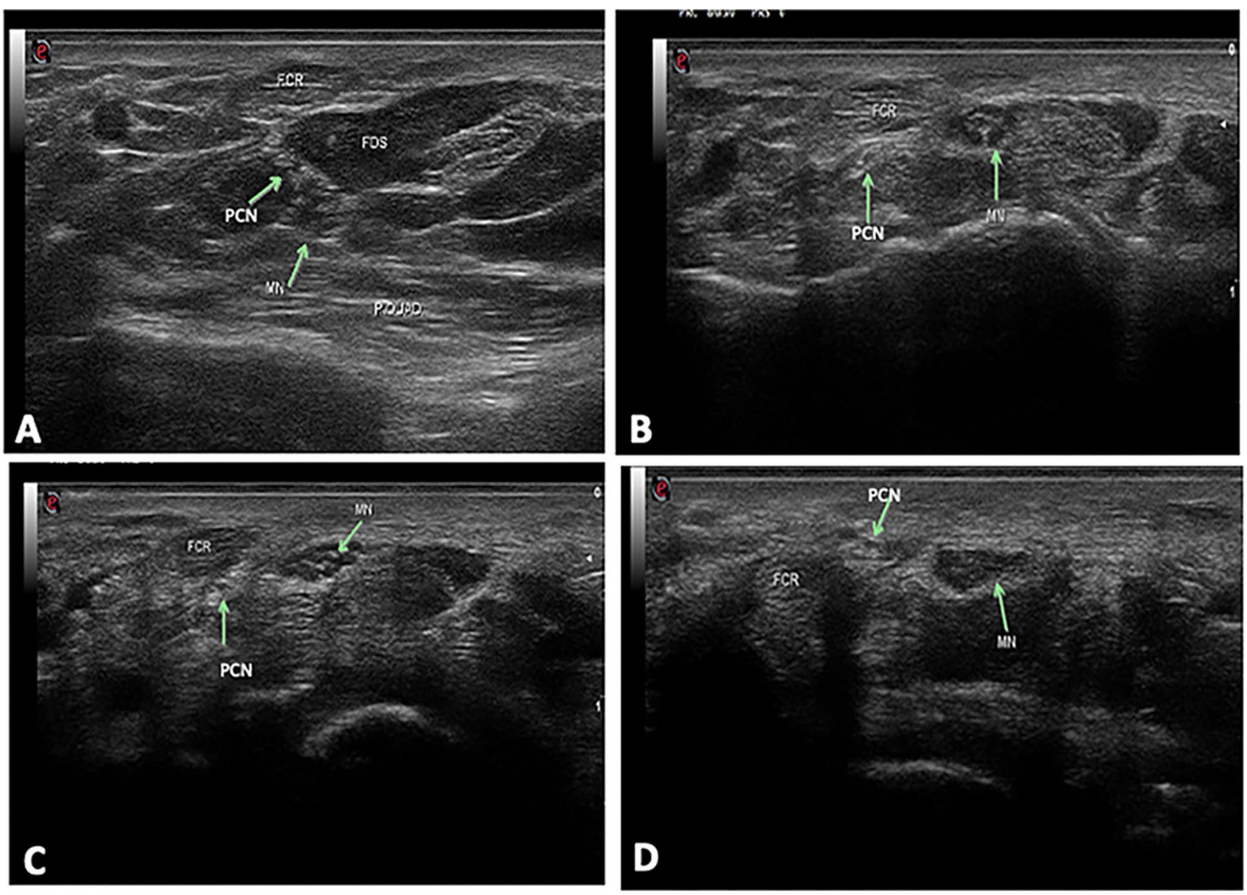


Fig. 1 Sonoanatomy of the palmar cutaneous branch of the median nerve. Short-axis views of the palmar cutaneous branch of the median nerve at different levels from the distal forearm to the wrist. **A** Origin of the PCN from the lateral aspect of the median nerve at the distal third of the forearm appearing as a tiny round hypoechoic fascicle separating from the main median nerve trunk. **B** A level distal to level A showing the PCN diverting away from the median nerve and running underneath the deep brachial fascia. **C** The PCN as it pierces the antebrachial fascia. **D** The PCN lying in the subcutaneous tissue after it pierces the deep brachial fascia, running superficial to the carpal tunnel and medial to the FCR tendon

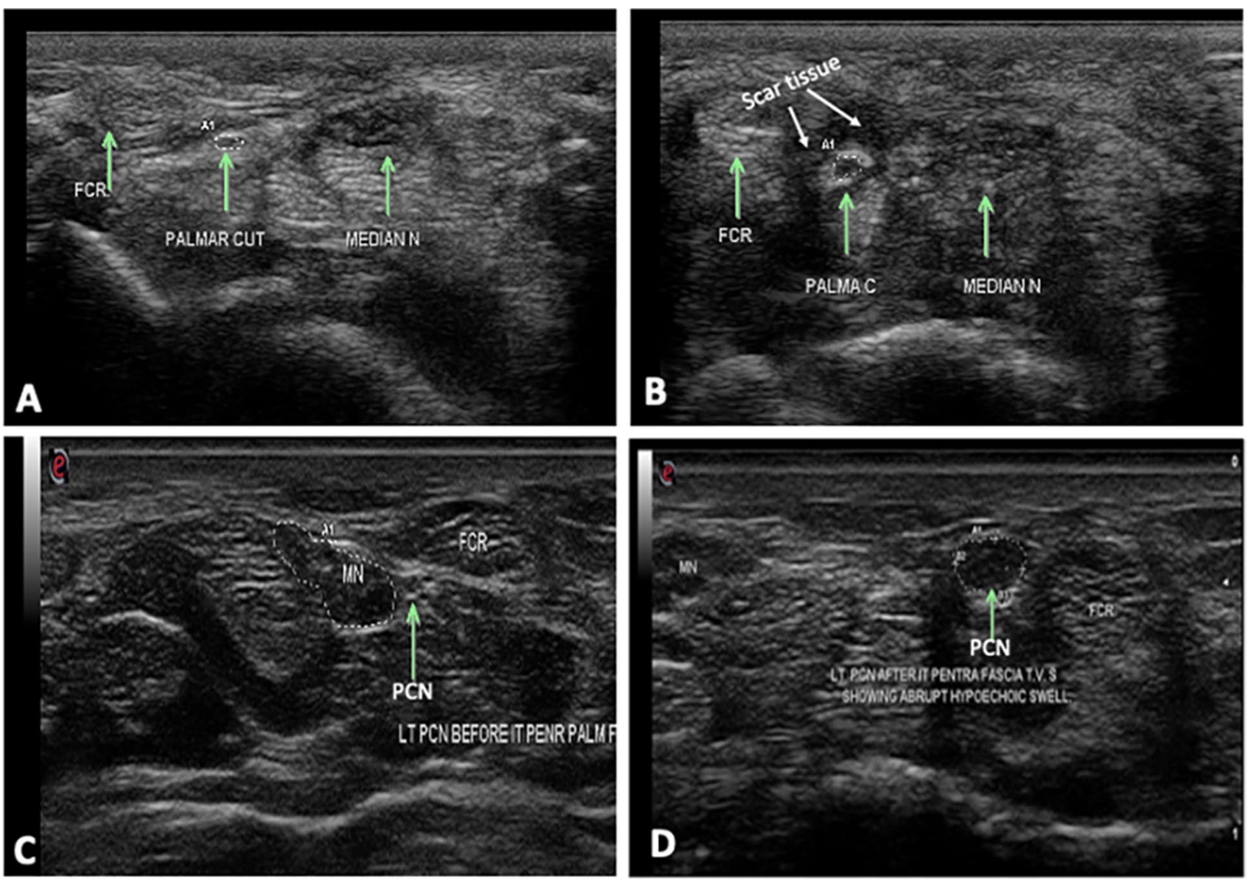
the subcutaneous tissue where it is visualized outside the carpal tunnel lying medial to the flexor carpi radialis tendon (Fig. 1D). The terminal lateral and medial branches are too tiny to be visualized via ultrasound except with an ultra-high frequency probe.

Pathologies Palmar cutaneous nerve injuries may be traumatic or iatrogenic. Knife, gunshots, or sharp tool injuries can easily injure the nerve along its course. The most common iatrogenic injury is during carpal tunnel release [28] due to direct nerve injury or encasement of the nerve by scar tissue post-carpal tunnel release (Fig. 2A, B).

Open trauma may result in complete or partial transection, while chronic axonal injury may result in formation of neuroma-in-continuity (Fig. 2C, D). Concomitant entrapment of the nerve in patients with carpal tunnel syndrome has also been reported [29, 30]. Rarely, benign tumors may involve the PCN [31, 32].

Terminal branches of the median nerve

Anatomy Distal to the carpal tunnel at the palm, the median nerve terminates by dividing into three branches. These branches are the recurrent thenar motor branch, and medial and lateral common palmar digital nerves. The recurrent motor branch curves laterally to innervate the thenar muscles while the medial and lateral common



PALMAR CUT: palmar cutaneous nerve, FCR: flexor carpi radialis, MN: median nerve, PCN: palmar cutaneous nerve

Fig. 2 Examples of palmar cutaneous nerve pathologies. **A, B** Short-axis views of the palmar cutaneous nerve in a patient who complained of pain and numbness along the right palm post-carpal tunnel surgery. **A** shows a normal sonographic appearance of the palmar cutaneous branch as it pierces the deep brachial fascia. **B** The PCN after it penetrates the fascia where it appears surrounded by hypoechoic tissue representing scar tissue encasing the nerve with thickening of the nerve epineurium. **C, D** Short-axis views of the palmar cutaneous nerve in a patient who complained of numbness at the lateral palm and severe pain on touch at the wrist post-carpal tunnel release. **C** Normal sonographic appearance of the palmar cutaneous branch (arrow) as it runs deep the antebrachial fascia. **D** Abrupt hypoechoic swelling of the PCN nerve after it pierces the fascia as it runs medial to the FCR tendon representing neuroma-in-continuity palmar digital nerves divide into two proper palmar digital nerves which run distally to the digits between the flexor tendons accompanied by the digital arteries [33].

Scanning technique *Patient's position*: Sitting with the wrist and hand resting on the examination table/bed with the forearm supinated, wrist extended, and palm up. Supporting the wrist with a pillow may facilitate proper wrist positioning.

Scanning window: Palm and digits.

Landmarks: Main trunk of the median nerve, digital arteries, flexor tendons.

Tracing and sonoanatomy: The optimum probe for scanning the digital nerves is hockey stick probe. However, it is not available everywhere. Given the small size of the distal median nerve branches, the conventional ultrasound machines with even high frequency of 20 MHz may not allow detailed visualization of these branches. Therefore, ultrahigh frequency of 70 MHz may allow better visualization of the terminal median nerve branches [34].

To capture the terminal branches of the median nerve at the palm, the main trunk of the median nerve is first identified at the carpal tunnel level then traced to the palm. Just distal to the carpal tunnel at the proximal palm, the median nerve is seen bifurcating into three divisions (Fig. 3A). The most lateral division is the

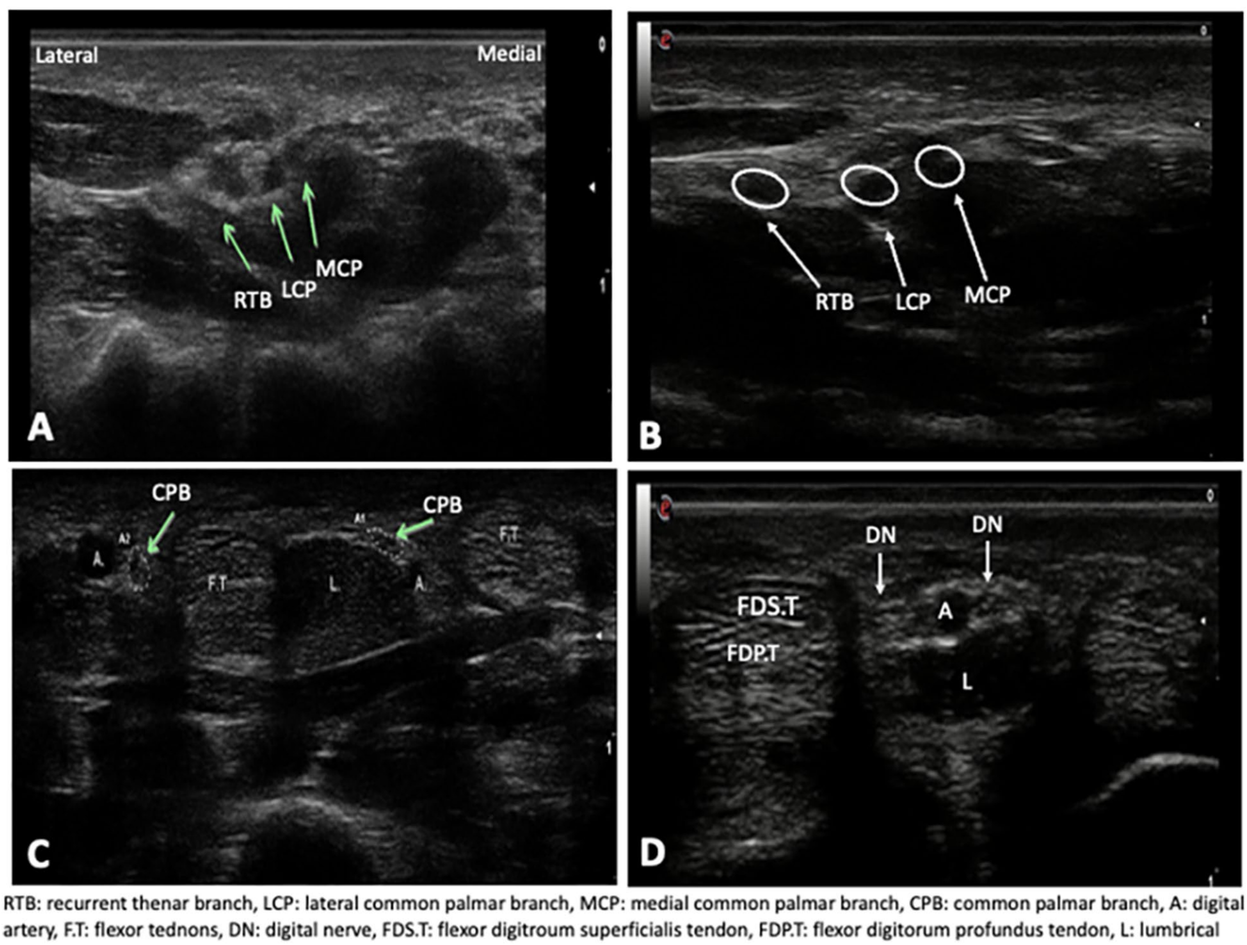


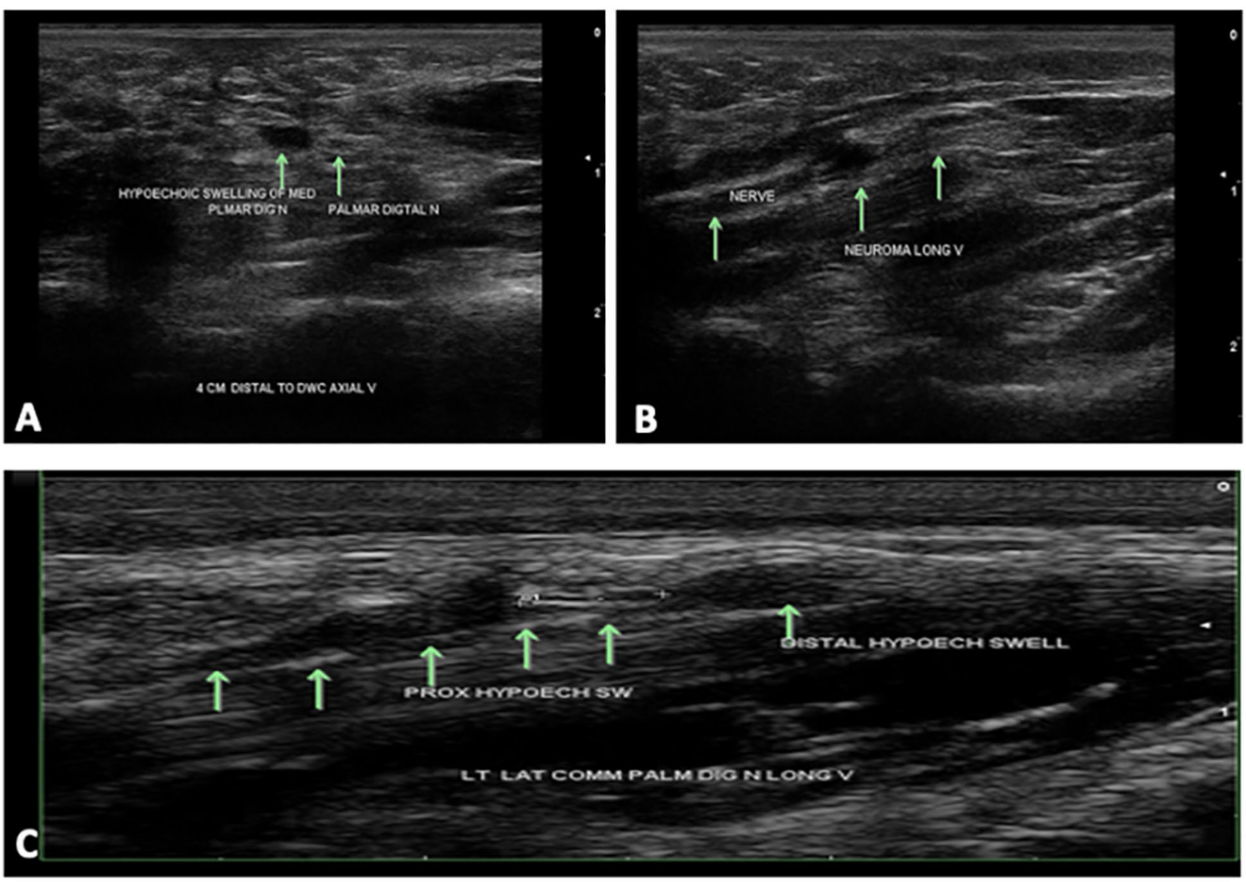
Fig. 3 Sonoanatomy of the terminal branches of the median nerve at the palm. Short-axis views of the terminal branches of the median nerve at different levels. **A** The median nerve seen bifurcating into three terminal branches (RTB, LCB, MCP) at the proximal palm distal to the carpal tunnel. **B** A level distal to level A: the three branches divert away. **C** The palmar digital nerves at the distal palm proximal to the digits. The nerves appear as small honeycomb structures running between the flexor tendons, accompanied by the digital arteries. **D** The digital nerves at the metacarpophalangeal joint: medial and lateral digital nerves lie on each side of the digital artery between the flexor tendons

recurrent thenar motor branch, the most medial division is the medial common palmar digital nerve, and the division in between is the lateral common palmar digital nerve (Fig. 3A). As these divisions traced distally, they become apart with the recurrent thenar motor branch seen curving laterally on its way to innervate the thenar muscles (Fig. 3B). Further distally proximal to the digits, the common palmar digital nerve is seen adjacent to the digital artery between the flexor tendons (Fig. 3C). Following the common palmar digital nerves distally allows visualization of their bifurcation into proper palmar digital nerves. At the level of metacarpophalangeal joint, two proper digital nerves can be identified in the web spaces between the flexor tendons lying on each side of the digital artery (Fig. 3D). From there, the digital nerves can be traced further distally to the digits by visually tracking them and using the digital artery as the landmark.

