INVITED REVIEW

NEUROMUSCULAR ULTRASOUND OF THE BRACHIAL PLEXUS: A STANDARDIZED APPROACH

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ABSTRACT: Reliable assessment of brachial plexus disorders can be challenging due to the complexity of the anatomy and variation of potential pathology. Electrodiagnostic testing can be both uncomfortable for the patient and inconclusive. Ultrasound can serve as a complement to clinical assessment, electrodiagnostic testing, and other imaging modalities. This study describes a systematic approach for performing neuromuscular ultrasound for suspected pathology in the brachial plexus. The literature regarding techniques for brachial plexus ultrasound was reviewed. A team composed of specialists in neurology, physiatry, anesthesiology, orthopedic surgery, and vascular surgery used this as the basis for describing standardized techniques for performing brachial plexus ultrasound. Four standard views, along with other supplemental views, are described for the evaluation of the brachial plexus. An illustrative case is presented. Ultrasound is a high-resolution point of care diagnostic tool that allows assessment of structural pathology affecting the brachial plexus.

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Brachial plexus lesions can be divided into those with traumatic and those with nontraumatic (neoplastic, autoimmune, inflammatory, and compressive) etiologies.[1] These lesions are often anatomically complex and, therefore, present diagnostic challenges. A history and physical examination is always the first step in a comprehensive evaluation of suspected brachial plexus pathology.[2] Electrodiagnostic testing aids in localization and diagnosis, but can be confounded by other factors. This includes temporal changes after an acute injury, patchy involvement of the brachial plexus and comorbid factors such as underlying generalized neuropathy or cervical radiculopathy.[3] Ultrasound is a painless, point of care imaging option that may assist the clinician in improving localization and diagnosis, and ultimately patient outcomes.[4,5]

Ultrasound has been used for decades for peripheral nerve blocks in anesthesia.[6] Only in the past decade has neuromuscular ultrasound been incorporated into the diagnosis and characterization of brachial plexus pathology.[4] In this study, we describe a reproducible, standardized technique for visualizing the brachial plexus as a complement to electrodiagnostic testing.

RELEVANT ANATOMY

The brachial plexus is an intricate web of nerve fibers that originate from the ventral portion of the C5 through T1 nerve roots and become trunks, cords, divisions, and ultimately branches.[7] The nerve roots exit the neuraxis between the anterior and middle scalene muscles and form nerve trunks. The upper trunk is formed by C5 and C6. C7 becomes the middle trunk while C8 and T1 make up the lower trunk. Superior to the clavicle, each trunk divides into anterior and posterior divisions. Inferior to the clavicle, the divisions coalesce into cords; anterior divisions of the superior and middle trunks form the lateral cord, the anterior division of the inferior trunk forms the medial cord and the posterior divisions of all trunks form the posterior cord. In the infraclavicular space, the brachial plexus travels underneath the pectoralis muscles, and the cords become the following nerve branches in the proximal axilla: musculocutaneous, axillary, radial, median, and ulnar.

Nerve bundles travel immediately adjacent to readily identifiable blood vessels. Familiarity with vascular anatomy will significantly enhance localization and reliable assessment of the brachial plexus (Supplementary Fig. S1, which is available online).[8] The subclavian artery is located between the anterior and middle scalene muscles in the lower interscalene triangle. The subclavian artery is deep and medial to the brachial plexus trunks. The subclavian

Additional supporting information may be found in the online version of this article.

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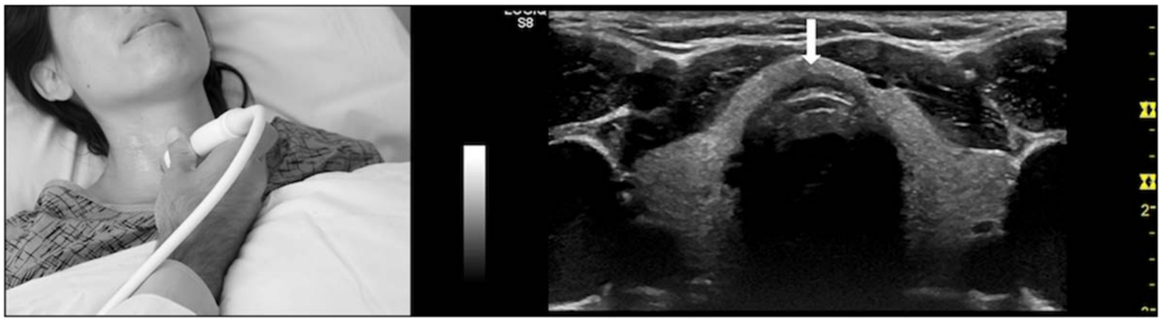

FIGURE 1. The left panel demonstrates the transducer placement for imaging the trachea and thyroid. The right panel shows the isthmus of the thyroid (arrow), superficial to the trachea. The isthmus of the thyroid is located at approximately the C6 level.