Pathologies The digital nerves may be injured during penetrating trauma to the palm or the digits. The sonographic features of traumatic injuries include incomplete or complete laceration, stump neuroma, and neuroma-in-continuity [35] (Fig. 4). Benign tumor of the digital nerves has also been reported [36].

Dorsal ulnar cutaneous nerve

Anatomy The dorsal ulnar cutaneous nerve (DUCN) arises from the ulnar nerve at the distal third of the forearm at a level about 4–8 cm proximal to the ulnar styloid [37]. After it emerges from the ulnar nerve, it runs medially underneath the flexor carpi ulnaris muscle and its tendon, penetrates deep brachial fascia to run in the subcutaneous tissue, and then continues over the radioulnar



MED PALMAR DIG N: medial palmar digital branch, COMM PALM DIG N: common palmar digital nerve

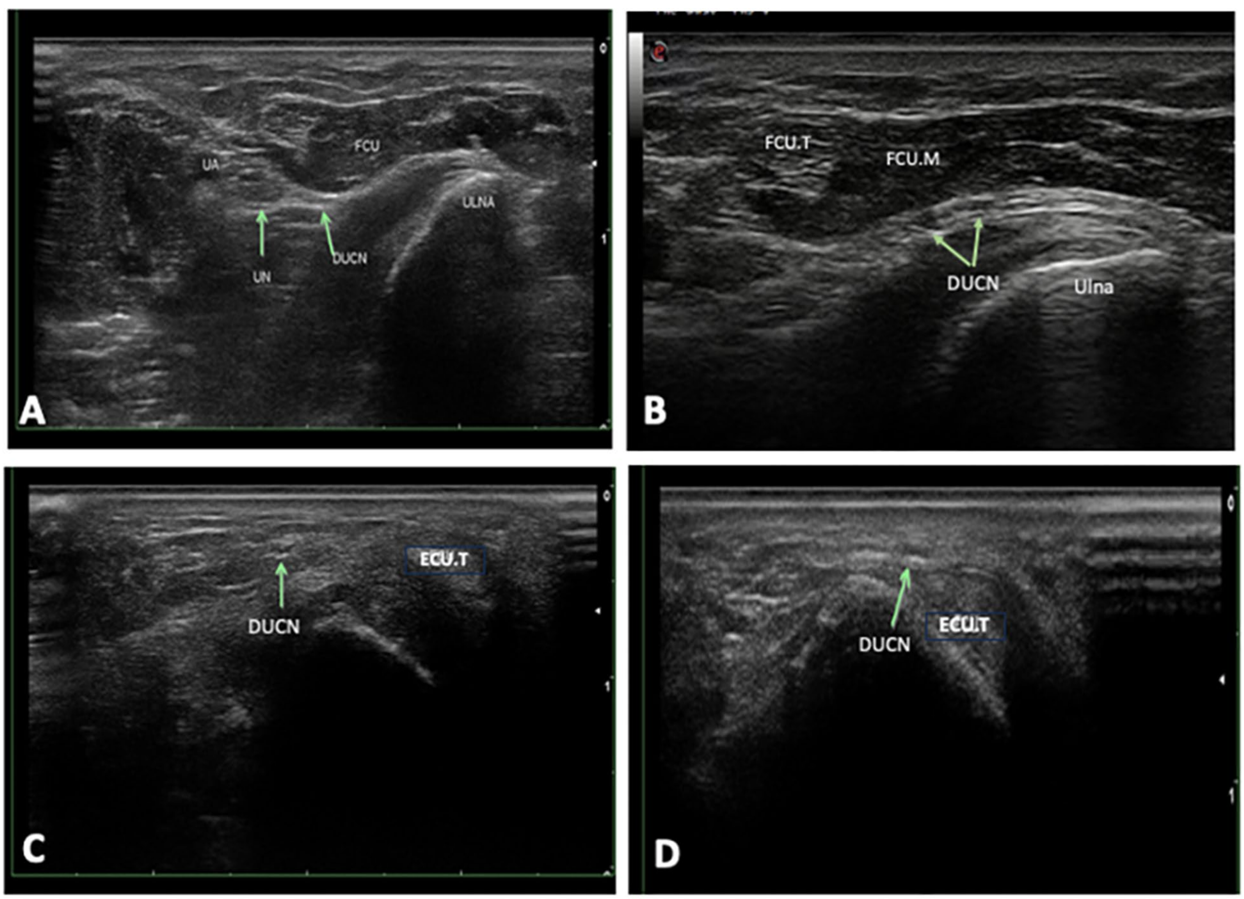
Fig. 4 Examples of pathologies of terminal branches of the median nerve. **A, B** Medial common palmar digital nerve in a patient post-carpal tunnel release. **A** Short-axis view showing a hypoechoic swelling of the nerve representing neuroma-in-continuity. **B** Long-axis view of the same nerve showing the neuroma appearing as a focal hypoechoic swelling of the nerve. **C** Long-axis view of the lateral common palmar digital nerve in a patient with traumatic injury to the palm showing two serial focal hypoechoic enlargement of the nerve representing serial neuroma-in-continuity joint to reach to the dorsal medial aspect of the wrist to run superficial to the sixth dorsal compartment which houses the extensor carpi ulnaris [24]. It provides sensation to the dorso-ulnar aspect of the hand and divides into 2–3 dorsal digital nerves to supply the dorsum of the fifth finger and dorso-ulnar aspect of the fourth finger [24].

Scanning technique *Patient's position*: Sitting with the wrist and hand resting on the examination table/bed, palm supinated, and wrist in neutral position. Supporting the wrist with a pillow may help proper positioning.

Scanning window: From the distal third of the medial forearm to the dorsomedial aspect of the wrist.

Landmarks: Main trunk of the ulnar nerve, flexor carpi ulnaris muscle and tendon, sixth dorsal wrist extensor compartment.

Tracing and sonoanatomy: To capture the DUCN, the probe is placed in the axial view at the medial aspect of the mid-arm and identify the main trunk of the ulnar nerve as it runs adjacent to the ulnar artery between the flexor carpi ulnaris superficially and flexor digitorum profundus deeply. As the main ulnar nerve trunk is traced distally, the dorsal ulnar cutaneous branch will appear as few fascicles (sometimes appear as train of fascicles) bifurcating from the medial aspect of the ulnar nerve at the distal third of the forearm (Fig. 5A), running underneath the flexor carpi ulnaris muscle (Fig. 5B). The nerve can then be visually tracked to the dorsum of the hand



UN: ulnar nerve, UA: ulnar artery, DUCN: dorsal ulnar cutaenous nerve, FCU: flexor carpi ulnaris, FCU.M: flexor carpi ulnaris muscle, FCU.T: flexor carpi ulnaris tendon, ECU.T: extenor carpi ulnaris tendon.

Fig. 5 Sonoanatomy of the dorsal ulnar cutaneous nerve. Short-axis views of the dorsal ulnar cutaneous branch from its origin to the sixth extensor compartment. **A** Origin of the DUCN: the nerve is seen bifurcating from the main trunk of the ulnar nerve at the distal third of the forearm. **B** A level distal to the nerve origin. The nerve is seen running away from the main ulnar nerve trunk passing underneath the flexor carpi ulnaris muscle and its tendon. **C** The DUCN after it turns dorsally as it approaches the sixth extensor compartment. **D** The DUCN at the 6th extensor compartment running in the subcutaneous tissue superficial to the extensor carpi ulnaris tendon where it will be seen as a tiny nerve running superficial to the 6th extensor compartment (Fig. 5C, D). The terminal branches of the DUCN can be difficult to visualize given their small size and the adjacent hyperechoic subcutaneous fat.

Pathologies Lesions of the DUCN may result from traumatic injuries or iatrogenic causes. Possible iatrogenic injuries may occur during open reduction and internal fixation of the distal ulnar fracture, ulnar osteotomy, ulnar lengthening or shortening operations, and arthroscopic surgery [38, 39]. Traumatic injuries may result in complete transection or neuroma-in-continuity (Fig. 6). The nerve can also be impinged at the 6th extensor compartment in cases of extensor carpi ulnaris tendinopathy [40].

Terminal branches of the ulnar nerve

Anatomy Guyon's canal can be divided into three zones [41]. Zone 1 is the zone at the level of the pisiform bone and contains the main trunk of the ulnar nerve and the ulnar artery. Zone 2 and Zone 3 are located distal to Zone 1 at the level of the hook of the hamate and it is the zone where the nerve typically bifurcates into deep motor and superficial sensory ulnar nerves. Zone 2 is the lateral zone and contains the deep motor branch while Zone 3 is the medial zone and contains the superficial sensory branch [41].

The deep motor branch follows the medial wall of the hook of the hamate bone and pass deep into the palm between the heads of origin of flexor and abductor digiti minimi and through the origin of opponens digiti minimi [33]. It then runs deep and lateral and follows the course of the deep palmar arch at the palm to reach the thenar eminence to innervate the adductor pollicis and flexor pollicis brevis muscles [33].

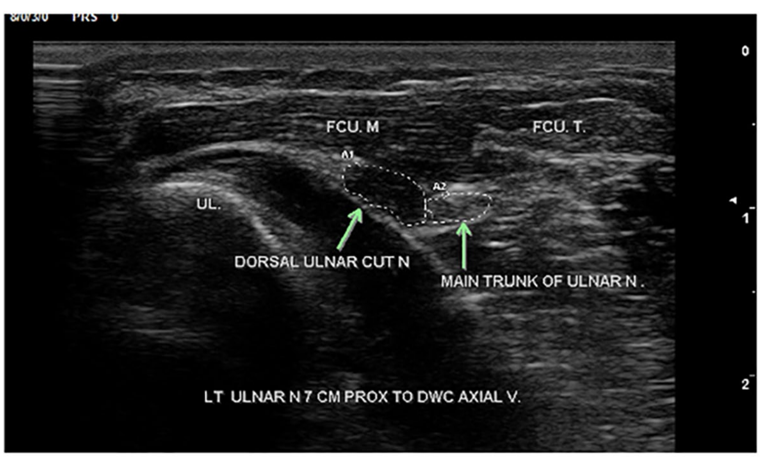
After it emerges from the ulnar nerve, the superficial sensory branch runs distally in the palm to divide into two digital nerves, which, similar to the digital branches of the median nerve, pass between the flexor tendons accompanied by the digital arteries [33].

Scanning technique *Patient's position*: Sitting in front of the sonographer with the hand resting on the examination bed, forearm supinated, and wrist extended.

Scanning window: From ulnar volar aspect of the wrist to the digits.

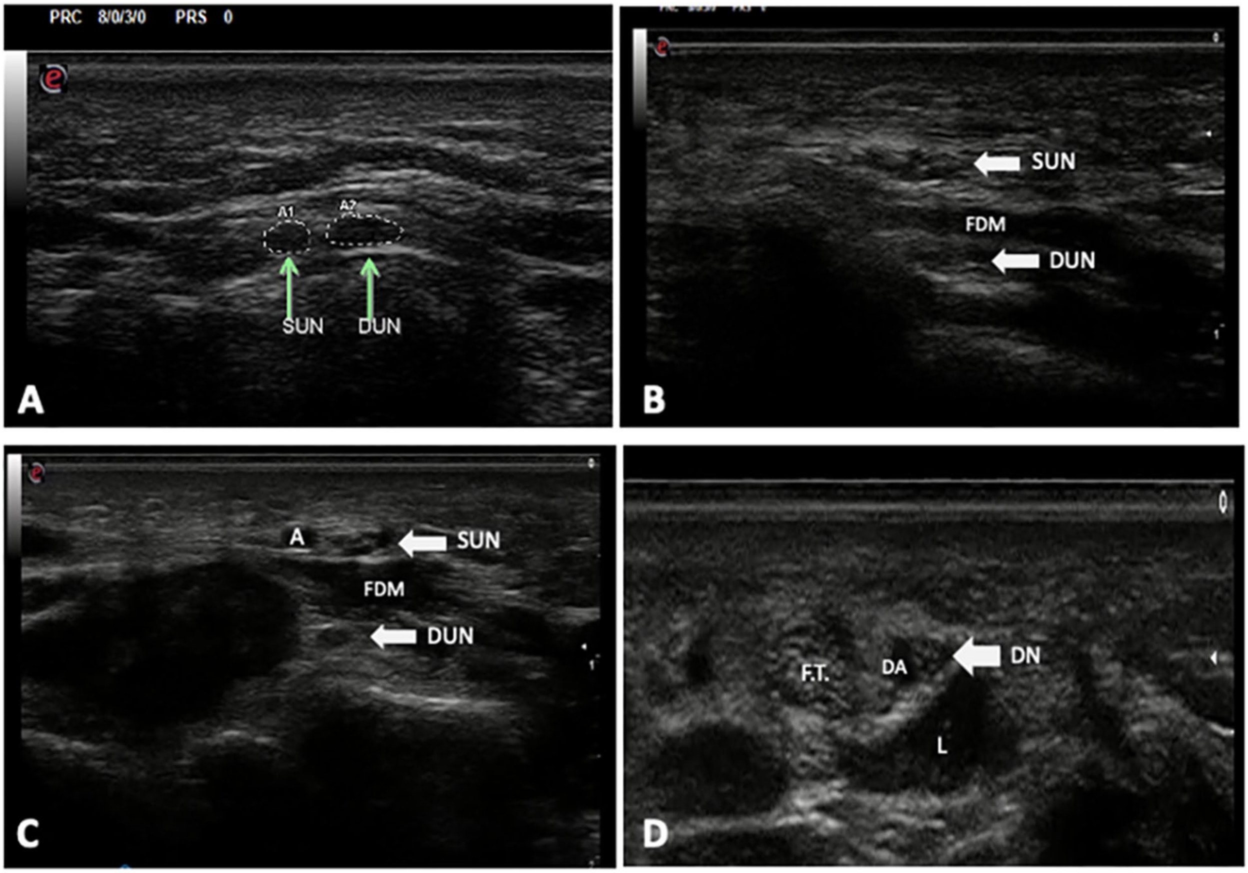
Landmarks: Main trunk of the ulnar nerve, digital arteries.

Tracing and sonoanatomy: To accurately identify the terminal branches of the ulnar nerve, it is preferable to start scanning at the pisiform bone level to visualize the main trunk of the ulnar nerve. The probe is then swept distally to see the ulnar nerve dividing into two branches at the level of the hook of hamate (Fig. 7A). The lateral branch is the deep motor branch while the medial branch



DORSAL ULNAR CUT N: dorsal ulnar cutaneous nerve, FCU.M: flexor carpi ulnaris muscle, FCU.T: flexor carpi ulnaris tendon, UL: ulna

Fig. 6 Example of a pathology of the dorsal ulnar cutaneous nerve. Short-axis view of the DUCN at its bifurcation point from the main ulnar nerve trunk in a patient with traumatic injury to the forearm showing a hypoechoic swelling of the DUCN representing neuroma-in-continuity. Note the normal sonographic appearance of the main ulnar nerve trunk



SUN: superfiical ulnar nerve, DUN: deep ulnar nerve, FDM: flexor digiti minimi, A: a ulnar artery branch, DN: digital nerve, DA: digital artery, F.T. flexor tendon, L: lumbrical

Fig. 7 Sonoanatomy of the terminal branches of the ulnar nerve. Short-axis views of the terminal branches of the ulnar nerve from the level of Guyon's canal to the palm. **A** Bifurcation of the ulnar nerve into deep and superficial ulnar nerves at the distal portion of Guyon's canal just distal to the pisiform bone. **B** A level just distal to Guyon's canal showing the deep ulnar nerve running deep while the superficial ulnar nerve running superficial and both are separated by the muscle belly of FDM. **C** Further distally, the two branches run away from each other. Note one of the branches of the ulnar artery running adjacent to the superficial sensory branch. **D** The termination of the superficial sensory ulnar nerve as palmar digital nerves running adjacent to the flexor tendons, accompanied by the digital artery

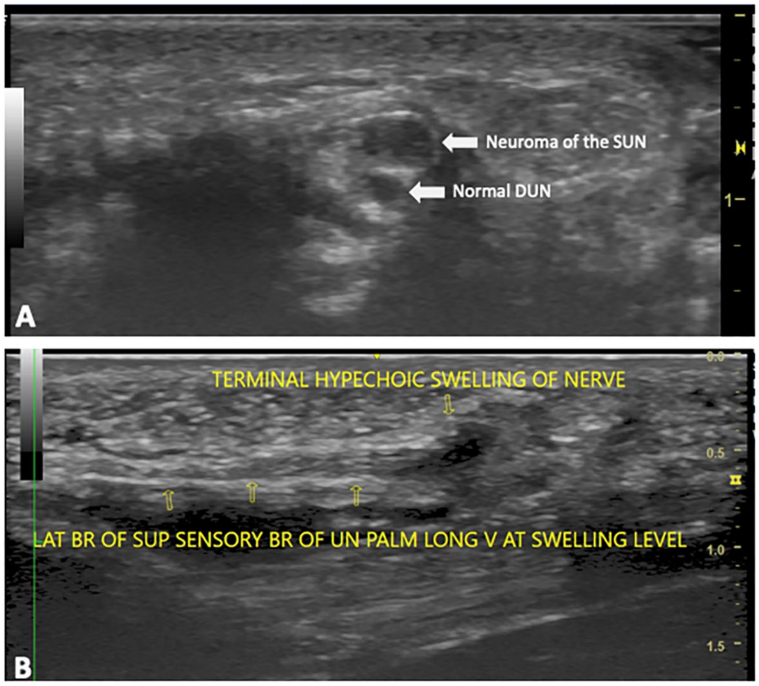
is the superficial sensory branch (Fig. 7A). Each branch is then traced distally by visually tracking them on the screen. The deep motor branch will be seen crossing over the hook of the hamate and runs deep to the flexor digit minimi which separates it from the superficial sensory branch at the proximal palm (Fig. 7B, C). To trace the nerve further, the probe should be manipulated in a curved course to follow the curved course of the nerve at the palm. However, it can be sometimes very challenging to scan the deep branch along its course especially if the skin of the palm is thick.

The superficial sensory branch can be easily traced distally by tracing each digital nerve to the distal phalanges using the digital artery as the landmark (Fig. 7D).

Pathologies The most common type of injury of the deep and sensory ulnar branches is local entrapment at the wrist either secondary to structural compressive factors like ganglion cyst at the wrist joint, or due to repeated compression of the nerve as in long distance cyclists or in individuals using vibratory tools [42, 43]. The branches can also be injured during open trauma at the wrist or the palm (Fig. 8).

Deep radial nerve

Anatomy The deep radial nerve is one of the two terminal branches of the radial nerve. It bifurcates from the radial nerve at the lateral aspect of the anterior elbow



SUN: superficial ulnar nerve, DUN: deep ulnar nerve, LAT BR OF SUP SENSPRY BR OF UN: lateral branch of the superifical sensory branch of the ulnar nerve.

Fig. 8 Example of pathologies of the superficial sensory branch of the ulnar nerve. **A** Short-axis view of the superficial sensory ulnar nerve just distal to the pisiform bone showing a hypoechoic enlargement of the nerve representing neuroma-in-continuity in a patient subjected to trauma to the wrist and palm. Note the normal size and appearance of the deep motor ulnar nerve. **B** Long-axis view of the lateral branch of the superficial sensory ulnar nerve at the proximal palm in another patient subjected to a palm trauma showing abrupt end of the nerve denoting nerve transection with formation of proximal stump neuroma

where the radial nerve runs in the fascial plane between the brachialis medially and the brachioradialis and extensor carpi radialis longus laterally. After it leaves the radial nerve, it descends distally, courses around the lateral aspect of the radius to reach the dorsal forearm [24]. It runs first underneath the Arcade of Frohse before it enters supinator tunnel then passes between the superficial and deep heads of the supinator. It exits the supinator muscle to divide into small terminal branches to innervate the forearm extensors. The distal portion of the nerve lies in the fourth extensor compartment deep to the extensor digitorum and extensor indicis [24].

Scanning technique *Patient's position*: Sitting in front of the sonographer with the arm resting on the examination table/bed. When scanning the nerve at its point of origin from the radial nerve, the elbow is kept in an extended and supinated position, but as the nerve is traced distally to the posterior forearm, it is better to fully pronate the forearm for easy scanning.

Scanning window: From the lateral elbow to the dorsal proximal third of the forearm.

Landmarks: The main radial nerve trunk, deep radial artery, brachialis and brachioradialis, supinator muscle.

Tracing and sonoanatomy: Scanning starts by placing the probe in short axis at the lateral aspect of the antecubital fossa. Two big muscles can be observed at this level; the brachialis muscle medially which forms the floor of the cubital fossa and the brachioradialis laterally which is a part of the mobile wad. Next, the main trunk of the radial nerve is identified as a structure consisting of two bundles running in the fascial plane separating the brachialis medially and the brachioradialis laterally (Fig. 9A). The lateral nerve component represents the deep radial nerve while the medial component represents the superficial radial nerve (Fig. 9A). The deep radial nerve is then visualized moving away from the superficial radial nerve as it is traced distally. Just proximal to the supinator tunnel, the nerve is seen running under a thin hyperechoic band known as the Arcade of Frohse (Fig. 9B). Visually tracking the nerve, the nerve is seen traversing the supinator to run between its superficial and deep heads (Fig. 9C). The nerve can be further followed as it exits the supinator muscle (Fig. 9D) to divide into small terminal

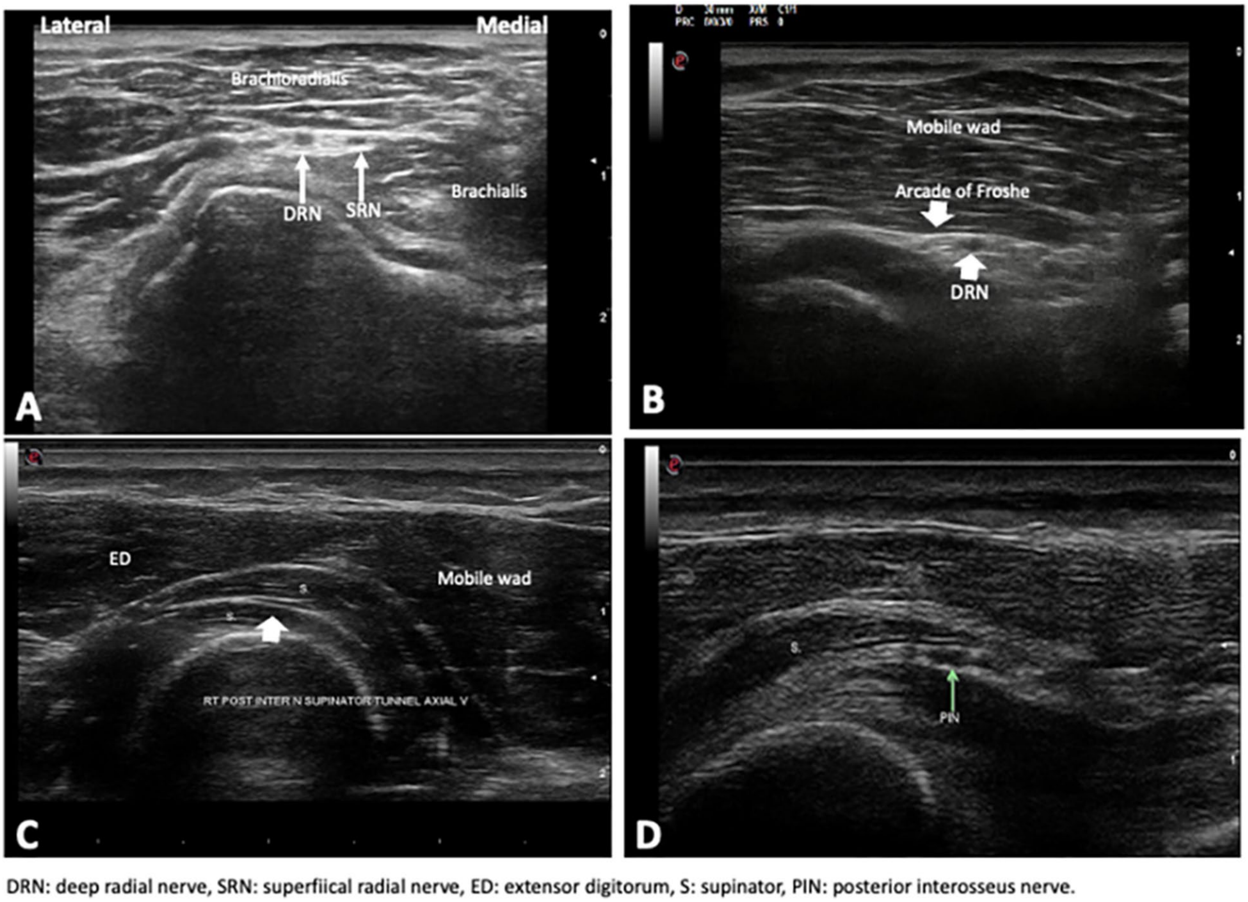


Fig. 9 Sonoanatomy of the deep radial (posterior interosseus) nerve. Short-axis views of the deep radial branch from its origin from the radial nerve to its exit from the supinator tunnel. **A** The origin of the deep radial nerve from the radial nerve trunk at the anterior lateral elbow appearing as a hypoechoic monofascicular structure. **B** The nerve distal to the elbow running under the Arcade of Froshe before it enters the supinator muscle. The arcade appears as a thin hyperechoic line over the nerve. **C** The deep radial (posterior interosseus nerve) running between the superficial and deep heads of the supinator muscle. **D** The posterior interosseus nerve as it exits the supinator muscle appearing as a train of fascicles

branches. These small branches can sometimes be followed distally using high or ultrahigh frequency probes.

Pathologies The deep radial nerve can be entrapped at certain levels and can be subjected to traumatic injuries. The most common sites of nerve entrapment are the supinator tunnel and the Arcade of Froshe (Fig. 10), but the nerve can be rarely entrapped as it exits the supinator muscle [24, 44]. The entrapment can be idiopathic or secondary to structural causes like ganglion cyst and soft tissue masses or can be compressed by branches of the radial recurrent artery known as the Leash of Henry [44, 45]. Secondary indirect posterior interosseus nerve lesion has been reported post humeral fracture [46]. Traumatic and iatrogenic injuries may also occur [47, 48]. Moreover, neuralgic amyotrophy may present as posterior interosseus neuropathy [45, 49, 50]

Superficial radial nerve

Anatomy Like the deep radial nerve, the superficial radial nerve bifurcates from the radial nerve trunk at the lateral aspect of the anterior elbow. At the proximal forearm, it runs superficial to the supinator, and deep to the brachioradialis. It then descends along the lateral aspect of the forearm deep to the brachioradialis and lies lateral to the radial artery [24]. It continues to run deep to the brachioradialis tendon, but usually gets distant from the artery at the distal third of the forearm [24]. At the distal forearm, it curves round the lateral aspect of the radius then penetrates the deep brachial fascia to divide into 4–5 dorsal digital nerves. At the dorsal wrist, it runs over the first extensor compartment and may communicate with the lateral and posterior cutaneous nerves of the forearm [24]

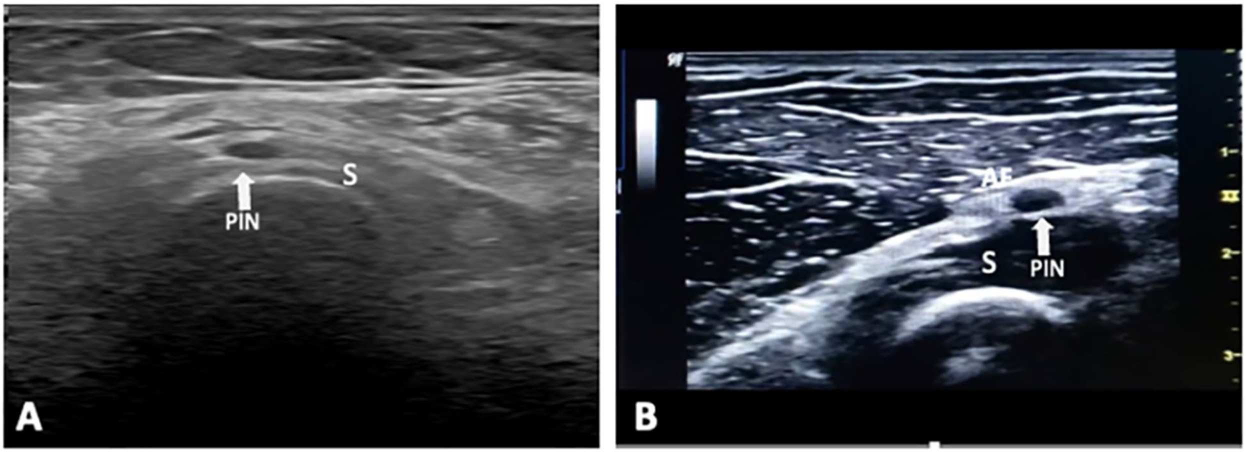


Fig. 10 Example of pathologies of the deep radial nerve. **A** Short-axis view of the posterior interosseus nerve showing nerve enlargement as the nerve passes between the two heads of the supinator denoting local entrapment with marked hyperechogenicity and atrophy of the supinator and the overlying ED. **B** Short-axis view of the PIN showing focal nerve enlargement at the Arcade of Froshe denoting local entrapment just proximal to the supinator tunnel

Scanning technique *Patient's position*: Sitting in front of the sonographer with the arm resting on the examination table/bed and forearm supinated or in the mid-prone position for easy tracing of the nerve along the lateral border of the forearm.

Scanning window: The entire radial aspect of the forearm.

Landmarks: The main radial nerve trunk, brachioradialis, radial artery.

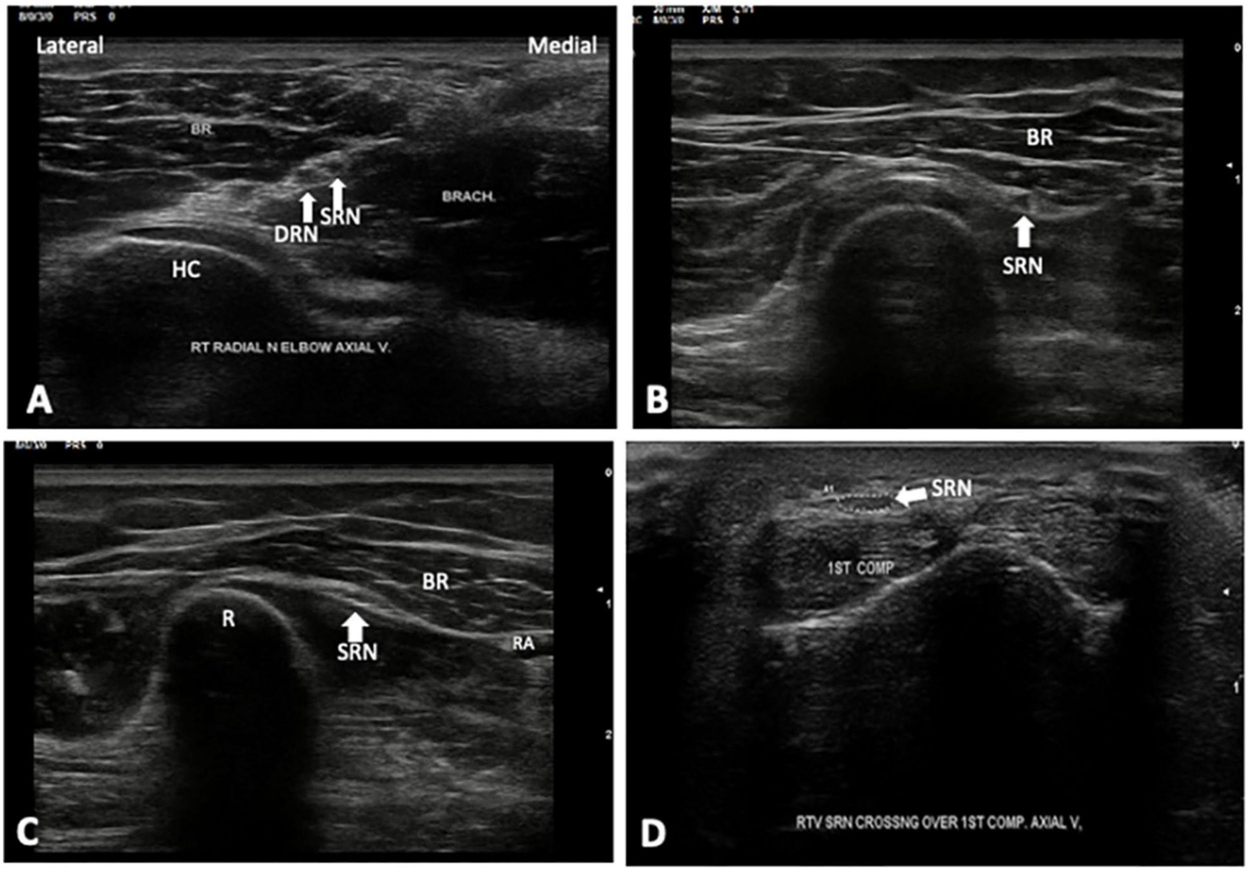
Tracing and sonoanatomy: As in scanning the deep radial nerve, the superficial radial nerve is first identified by placing the probe in short axis at the lateral elbow to identify the radial nerve and its two lateral and medial components with the medial bundle representing the superficial radial nerve (Fig. 11A). As the nerve is traced distally, it will be seen as a small round or sometimes oval, or oblong nerve leaving the elbow and running deep to the brachioradialis and over the supinator (Fig. 11B). The nerve sometimes appears as one oblong fascicle or may acquire the typical honeycomb appearance. Keeping the nerve at the center of the image, the nerve keeps running under the brachioradialis muscle along the entire forearm. At the distal forearm, the radial artery approaches the nerve (Fig. 11C). At the distal radius, the nerve crosses over the radial styloid and may be seen dividing into two or more terminal branches. If followed further distally, the lateral branch will be seen crossing over the first extensor wrist compartment (Fig. 11D).

Pathologies Given its superficial position, the superficial radial nerve is subjected to injury by variable causes. The nerve may be locally entrapped at the wrist by tight watch or cast [51, 52]. It can be injured during closed or open trauma to the radial aspect of the forearm or wrist [51]. Trauma may cause complete or partial transection, neuroma-in-continuity, or scar tissue may encase the nerve in chronic conditions (Fig. 12A). Metal wires may also compromise the nerve post-radius fracture (Fig. 12B). Moreover, the nerve may be compressed by a ganglion cyst or lipoma [51, 52]. Because the nerve runs over the first extensor wrist compartment, it can be affected in de Quervain's tenosynovitis [51, 52]. Therefore, the nerve should be screened for any abnormalities in any patient with de Quervain's tenosynovitis.

Important branches of the main lower limb nerves

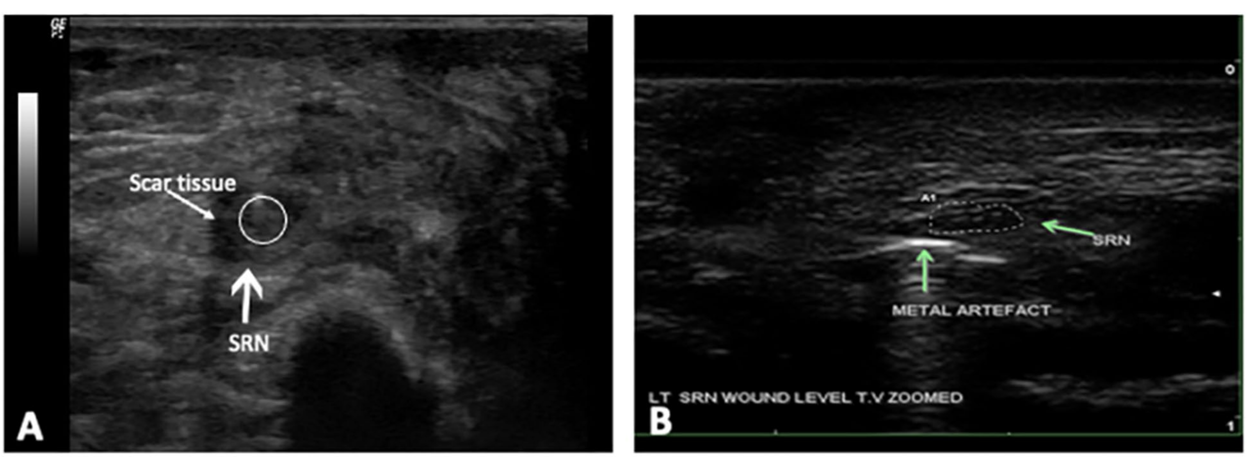
Deep fibular nerve

Anatomy The deep fibular nerve is one of the terminal branches of the common fibular nerve. It bifurcates from the common fibular trunk at the fibular tunnel. It then descends in the anterior leg compartment along the fibula deep to the tibialis anterior and extensor digitorum longus to run on the interosseus membrane along with the anterior tibial artery [53, 54]. It continues its pathway along the anterior leg deep to the anterior group of leg muscles and becomes superficial at the distal third of the leg. At the anterior ankle, it runs over the tibia adjacent to the anterior tibial artery (becomes dorsalis pedis



DRN: deep radial nerve, SRN: superfiical radial nerve, BR: brachioradialis, BRACH.: brahcialis, HC: humeral capitulum, R: radius, RA: radial artery, 1ST COMP: first extensor compartment.

Fig. 11 Sonoanatomy of the superficial radial nerve. Short-axis views of the superficial radial nerve from its origin from the radial nerve trunk to the distal radial wrist. **A** The origin of the superficial radial nerve from the radial nerve at the anterior lateral elbow appearing as a hypoechoic monofascicular structure. **B** The nerve distal to the elbow running deep to the brachioradialis. **C** At the distal third of the forearm, the nerve still runs deep to the brachioradialis together with the radial artery. **D** The termination of the superficial radial nerve at the distal radial wrist running superficial to the first extensor compartment



SRN: superficial radial nerve

Fig. 12 Example of pathologies of the superficial radial nerve. **A** Short-axis view of the superficial radial nerve in a patient with history of old cut wound at the distal forearm showing encasement of the nerve by scar tissue. **B** Short-axis view of the superficial radial nerve at the distal forearm showing metal wire artefact touching the nerve in a patient with fracture distal radius which was fixated by wires artery) deep to the extensor tendons then runs crosses anterior to the artery to lie medial to it. Distal to the anterior ankle, it divides into medial and lateral terminal branches [53, 54].

Scanning technique *Patient's position*: Lying supine with the knee extended or the patient may lie in lateral decubitus position with the examined side on top.

Scanning window: From the fibular tunnel to the anterior ankle.

Landmarks: At the anterior ankle: anterior tibial artery (dorsalis pedis artery), tibial bone profile, extensor tendons.

At the mid-leg: interosseus membrane, and anterior tibial artery.

At the proximal leg: the common fibular nerve trunk at the fibular tunnel.

Tracing and sonoanatomy: The deep fibular nerve can be identified as it bifurcates from the common fibular nerve at the fibular tunnel. The fibular tunnel is identified at the fibular neck just distal to the fibular head. The deep fibular nerve can be seen inside the tunnel where it represents the anterior terminal branch of the common fibular nerve (Fig. 13A). The nerve is then traced along its leg course. To identify the nerve at the middle leg, the interosseus membrane is first identified as a hyperechoic thin

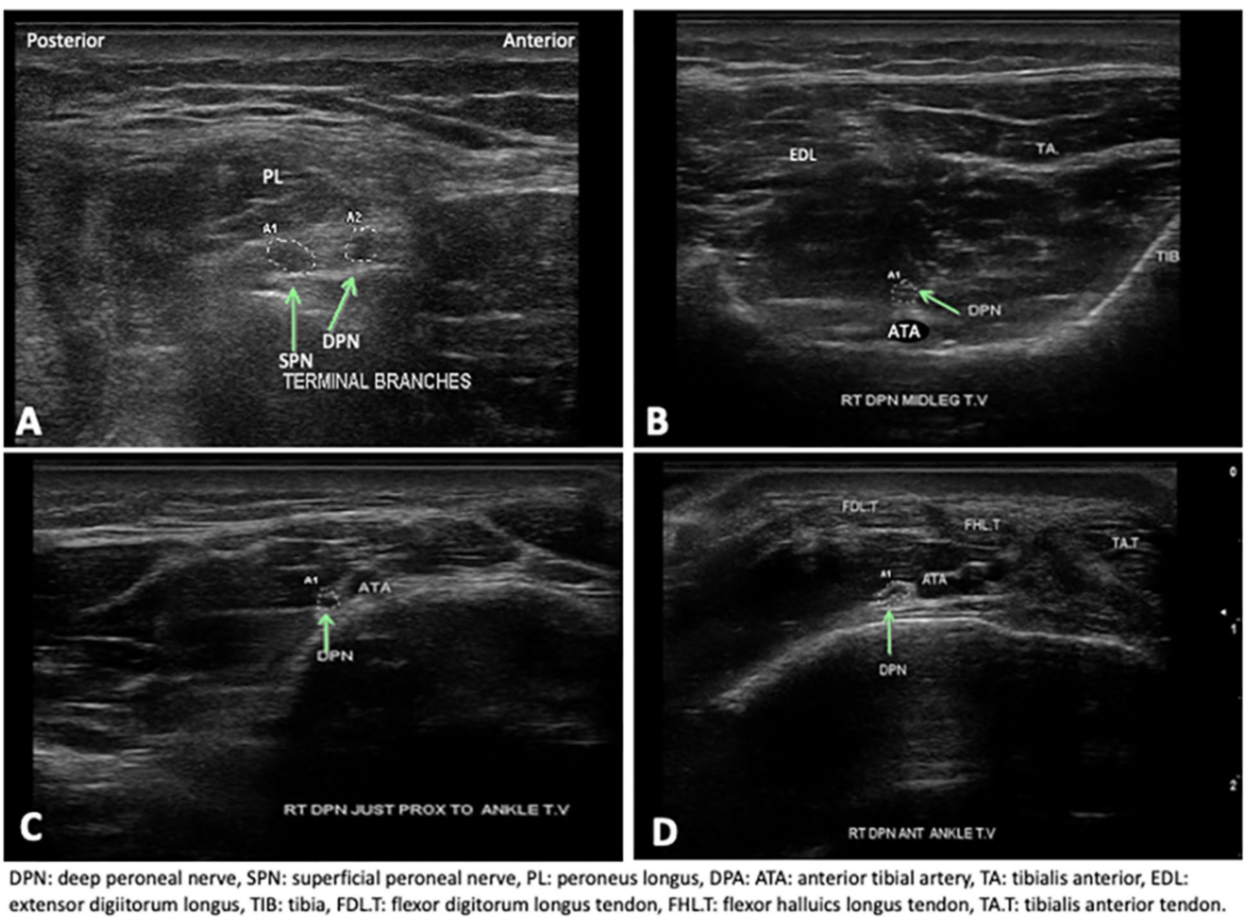


Fig. 13 Sonoanatomy of the deep peroneal (fibular) nerve. Short-axis views of the deep peroneal nerve from its origin from the fibular nerve to the anterior ankle. **A** Terminal division of the common peroneal nerve into deep and superficial peroneal (fibular) nerves at the fibular tunnel level. The anterior branch is the deep peroneal nerve and the posterior branch is the superficial peroneal nerve. **B** The deep peroneal nerve at the mid-leg level seen as a tiny monofascicular structure on top of the anterior tibial artery on the interosseus membrane deep to the tibialis anterior and extensor digitorum longus muscles. **C** The deep peroneal nerve just proximal to the ankle, running adjacent to the anterior tibial artery on its way to the anterior ankle. **D** The deep peroneal nerve at the anterior ankle seen adjacent to the anterior tibial artery (dorsalis pedis artery) and both are coursing over the tibia deep to the extensor tendons

band extending between the tibia and fibula deep to the anterior leg muscles (tibialis anterior and extensor digitorum longus). Next, one should look for a small artery running over the interosseus membrane representing the anterior tibial artery. The deep fibular nerve can then be identified as tiny monofascicular structure located adjacent or sometimes on top of the artery (Fig. 13B). As the nerve approaches the ankle, it becomes superficial and can be recognized running adjacent to the anterior tibial artery (Fig. 13C). Tracing further distally, the nerve can be easily identified running over the distal end of the tibia accompanied by the anterior tibial artery (dorsalis pedis artery) deep to the extensor tendons (Fig. 13D).

It should be noted that sometimes it is difficult to identify the nerve at the proximal leg due to its relatively curved course from lateral compartment to the anterior leg compartment. Therefore, it may be easier to start tracing the nerve from the anterior ankle where the nerve can be clearly seen. Scanning at this level starts by placing the probe in the axial view at the anterior ankle. The distal end of the tibia is identified as a flat hyperechoic bone with posterior acoustic shadow. Looking over the bone profile, the anterior tibial artery is identified by its anechoic appearance and pulsating nature. The nerve is then recognized as a small honeycomb or sometimes monofascicular tiny structure lateral to the artery (Fig. 13D). From the anterior ankle, the nerve can be traced proximally until it reaches the fibular tunnel.

Pathologies The deep fibular nerve is most vulnerable to injury at the anterior ankle where it is relatively superficial. At this level, the nerve can result from ankle sprain or follows external fixation of the ankle [55, 56]. Rarely, idiopathic nerve entrapment can occur at the anterior ankle which is known as anterior tarsal tunnel syndrome [57]. Predisposing factors for anterior tarsal tunnel syndrome include cast, and tight-fitting shoes [57, 58]. At the midleg and proximal leg, the nerve is protected due to its position deep the anterior leg compartment muscles, but it can be compromised in compartment syndromes [59]. Deep fibular nerve palsy may develop secondary to extraneural [60] or intraneural ganglion cyst [61] (Fig. 14).

Superficial fibular nerve

Anatomy The superficial fibular nerve is the second terminal branch of the common fibular nerve that bifurcates from the main nerve trunk at the fibular neck level and runs in the lateral leg compartment. As it leaves the fibular tunnel, it descends deep to the fibularis longus, passes forward and downward to emerge between the fibularis longus and extensor digitorum longus muscle then courses superficially in the lateral compartment between fibularis brevis and extensor digitorum longus [53, 54]. It pierces the crural fascia at the distal third of the leg to run in the subcutaneous tissue towards the ankle anterior to the lateral malleolus where it courses superficial to the tendons of the tibialis anterior, extensor hallucis longus, and extensor digitorum longus and the overlying superior extensor retinaculum [53, 54]. At the anterior ankle or proximal to it, the nerve divides into medial and intermediate dorsal cutaneous nerves. Proximal division of the nerve may occur while the nerve is still deep to the crural fascia [53, 54].

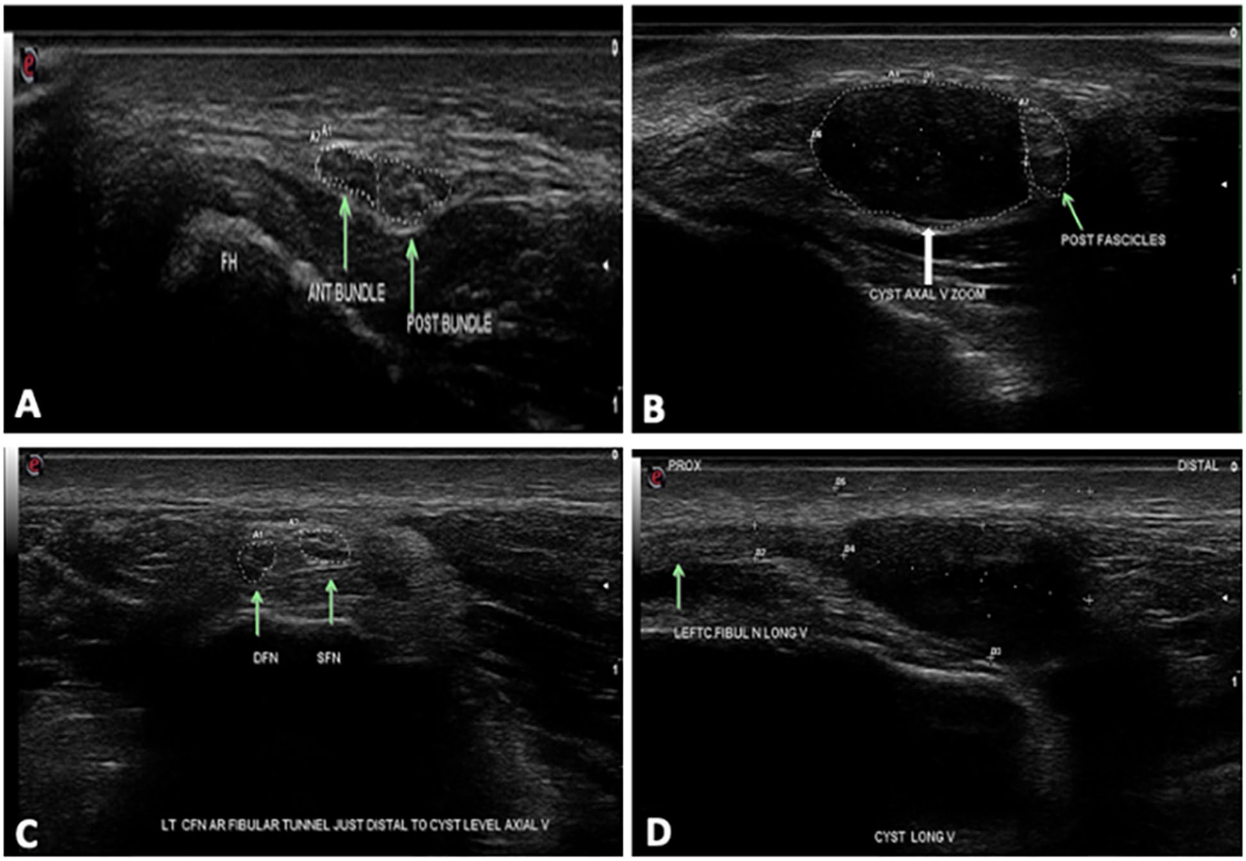
Scanning technique *Patient's position*: Supine or side-lying with the examined leg on top.

Scanning window: from the fibular tunnel to the anterior ankle.

Landmarks: Peroneus longus/brevis, extensor digitorum longus, fibula and lateral intermuscular septum.

Tracing and sonoanatomy: Scanning can start at the mid- or lower third of the lateral leg where the nerve lies superficially under the fascia in the junction between the peroneus brevis and the extensor digitorum longus. To capture the image at this level, the probe is placed in the axial view at the distal third of the lateral leg along a line extending between the fibular head and lateral malleolus. Two muscles are identified at this level: the peroneus longus (PL) laterally and the extensor digitorum longus (EDL) medially or anteriorly. The identity of the two muscles can be confirmed by dynamic passive or active movement or by following them distally to their tendons. The superficial fibular nerve is then identified as a honeycomb structure lying superficially just under the deep fascia of the leg at the junction between the PL and EDL (Fig. 15A). Next, the nerve can be traced proximally to see it passing under the peroneus longus (Fig. 15B) and ending by joining the deep fibular branch at the fibular tunnel (Fig. 15C) to form the main common fibular nerve trunk. It can also be traced distally to the ankle. As it courses distally, it can be seen traversing the deep fascia to run in the subcutaneous tissue (Fig. 15 D) to reach the anterior ankle medial to the lateral malleolus where it can be seen as flat small nerve lying superficial to the extensor tendons and the superior extensor retinaculum.

An alternative tracing technique is to start at the fibular head by identifying the common fibular nerve then tracing the nerve distally as it passes through the fibular tunnel and bifurcates into deep fibular nerve



ANT BUNDLE: anterior bundle, POST BUNDLE: posterior bundle, FH: fibular head, POST FASCICLES: posterior fascicles, DPN: deep peroenal nerve, SPN: superifical peroneal nerve, CFN: common fibular nerve, FIBUL N: fibular nerve.

Fig. 14 Example of a pathology of the deep peroenal (fbular) nerve. Ultrasound images of left common peroneal (fibular) nerve in a patient presented with left foot drop. **A** Short-axis view of the common fibular nerve at the fibular head showing normal appearance and average nerve cross-sectional area. Note how the nerve consists of anterior bundle which will eventually form the deep peroneal nerve and posterior bundle which will eventually form the superficial peroneal nerve. **B** Short-axis view of the common fibular nerve distal to the fibular head and just proximal to the fibular tunnel showing a well-defined anechoic avascular and non-compressible swelling emerging from the anterior bundle consistent with intraneural ganglion cyst. Note that the posterior nerve bundle is intact with preserved fascicular pattern. **C** Short-axis view of the CFN at the fibular tunnel distal to the swelling level showing normal appearance of the deep and superficial fibular nerves. **D** Long-axis view of the cyst showing its continuity with the nerve

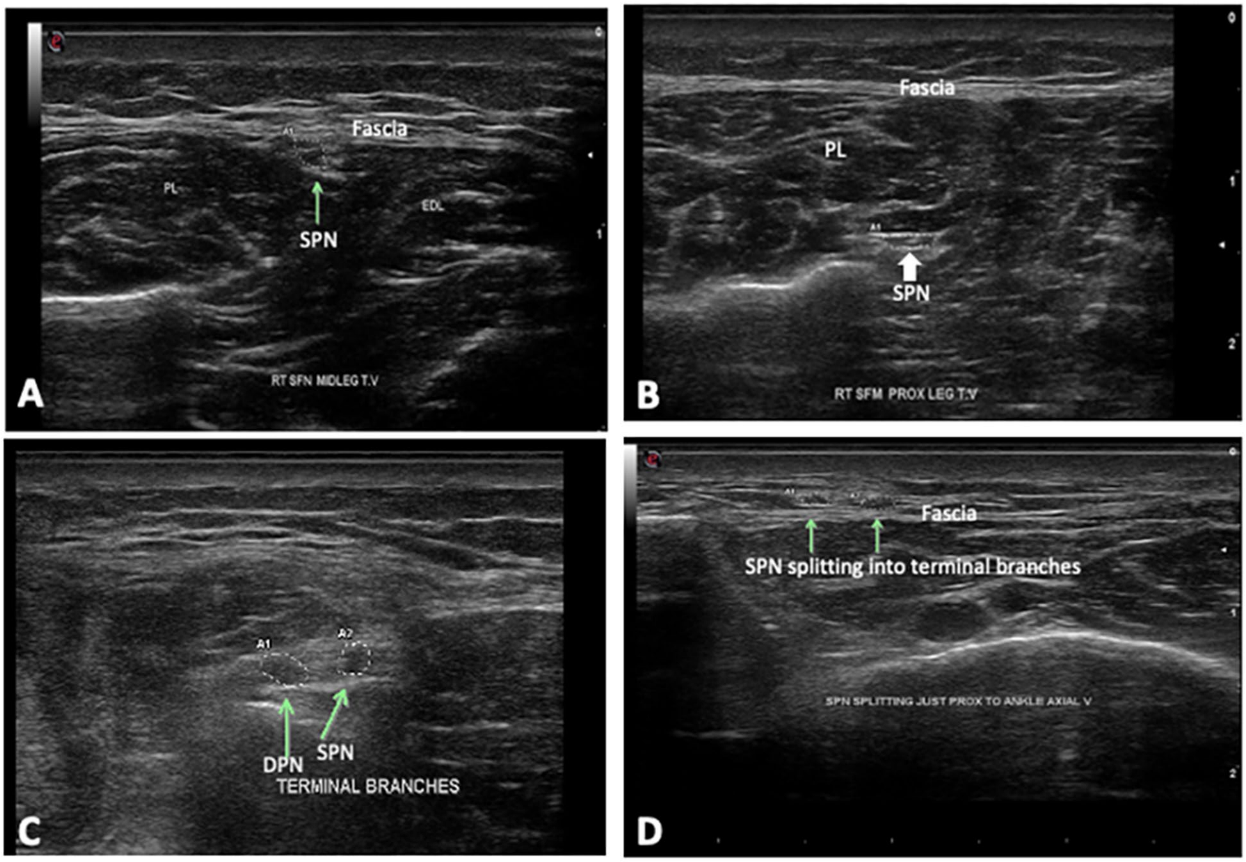
(anterior branch) and superficial fibular (posterior branch) (Fig. 15C). From there, the superficial can be traced distally down to the anterior ankle as described above.

Pathologies The superficial fibular nerve can be directly injured by open or closed trauma to the lateral leg (Fig. 16). Iatrogenic injury during surgery as in anterior compartment fasciotomy is possible [62]. Therefore, preoperative ultrasound nerve mapping can be useful to avoid nerve injury during surgery. Repetitive nerve stretch can be triggered by prolonged kneeling or squatting, long-distance running, muscle fat herniation, and recurrent ankle sprains or instability [63]. Superficial fibular nerve entrapment has also been described in dancers due to peroneal muscle hypertrophy or tight ballet slippers around the mid-calf [64].

Small nerves of the upper limb

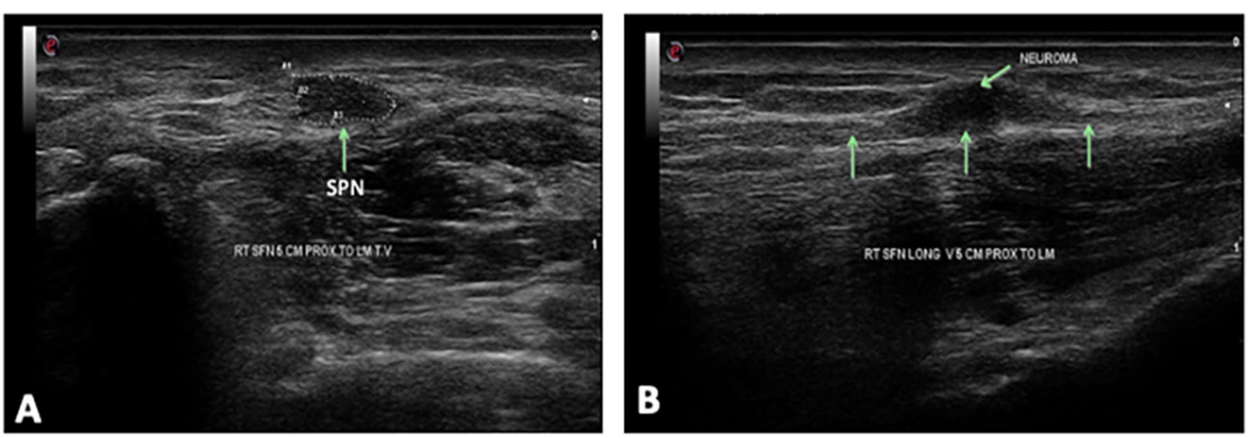
Musculocutaneous nerve

Anatomy The musculocutaneous nerve originates from the lateral cord of the brachial plexus. It first descends along the medial border of the coracoid process, then pierces the coracobrachialis muscle [65]. At the axilla, it lies lateral to the axillary artery and median nerve and runs between the short head of the biceps brachii



SPN: superifical peroenal nerve,, PL: peroenus longus, EDL: extensor digitorum longus.

Fig. 15 Sonoanatomy of the superficial peroenal (fibular) nerve. Short-axis views of the superficial fibular nerve from its origin from the fibular nerve to the ankle. **A** Terminal division of the common peroneal nerve into deep and superficial peroneal nerves. The anterior branch is the deep peroneal nerve and the posterior branch is the superficial peroneal nerve. **B** The superficial peroneal nerve distal to the fibular tunnel at the proximal third of the leg coursing deep to the peroneus longus muscle. **C** The superficial peroneal nerve at the mid-leg running between the peroneus longus and extensor digitorum longus under the deep crural fascia. **D** The superficial peroneal nerve at the distal leg running in the subcutaneous tissue after it traverses the deep crural fascia. The nerve splits into two terminal branches



SPN: superifical peroenal nerve

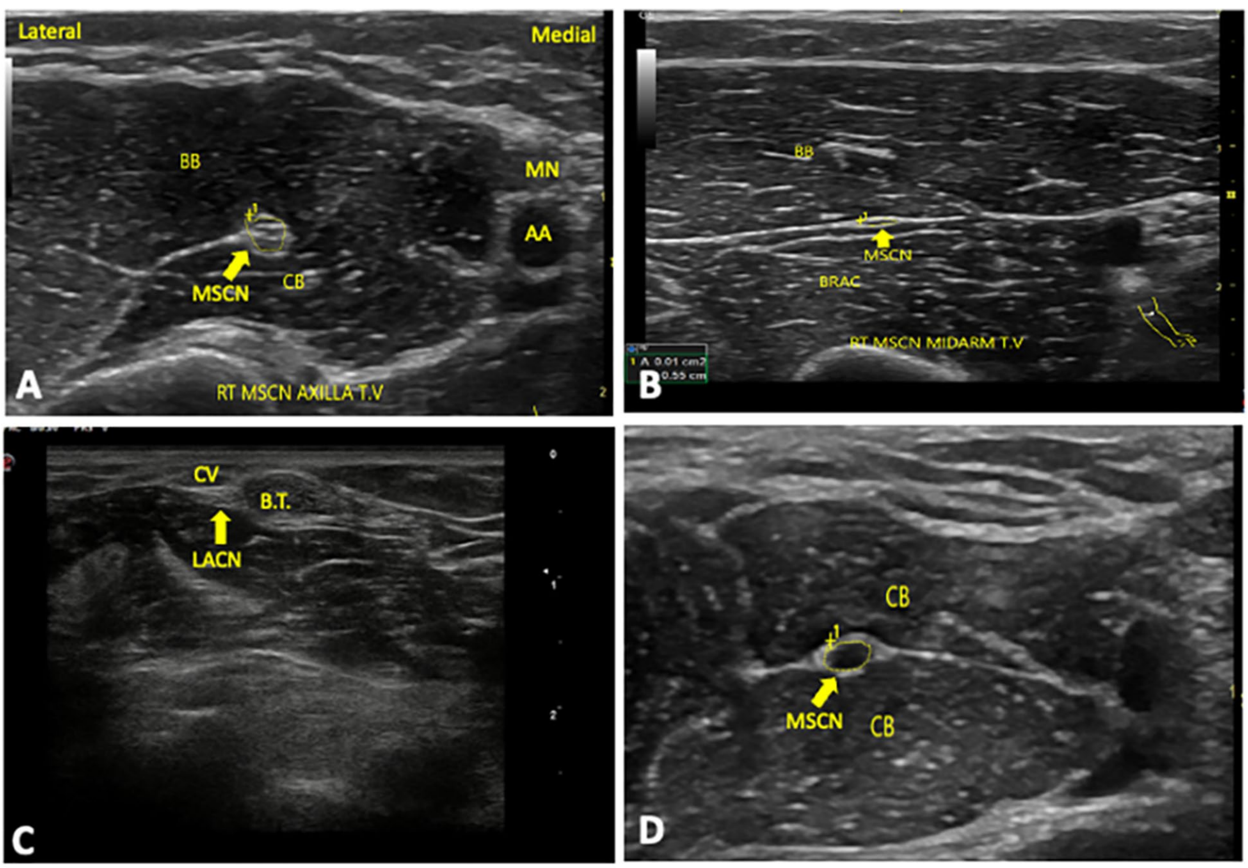
Fig. 16 Example of a pathology of the superficial fibular nerve. Ultrasound images of the superficial peroneal nerve in a patient with traumatic injury to the distal third of the leg. **A** Short-axis view of the nerve showing hypoechoic swelling of the nerve at a level 5 cm proximal to the ankle. **B** Long-axis view showing a fusiform hypoechoic swelling in continuity with the nerve denoting neuroma-in-continuity superficially and the coracobrachialis deeply. It then descends along the arm running in the fascial plane between the biceps brachii and brachialis [65]. As it approaches the elbow, it courses laterally and become more superficial. At the elbow, it runs lateral to the biceps tendon and penetrates the deep fascia of the forearm to continue as the lateral cutaneous nerve of the forearm [65]. Several anatomic variations of the nerve have been reported. The most common is presence of a communicating branch between the musculocutaneous nerve and the median nerve. Rarely, the nerve may not penetrate the coracobrachialis and may be absent [66].

Scanning technique *Patient's position*: Supine position with the shoulder abducted and externally rotated to open the axilla.

Scanning window: From the axilla to the antecubital fossa.

Landmarks: Axillary artery, median nerve, biceps brachii, coracobrachialis, brachialis.

Tracing and sonoanatomy: An easy way to identify the musculocutaneous nerve is to start at the axilla. The initial landmarks to recognize are the axillary artery and the median nerve. The artery can be identified by its anechoic appearance, pulsating nature, and Doppler signal. The median nerve is seen as a honeycomb structure lateral or superolateral to the axillary artery (Fig. 17A). Looking lateral to the axillary artery and median nerve, the musculocutaneous nerve can be readily visualized as a honeycomb structure running between two muscles bellies:



MSCN: musculocutaneous nerve, CB: coracobrachialis, BB: bicpes brachii, MN: median nerve, AA: axillary artery, BRAC: brachialis, B.T: biceps tendon, LACN: lateral antebrahcial cutaneous nerve, CV: cephalic vein.

Fig. 17 Sonoanatomy of the musculocutaenous nerve. **A** Short-axis view of the musculocutaneous nerve at the axilla appearing as honeycomb oblong structure running between the superficial short and long heads of the biceps and the deeper coracobrachialis. **B** Short-axis view of the musculocutaneous nerve at the midarm appearing as a tiny flat structure running in the fascial plane between the superficial biceps brachii and the deep brachialis. **C** Short-axis view at the anterior lateral aspect of the cubital fossa showing the musculocutaneous nerve terminating superficially as the lateral antebrachial cutaneous nerve adjacent to the cephalic vein and lateral to the biceps tendon. **D** Short-axis view of the musculocutaneous nerve at the proximal axilla traversing the coracobrachialis the two heads of the biceps brachii superficially and the coracobrachialis deeply (Fig. 17A). At this level, the nerve shape can be variable appearing as a round, oval, or even a triangular structure. Once the nerve is identified, it is best to keep it at the center of the image and trace it distally to the midarm level where it is seen running in the fascial plane separating the superficial biceps brachii and the deep brachialis level (Fig. 17B). At this level, it typically acquires a flat monofascicular appearance or sometimes appear as train of few fascicles. A better recognition of the nerve can be achieved by back and forth tracing several times. Sweeping the probe distally towards the elbow, the nerve can be recognized running more superficially and laterally to continue as the lateral antebrachial cutaneous nerve at the lateral aspect of the antecubital fossa (Fig. 17C). From the same starting point at the axilla, sweeping the probe slowly up allows the visualization of the nerve as it pierces the coracobrachialis (Fig. 17D) and can be further followed to the level of the coracoid process.

Pathologies Any open or closed trauma can injure the musculocutaneous nerve along its course from the axilla to the elbow although isolated nerve lesion is uncommon [67]. It can also be compromised by extrinsic factors like intramuscular masses (Fig. 18 A) or metal plates and screws (Fig. 18B). Forced abduction and external rotation of the shoulder may cause stretch injury to the nerve [68]. Heavy exercise may also lead to nerve compression [69]. Parsonage-Turner syndrome may occasionally affect the musculocutaneous nerve causing an hour-glass constriction of the nerve [70].

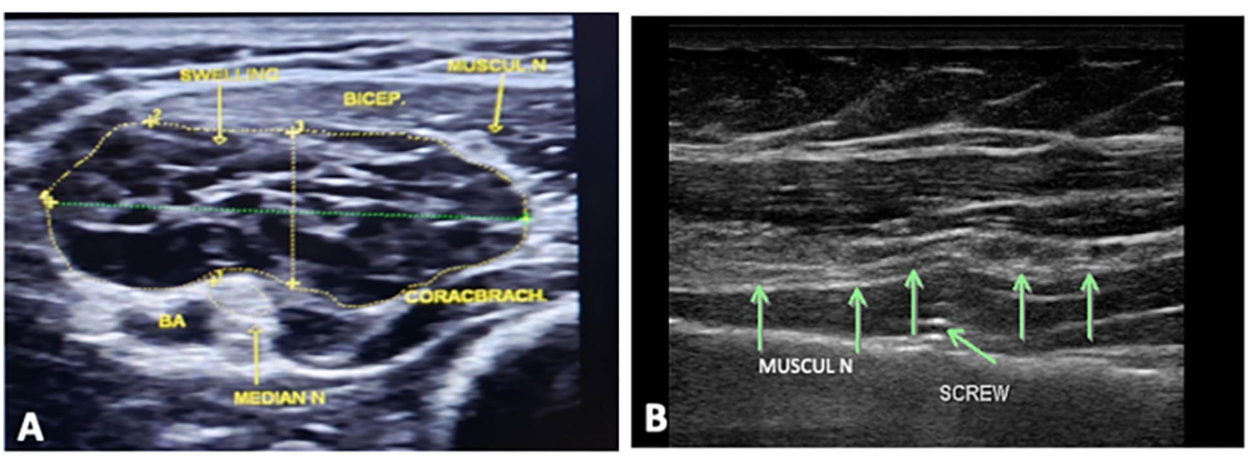
Suprascapular nerve

Anatomy The suprascapular nerve arises from the upper trunk of the brachial plexus. At the neck, the nerve crosses the posterior triangle of the neck parallel to the inferior belly of omohyoid [71]. It then runs along the superior border of the scapula and passes through the suprascapular canal formed by the suprascapular notch and the superior transverse scapular ligament to enter the supraspinous fossa where it runs deep to the trapezius and supraspinatus [65]. It leaves the supraspinous fossa to curve round the lateral border of the spine of the scapula with the suprascapular artery and continues through the spinoglenoid underneath the inferior transverse scapular ligament to reach the infraspinous fossa, where it gives two branches to infraspinatus and articular rami to the shoulder and acromioclavicular joints [65].

Scanning technique *Patient's position*: To scan the nerve at the scapular region, the patient may either lie prone or sit with the back facing the physician. To scan the nerve at the neck, the patient may lie supine with the neck rotated to the opposite side or the patient may sit facing the machine while the sonographer stands behind the patient.

Scanning window: Supraclavicular fossa and scapular region.

Landmarks: At the neck: upper trunk of the brachial plexus, inferior belly of omohyoid.



MUSCUL.N: musculocutaneous nerve, CORACOBRACH.: coracobrachialis, BA: brachial artery.

Fig. 18 Examples of pathologies of the musculocutaneous nerve. **A** Short-axis view at the proximal arm in patient with medial arm soft tissue swelling showing an intramuscular lipoma inside the biceps brahcii muscle pushing and displacing the musculocutaneous nerve. **B** Long-axis view of the musculocutaneous nerve in a patient with fracture humerus, fixated by plate and screws. One of the screws is seen indenting and pushing the nerve

At the supraspinous fossa: trapezius, supraspinatus, suprascapular notch, and suprascapular artery.

At the infraspinous fossa: infraspinatus, glenohumeral joint, infraglenoid notch, and suprascapular artery.

Tracing and sonoanatomy: At the neck, scanning starts at the interscalene groove level to identify the trunks of the brachial plexus running between the anterior and middle scalene muscles. The upper trunk is then traced distally to the supraclavicular level to identify the suprascapular nerve as a small monofascicular branch bifurcating from the upper trunk to run laterally under the inferior belly of the omohyoid muscle (Fig. 19A).

To capture the suprascapular nerve at the supraspinatus fossa, the probe is placed in a transverse position over the supraspinatus fossa. Two muscles are visualized deep to the skin and subcutaneous tissue: the trapezius superficially and the supraspinatus deeply. Deep to the supraspinatus muscle, the suprascapular notch appears as a hyperechoic concavity at the bottom of the image with posterior acoustic shadow. The suprascapular nerve can then be identified lying in the notch (Fig. 19B) adjacent to the suprascapular artery. The artery can be differentiated from the nerve using Doppler, but sometimes it does not display signal due to its deep location. By angulating and tilting the probe, the suprascapular ligament can sometimes be recognized as a thin hyperechoic line overlying the nerve and the artery.

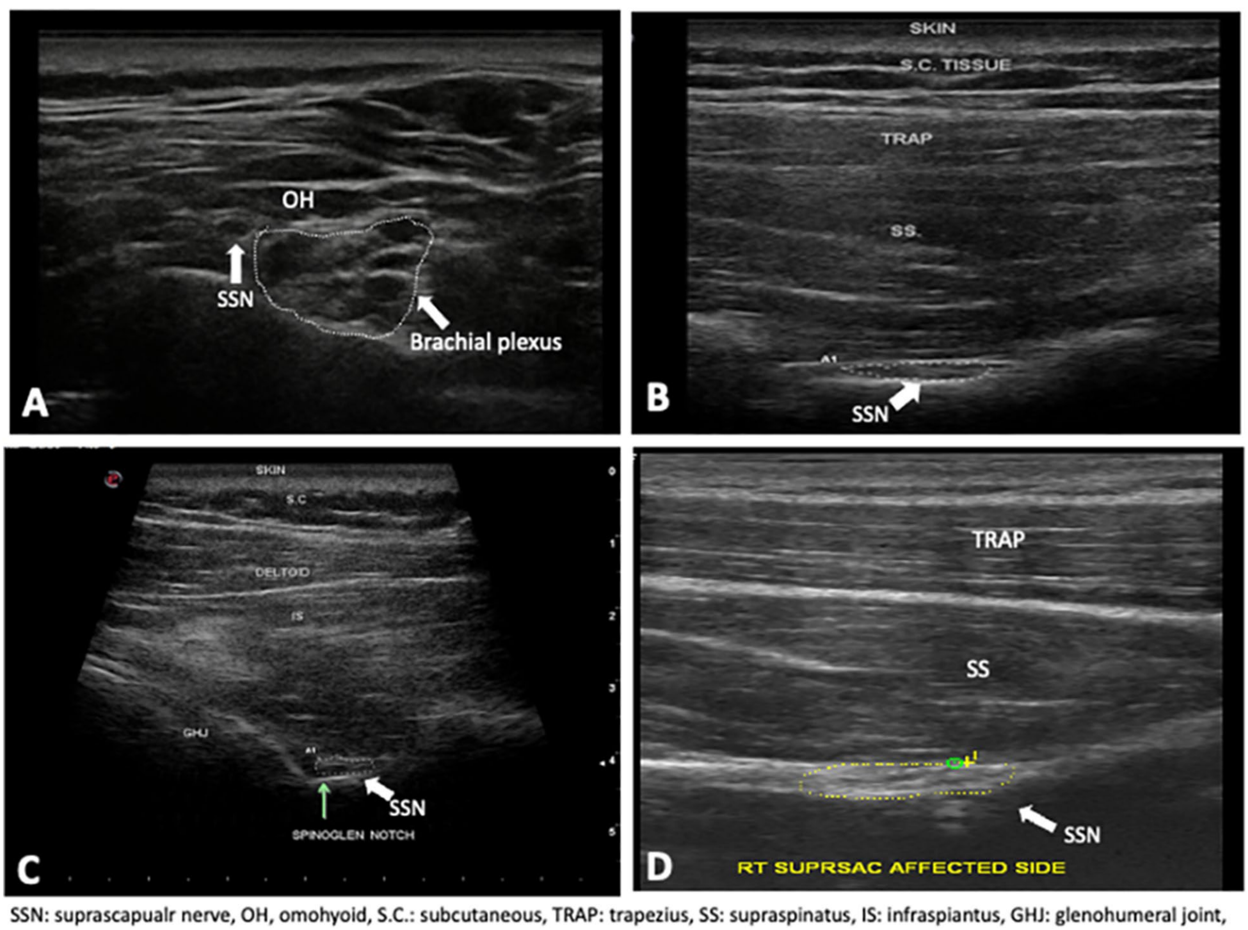


Fig. 19 Sonoanatomy and example of a pathology of the suprascapular nerve. **A** Short-axis view of the suprascapular nerve at the supraclavicular fossa identified as a small monofascicular structure originating from the superolateral aspect of the brachial plexus and running under the omohyoid muscle. **B** Short-axis view of the suprascapular nerve at the supraspinous fossa lying in the supraspinatus notch deep to the trapezius and supraspinatus muscles. **B, C** Short-axis view of the suprascapular nerve at the spinoglenoid notch deep to the infraspinatus muscle. **D** Short-axis view of the suprascapular nerve at the supraspinous fossa in a patient with suprascapular neuropathy showing marked nerve enlargement with a cross-sectional area of 41 mm^2

To scan the nerve at the spinoglenoid notch, the probe is initially placed at the posterior shoulder to identify the glenohumeral joint. Once the joint is found, the probe is swept laterally to identify the spinoglenoid notch as a hyperechoic concavity. The nerve can then be visualized at the notch as a honeycomb or sometimes hypoechoic structure (Fig. 19C).

Pathologies The most common cause of suprascapular neuropathy is nerve compression at either the supraspinous or the spinoglenoid notch by a labral ganglion cyst [72]. Traumatic injuries of the nerve at the scapular region are rare because the nerve is protected by the overlying muscles. However, the nerve can be injured at the neck as part of the brachial plexus injury [73]. In entrapment, ultrasound usually shows increased nerve cross-sectional area (Fig. 19D) with significant side-to-side difference in cross-sectional area. Localization of the entrapment site can be indirectly achieved through the assessment of the echotexture and thickness of the supraspinatus and infraspinatus muscles [74]. Nerve compression at the supraspinous notch will lead to hyperechogenicity and atrophy of the both the supraspinatus and infraspinatus, while the echotexture changes will be confined to the infraspinatus if the nerve is compressed at the spinoglenoid notch.

Dorsal scapular and long thoracic nerves

Anatomy The dorsal scapular nerve originates at the neck from the C5 root. It passes posteriorly through the substance of the scalenus medius, then descends down between levator scapulae and serratus posterior superior and the posterior scalene muscles. It then runs along the anterior border of the rhomboid muscles medial to the medial border of the scapula and is closely related to the dorsal scapular artery. It innervates the rhomboid and levator scapulae [65].

The long thoracic nerve originates also from the C5, C6, and C7 roots. Similar to the dorsal scapular nerve, it penetrates the scalenus medius where it lies deep to the dorsal scapular nerve. Further distally, it descends towards the floor of the posterior triangle running with the suprascapular nerve under the omohyoid muscle. It ends by coursing over the serratus anterior to supply it [65].

Scanning technique *Patient's position*: The patient may lie supine with the neck slightly extended and rotated to the opposite side or may sit in front of the machine and the sonographer stands behind the patient.

Scanning window: Lateral neck.

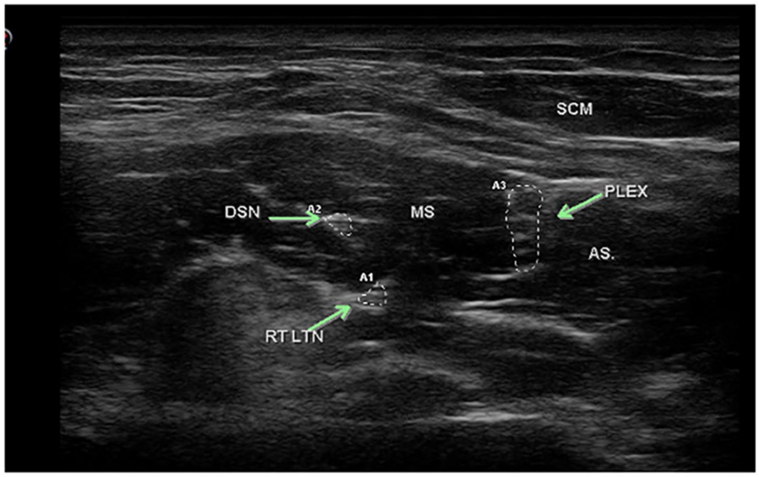
Landmarks: Anterior and middle scalenes and brachial plexus trunks.

Tracing and sonoanatomy: The two nerves can be visualized at the lateral neck as both traverse the middle scalene. The probe is placed in a transverse position at the lateral neck to get the interscalene level. The sonographer may look first for the carotid artery and internal jugular veins which represent clear landmarks at the lateral neck. Sweeping the probe posteriorly, the anterior and middle scalenes can be identified posterior to the carotid sheath with the brachial plexus trunks passing between them (Fig. 20). The long thoracic and dorsal scapular nerves can be recognized as tiny monofascicular structures running in the substance of the middle scalene with the dorsal scapular nerve lying superior to the long thoracic nerve (Fig. 20). Moving the probe back and forth several times can facilitate their visualization. Tracing the dorsal scapular and long thoracic nerves proximally allows their visualization as they emerge from C5 and C6 roots, respectively.

Pathologies Dorsal scapular neuropathy is uncommon, but it is an overlooked cause of scapular winging. Dorsal scapular nerve injury may result from repeated overhead activities or lifting of heavy objects during work or sports, motor car accidents, or post-shoulder surgery [75]. It may also be entrapped within the scalenus medius in athletes with scalene hypertrophy [75]. On the other hand, long thoracic nerve neuropathy is a common cause of scapular winging. Neuropathy from athletic activities and heavy load bearing have been reported [76, 77]. The long thoracic nerve may be also get involved in multifocal motor neuropathy and neuralgic amyotrophy [78, 79].

Lateral antebrachial cutaneous nerve

Anatomy The lateral antebrachial cutaneous nerve represents the continuation of the musculocutaneous nerve. After the musculocutaneous nerve crosses the arm running between the biceps brachii and the brachialis, it descends laterally towards the cubital fossa. As it descends down, it becomes superficial and ends as the lateral antebrachial cutaneous nerve [24]. At the lateral aspect of the antecubital fossa, the lateral antebrachial cutaneous nerve lies lateral to the biceps tendon and posterior or adjacent to the cephalic vein [80] then descends distally along the radial border of the forearm to the wrist [24].



DSN: dorsal scapular nerve, RT LTN: long thoracic nerve, AS: anterior scalene, MS: middle scalene, PLEX: brahcial plexus, SCM: sternocleidomastoid

Fig. 20 Sonoanatomy of the dorsal scapular and long thoracic nerves at the neck. Short-axis view of the dorsal scapular and long thoracic nerves at the neck. The two nerves appear as tiny hypoechoic or sometimes fascicular structures running in the substance of the middle scalene. The dorsal scapular nerve lies superficial to the long thoracic nerve

Scanning technique. Patient's position: Supine or sitting position with the elbow extended and forearm supinated.

Scanning window: Lateral elbow.

Landmarks: Biceps tendon, cephalic vein, musculocutaneous nerve.

Tracing and sonoanatomy: The probe is placed in short axis over the lateral aspect of the anterior elbow. The biceps tendon is first identified as a tightly packed round or oval structure lateral to the brachial artery and the median nerve (Fig. 21). The probe is slightly shifted laterally to look for the cephalic vein (Fig. 21B). The lateral antebrachial cutaneous nerve can then be identified as a honeycomb oval or triangular structure running under the antebrachial fascia adjacent or posterior to the cephalic vein and lateral to the biceps tendon (Fig. 21A, B). If the vein is not seen, release of the pressure by the probe will allow its expansion and visualization. Another recommended scanning technique is not to start at the elbow but rather capture the lateral antebrachial cutaneous nerve by tracing the musculocutaneous nerve from the mid-arm level (See musculocutaneous nerve scanning) and follow it distally to the cubital fossa level where it becomes superficial and ends as the lateral antebrachial cutaneous nerve. The relation of the nerve to the cephalic vein is variable. It may run dorsal, ventral, or adjacent to the cephalic vein.

Pathologies The nerve can be compromised or compressed secondary to biceps tendon tear/rupture or during tendon repair surgery [81–83]. It can also be injured during cephalic vein phlebotomy [84, 85] given its close location to the vein, and in cases of elbow or proximal radius fractures. The nerve may get stretched as a result of faulty arm position during prolonged surgeries [86] or pull-up exercise during vigorous training [87].

Medial antebrachial cutaneous nerve

Anatomy The medial antebrachial cutaneous nerve is a branch of the medial cord of the brachial plexus, receiving contribution from the C8 and T1 roots. At the axilla, it runs superficial to the axillary artery and vein in the area between the median nerve laterally and ulnar nerve medially. It then descends along the medial arm, running adjacent to the basilic vein and penetrates the brachial fascia nearly at the mid-arm. After piercing the brachial fascia, it divides into volar and dorsal branches [65]. The volar branch runs in the subcutaneous tissue over the medial part of the anterior elbow adjacent to median basilic vein. On the other hand, the dorsal branch descends anterior, over, or sometimes posterior to the medial epicondyle [65].

Scanning technique Patient' s position: Supine with the shoulder abducted and externally rotated, and the

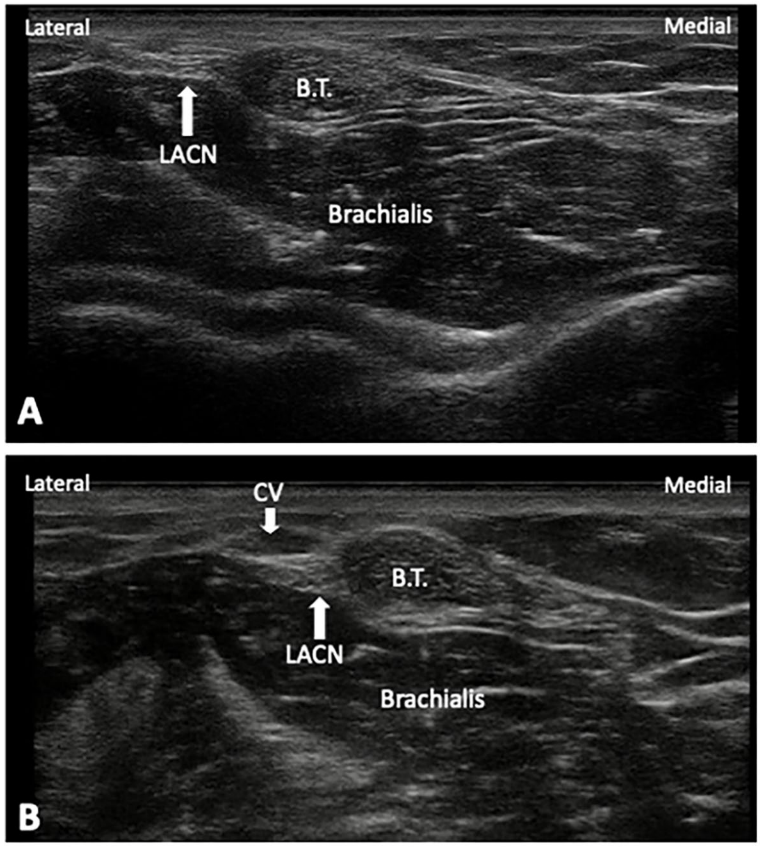


Fig. 21 Sonoanatomy of the lateral antebrachial cutaneous nerve. **A** Short-axis view of the lateral antebrachial cutaneous nerve at the lateral aspect of the antecubital fossa. The nerve appears as small honeycomb structure lying superficially lateral to the biceps tendon and deep to the cephalic vein (the vein is compressed in this image). **B** A zoomed image with releasing the pressure by the probe to expand the cephalic vein showing the lateral antebrachial cutaneous nerve lying deep to the vein and directly lateral to the biceps tendon

forearm supinated with the elbow extended if scanning extends to the antecubital fossa.

Scanning window: Axilla and medial arm down to the elbow. The terminal branches distal to the elbow can be difficult to visualize.

Landmarks: Axillary artery at the axilla, basilic vein along the arm and at the elbow.

Tracing and sonoanatomy: Scanning starts at the axilla by placing the probe in a transverse position over the medial axilla. The axillary artery and vein are identified by their anechoic appearance with posterior acoustic enhancement (Fig. 22A), Doppler signal, and pulsating/ccollapsible nature. Looking superficial to the axillary artery, the medial antebrachial cutaneous nerve can be identified by searching for a small honeycomb structure on top of the axillary artery and vein, lying in the space between the median and ulnar nerves (Fig. 22A). The nerve can be followed distally along the medial arm using the basilic vein as the landmark which runs together with the nerve between the brachialis and the triceps brachii muscles down to the distal arm (Fig. 22B, C). At the cubital fossa, the basilic vein is also used as the vascular landmark to identify the nerve. At this level, both the nerve and the vein run in the subcutaneous tissue superficial to the pronator teres (Fig. 22D).

Pathologies The medial antebrachial cutaneous nerve may get injured during venipuncture of the adjacent basilic vein [88]. Open trauma at the axilla can lead to nerve transection or partial nerve injury given its superficial position at this level (Fig. 23). Snapping of the nerve at the ulnar groove has also been reported [89]. Iatrogenic injury of the nerve may occur during arm brachioplasty surgery [90, 91], cubital tunnel release surgery [92, 93], or local injection for medial epicondylitis [94].

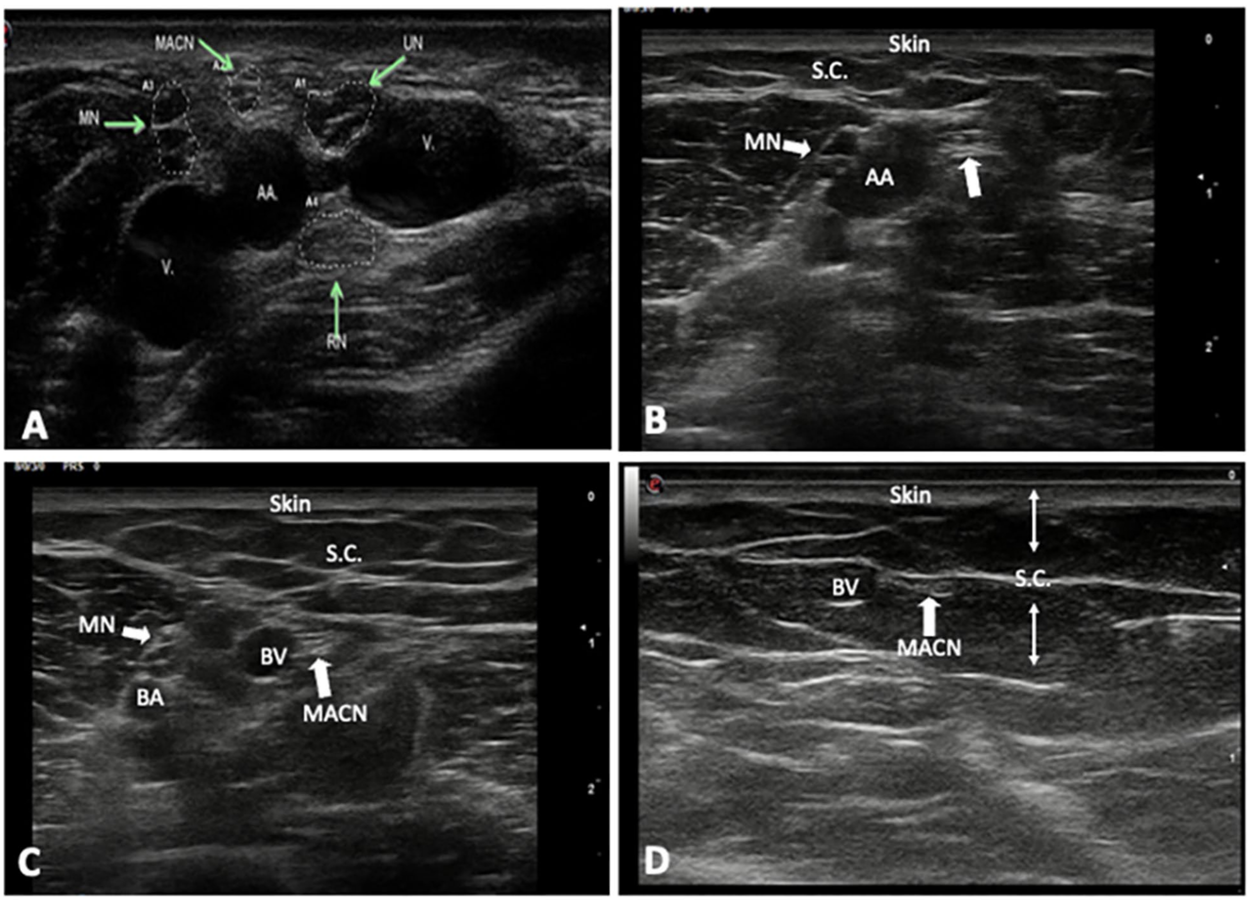


Fig. 22 Sonoanatomy of the medial antebrachial cutaneous nerve. Short-axis views of the medial antebrachial cutaneous nerve from the axilla to the elbow. **A** The medial antebrachial cutaneous nerve at the axilla appearing as a small honeycomb structure lying underneath the brachial fascia superior to the axillary artery in the space between the median and ulnar nerves. Note the orientation of the median, ulnar, and radial nerves around the axillary artery and veins. **B** The medial antebrachial cutaneous nerve just distal to the axilla coursing superomedial to the axillary vein. **C** The medial antebrachial cutaneous nerve at the mid-arm level seen coursing adjacent to the basilic vein and both are running medial to the median nerve and brachial artery. Note the median nerve as it crosses over the brachial artery at the same level. **D** The medial antebrachial cutaneous nerve at the medial aspect of the antecubital fossa showing the anterior branch of the nerve running in the subcutaneous tissue layer adjacent to the basilic vein which is used as the anatomical landmark to identify the nerve

Small nerves of the lower limb

Sural nerve

Anatomy The sural nerve is a purely sensory nerve formed by the union of the medial sural communicating branch which originates from the tibial and the common fibular nerves, respectively. However, the tibial nerve typically provides the major contribution [54]. After bifurcating from the tibial nerve at the popliteal fossa, the medial sural cutaneous branch descends in the groove between the two heads of gastrocnemius and pierces the deep fascia at the proximal leg to join the lateral sural communicating branch at the middle third of the calf to form the one sural nerve trunk [54]. However, the level of union of the two components may vary [95]. The nerve then travels superficial to the two heads of the gastrocnemius. Distal to the gastrocnemius-soleus junction, it descends lateral to the Achilles tendon then passes behind the lateral malleolus posterior to the fibularis longus and brevis tendons where it lies adjacent to the small saphenous vein [54]. Distal to the ankle, it crosses the lateral edge of the foot, ending at the lateral side of the fifth toe in its distal branch (lateral dorsal cutaneous nerve). At the dorsum of the foot, it may communicate with the intermediate dorsal cutaneous branch of the superficial peroneal nerve [54].

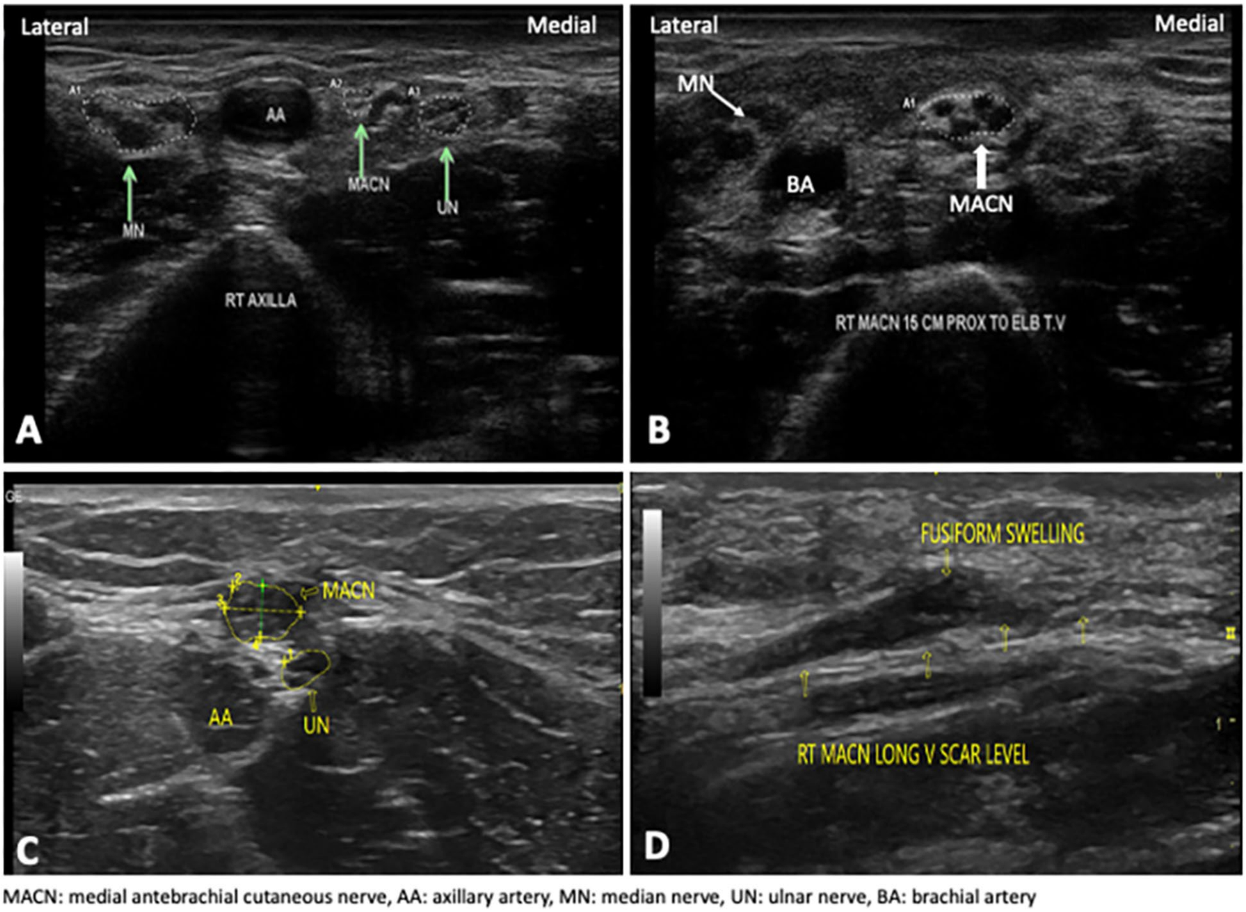


Fig. 23 Examples of pathologies of the medial antebrachial cutaneous nerve. **A, B** Short-axis views of the medial antebrachial cutaneous nerve in a patient with a traumatic injury to medial proximal arm. **A** At the axilla, the medial antebrachial cutaneous nerve is of average cross-sectional area and its echotexture is preserved. However, in **B**, a level of 15 cm proximal to the elbow, the nerve is enlarged and the internal nerve fascicles are swollen, mostly reflecting axonal and fascicular edema secondary to axonal nerve lesion. **C,D** Short-axis and long-axis views of the medial antebrachial cutaneous nerve in a patient with bullet injury to the medial arm which resulted in neuroma-in-continuity. **C** shows hypoechoic swelling of the nerve. **D** shows the neuroma in the longitudinal view appearing as a fusiform hypoechoic swelling in continuity with the nerve

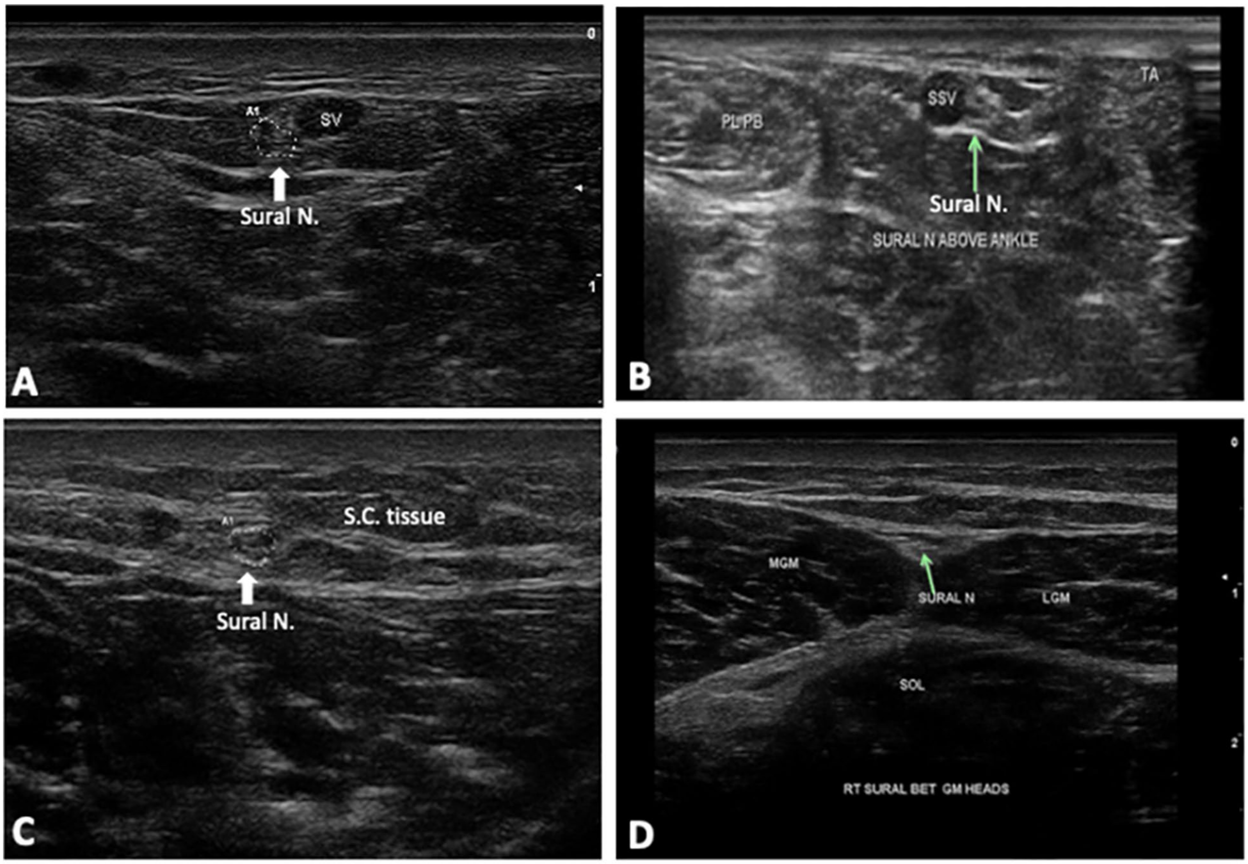
Scanning technique Patient's position: To trace the nerve along its entire course, the patient is asked to lie in the prone position with the foot hanging over the bed.

Scanning window: The nerve can be traced along its entire course from the ankle to the knee.

Landmarks: Small saphenous vein, lateral malleolus at the ankle.

Tracing and sonoanatomy: Scanning can start from the popliteal fossa to see the medial sural and lateral sural nerves bifurcating from the tibial and common fibular nerves, respectively and then each is followed along the leg till they unite to form the sural nerve trunk. However, starting at the lateral ankle and then tracing the nerve proximally to the popliteal fossa is the preferred technique because the nerve can be readily visualized distally using the saphenous vein as the landmark.

To scan the nerve at the lateral ankle, the probe is placed in a short axis posterior to the lateral malleolus spanning the space between the malleolus and the tendoachilles. The lateral malleolus is identified as a convex hyperechoic bone and the tendons of the peroneus longus and brevis can be seen posterior to the lateral malleolus. The next step is to slide the probe posteriorly and search for the small saphenous vein making sure to exert least pressure by the probe to avoid vein collapse. Once the vein is recognized, the sural can be clearly seen as a small honeycomb structure lying adjacent to the vein (Fig. 24A). Just proximal to the ankle, the nerve continues



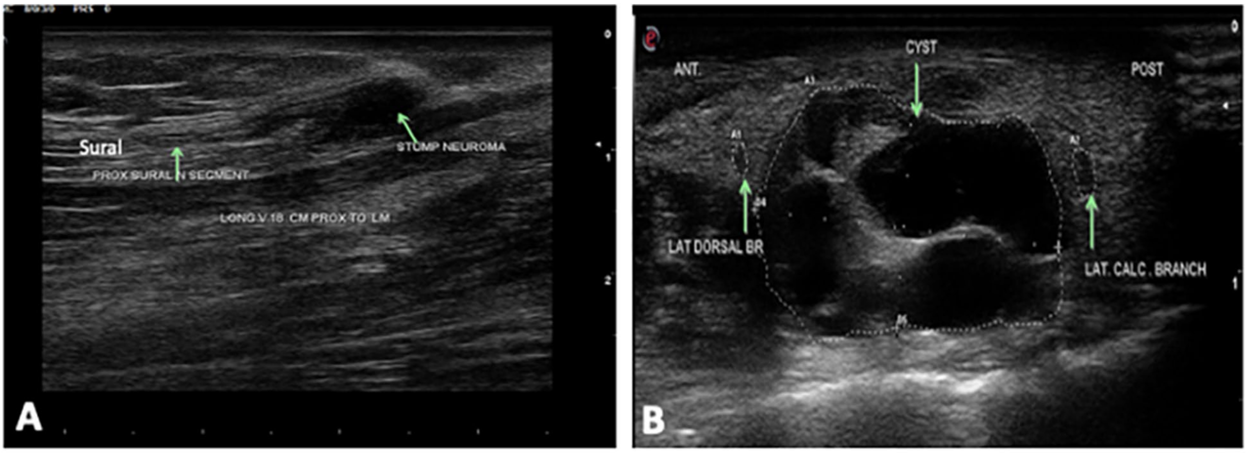
PL: peroenus longus, SV: small saphenous vein, SSV: small saphenous vein, PLPB: peroenus longus and peroneus brevis, TA: tendoachillus, S.C.: subcutaneus, MGM: medial gastrocnemius muscle, LGM: lateral gastrocnemius, SOL: soleus.

Fig. 24 Sonoanatomy of the sural nerve. Short-axis views of the sural nerve from the lateral ankle to the mid-leg. **A** At the lateral ankle, the nerve is identified as a small honeycomb structure adjacent to the small saphenous vein in the space between the peroneal tendons anteriorly and the Achilles tendon posteriorly. **B** Just proximal to the ankle, the sural nerve is still running adjacent to the small saphenous vein. **C** The sural nerve at the distal leg runs in the subcutaneous tissue layer and moves away from the vein. **D** The sural nerve at the calf running in the groove between the two heads of the gastrocnemius

to accompany the vein (Fig. 24B). The nerve is then kept at the center of the image and visually tracked along the leg. As the nerve is scanned proximally, the nerve becomes superficial and runs in the subcutaneous tissue (Fig. 24C) and here it gets relatively distant from the vein. Further proximally, the nerve is seen running between the two heads of the gastrocnemius (Fig. 24D) then emerges to become again superficial. Tracing the nerve to the popliteal fossa, the medial sural communicating nerve will be seen joining the tibial nerve, while the lateral sural communicating branch will be seen joining the common fibular nerve.

Alternatively, scanning can start at the popliteal fossa by identifying the tibial and common fibular nerves and tracing them back and forth several times looking for monofascicular branches leaving them reparenting the medial and lateral sural communicating branches. Each of the two branches is then traced distally until they unite at the mid leg or distal leg. At the distal leg, the small saphenous vein is used as the landmark to identify the nerve. At the ankle level or just distal to it, the nerve may seen dividing into terminal anterior and posterior branches.

Pathologies The most common sural nerve injuries are iatrogenic and traumatic injuries. Iatrogenic injury may result from venous stripping surgery, Achilles tendon repair, or peroneal tendon repair [96–99]. Traumatic leg and ankle injures can easily injure the nerve because of its superficial location [99, 100]. Stump neuroma may develop in the sural nerve post-below knee amputation or post-leg trauma (Fig. 25A). Sural nerve tumors have also been reported [101]. Idiopathic local entrapment is rare but may occur secondary to extrinsic compression by masses like abscess [101] or ganglion cyst (Fig. 25B).



LAT DORSAL BR: lateral dorsal branch, LAT CALC: lateral calcaneal , ANT: anterior, POST: posterior.

Fig. 25 Example of sural nerve pathologies. **A** Long-axis view of the sural nerve in a patient with open leg trauma showing abrupt end of the nerve and a terminal hypoechoic swelling denoting complete nerve transection with formation of proximal stump neuroma. **B** Short-axis view of the sural nerve at lateral ankle just distal to the lateral malleolus in a patient with soft tissue swelling at the lateral ankle showing a well-defined hypoechoic non-compressible swelling with posterior acoustic enhancement and internal septa consistent with ganglion cyst. The cyst is located between the lateral dorsal and the lateral calcaneal branches of the sural nerve

Lateral femoral cutaneous nerve

Anatomy The lateral femoral cutaneous nerve (LFCN) is a purely sensory nerve that originates directly from the lumbar plexus, deriving its fibers from L2 and L3 nerve roots. It exits the pelvis and enters the anterior thigh medial to the anterior superior iliac spine (ASIS), passing under or sometimes through the lateral aspect of the inguinal ligament and over the sartorius muscle [33, 102]. Running distally, the LFCN enters a fascial compartment formed by a double layer of the fascia lata and fascia iliaca between the sartorius muscle medially and the tensor fasciae lata muscle laterally [33, 102]. The nerve then crosses superficial to the sartorius muscle and divides into several terminal branches [33, 102].

It should be noted that the course of the LFCN can vary. The nerve typically passes medial to the anterior superior iliac spine, but it may pass over the ASIS and may pass lateral to it [103].

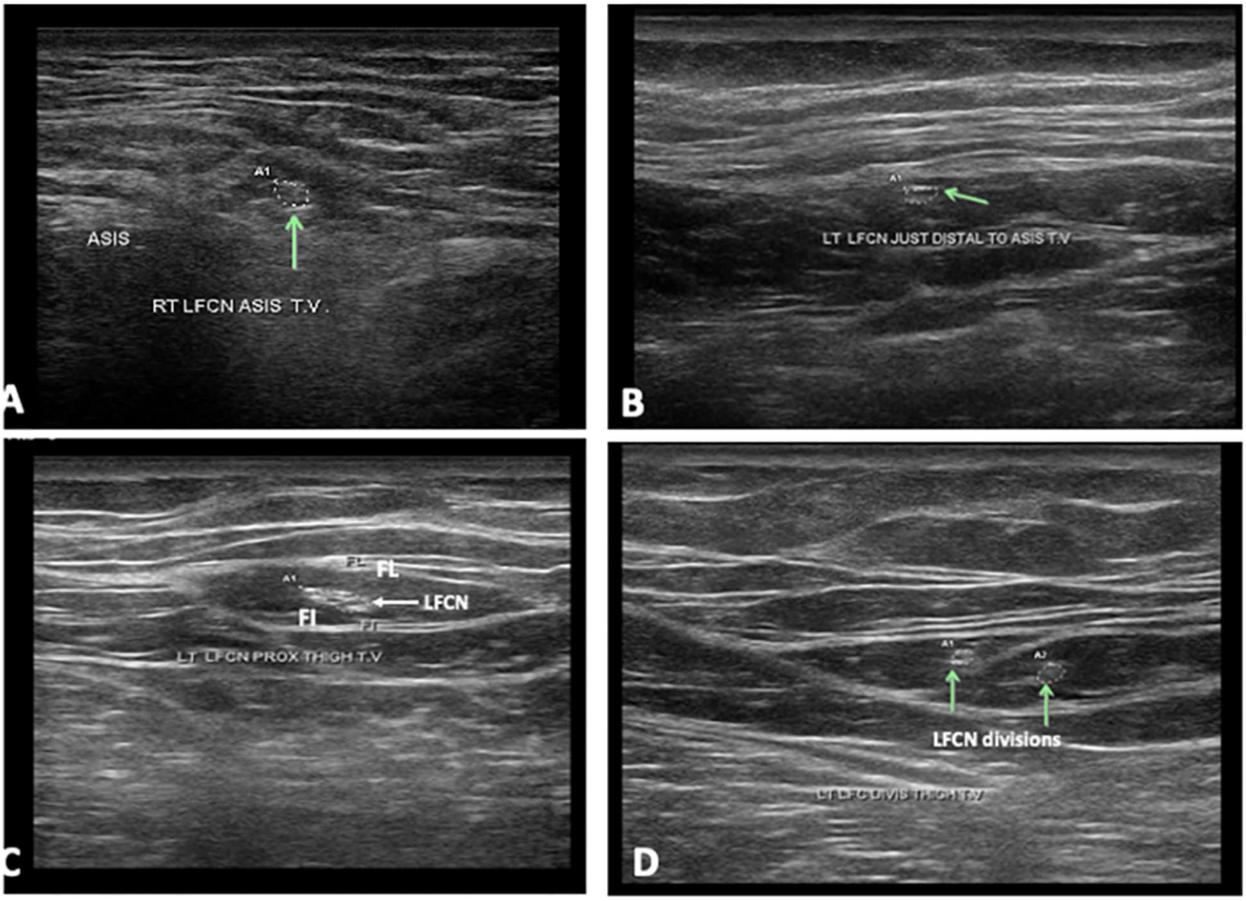
Scanning technique *Patient's position*: Supine with the limb extended and the hip in neutral position.

Scanning window: Proximal third of the thigh.

Landmarks: Anterior superior iliac spine, sartorius muscle, tensor fascia lata, fascia lata, and fascia iliaca.

Tracing and sonoanatomy: Scanning starts by placing the lateral edge of the probe on the anterior superior iliac spine which can be clinically palpated. The probe is then moved medially while trying to keep it parallel to the inguinal ligament to look for a small honeycomb structure running medial to the ASIS (Fig. 26A) over the iliacus muscle representing the lateral femoral cutaneous nerve. The nerve is kept at the center of the image and traced caudally to visualize the nerve coursing distal to the ASIS (Fig. 26B) then running in a lacunar compartment formed by the fascia lata and fascia iliaca (Fig. 26C) superficial to the sartorius muscle. The nerve can be further traced distally for a short distance because it usually divides into several terminal branches (Fig. 16D) which cannot be readily visualized via ultrasound.

Sometimes it is difficult to identify the nerve at the ASIS level because the nerve lies just under the hyperechoic inguinal ligament which makes the nerve ambiguous. In such case, it may be more helpful to start scanning 1–2 cm distal to the inguinal ligament where the contrast between nerve and the surrounding tensor fascia lata and the sartorius facilitates nerve visualization. The tensor fascial lata is located laterally while the sartorius is located medially. The identity of the two muscles can be verified by tracing them distally. The LFCN can then be recognized as an ovoid structure in the intermuscular space between the tensor fasciae latae muscle and the sartorius. At this level, the nerve may appear as a single structure or sometimes it appear as two split nerves which may denote early branching of the nerve.



.FCN: lateral femoral cutaneous nerve, ASIS: anterior superior iliac spine, FL: fascia lata, FL: fascia iliaca

Fig. 26 Sonoanatomy of the lateral femoral cutaneous nerve. Short-axis views of the lateral femoral cutaneous nerve at different levels along the thigh. **A** At the anterior superior iliac spine, the nerve is typically seen running medial to the ASIS which is used as the landmark to identify the nerve. **B** Just distal to the ASIS, the nerve is seen running under the subcutaneous tissue. **C** At the proximal thigh, the nerve can be identified running in a small lacunar-like compartment formed by the superficial fascia lata and the deeper fascia iliaca. **D** Further distally at the thigh, the nerve is seen dividing into two terminal branches

When he LFCN is not seen at its expected location medial to the ASIS, the sonographer should search for it lateral to the ASIS.

Pathologies Entrapment neuropathy of the LFCN or what is known as meralgia paresthetica is the most common lesion affecting the nerve. The LFCN may be entrapped within the pelvis, or as the nerve exits the pelvis deep into the inguinal ligament in close proximity to the anterior superior iliac spine [102, 103].

Meralgia paresthetica usually results from either acute or chronic mechanical irritation near the anterior superior iliac spine where the LFCN passes under the inguinal ligament. It may result from external compression of the nerve by tight-fitting pants or a tight belt especially in thin individuals [104]. Nerve conduction study of the lateral femoral cutaneous nerve can be challenging and difficult to elicit in many instances especially in obese patients. Therefore, ultrasound is considered a helpful alternative tool. Ultrasound allows the visualization of the nerve along its thigh course and may detect focal enlargement of the nerve indicative of entrapment neuropathy, hypochogenicity, or hypervascularity [105, 106]. Ultrasound can also be used to map the course of the nerve prior to nerve conduction study to ensure optimum positioning of the stimulator and the recording electrodes [107].

Conclusion

Neuromuscular ultrasound has emerged as a valuable complementary diagnostic tool for various nerve disorders. Efficient assessment of the nerve branches and small nerves using ultrasound require solid knowledge of the anatomy and mastering the scanning technique. This article provides an overview of some important nerve branches and small nerves with a focus on the scanning and tracing techniques to facilitate the diagnosis of different pathologies using ultrasound.

Abbreviations

ASIS	Anterior superior iliac spine
DUCN	Dorsal ulnar cutaneous nerve
EDL	Extensor digitorum longus
FCR	Flexor carpi radialis
LFCN	Lateral femoral cutaneous nerve
PCN	Palmar cutaneous nerve
PIN	Posterior interosseus nerve
PL	Peroneus longus

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