vein travels superficial to the anterior scalene muscle. The thyrocervical trunk branches from the subclavian artery. It arises lateral to the vertebral artery and adjacent to the anterior scalene muscle. It has four branches; the inferior thyroid artery, the suprascapular artery, the ascending cervical artery, and the transverse cervical artery. The transverse cervical artery has two branches; the superficial cervical artery and the dorsal scapular artery. The dorsal scapular artery typically enters the brachial plexus at the division level, splits the middle and lower trunks, and runs adjacent to the dorsal scapular nerve. In the infraclavicular region, the subclavian artery becomes the axillary artery, is lateral to the axillary vein, and travels adjacent to the cords of the brachial plexus. This forms a triangular appearance around the artery. Distally, the branches of the plexus surround the brachial artery and vein, which are continuations of the axillary artery and vein, in the axilla and proximal arm

ULTRASONOGRAPHIC APPROACH

Optimal positioning of patient and sonographer is helpful when performing brachial plexus ultrasound. We recommend the patient be positioned supine with 2 to 3 pillows or a wedge supporting their head so that they are at a 30° to 45° incline. Consider placing a pillow across the patient's chest to serve as a brace for the examiner's arm. The patient's head should be slightly extended and turned away from the side of the neck being imaged. The sonographer is positioned on the side of the brachial plexus being studied with the machine at the head of the patient. In this position the sonographer can easily visualize both the screen and the relevant external anatomy in the same orientation (Supplementary Fig. S2). An alternate approach would be to have the patient sit in a chair with the examiner standing behind the patient while both patient and examiner are looking at the ultrasound machine screen.

A high-frequency (≥ 12 MHz) linear array transducer should be used, given the typically shallow depth of the plexus. The images obtained in this manuscript were made using a GE logic S8 device with a 15 MHz linear array transducer. Images obtained with other devices and transducers may appear slightly different. Adjustments should be made to the frequency, focus, gain, and depth to optimize the image. The examination should include assessment of static images as well as the dynamic effect of selected provocative maneuvers. This can include abduction and external rotation of the shoulder as well as other passive and active movements to assess for compression of the neurovascular structures. This can be especially valuable in cases of suspected thoracic outlet syndrome.

In the following sections, a systematic approach for imaging the entire brachial plexus will be described. This approach starts medially and progresses laterally and will describe major nerves, muscles, vessels, and other tissues that will be in view. The ultrasound examination should be initiated at the most appropriate location dictated by the history, physical examination, and other diagnostic testing such as electrodiagnosis and imaging. Examples of this include visualizing the trunks of the plexus at the supraclavicular level or the cords at the infraclavicular level.

Segment 1: Interscalene/Supraclavicular View (Roots, Trunks, Divisions). Start with a transverse orientation of the probe over the anterior neck. Determine the location of the trachea and overlying isthmus of the thyroid, which coincides with the C6 nerve root level (Fig. 1). As the transducer is moved laterally, the carotid artery, jugular vein, and vagus nerve can be seen (Fig. 2). Lateral to this, the roots can be seen emerging superficial to the transverse processes of the cervical spine. The C5, C6, and C7 transverse processes have characteristic appearances. The C5 transverse process has equally sized anterior and posterior tubercles and creates a relatively narrow shelf that resembles a molar tooth (Fig. 3a). The C6 transverse process has a prominent anterior tubercle and creates a wide shelf resembling a "thumbs up" sign (Fig. 3b). The C7 transverse process lacks an anterior tubercle and has

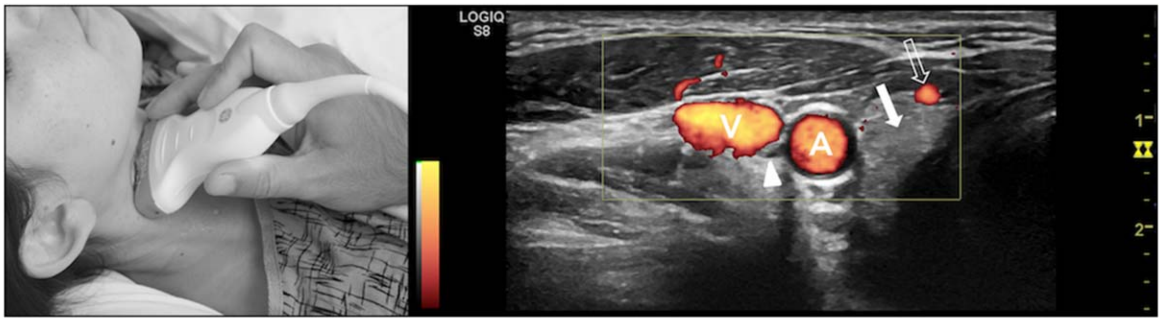

FIGURE 2. The left panel demonstrates the transducer over the lateral neck. The right panel shows the carotid artery (A), jugular vein (V), vagus nerve (arrowhead), thyroid (solid arrow), and superficial thyroid vein (open arrow). Images obtained using power Doppler.

a prominent posterior tubercle which resembles the back of a lounge chair (Fig. 3c). The C8 root can be identified caudal to C7 but does not arise from a transverse process. C8 and T1 can be more challenging to visualize in some individuals. These characteristic findings are helpful in confirming the nerve root level being imaged.

The distal roots and proximal trunks lie between the anterior and middle scalene muscles. This is a high yield view where many clinically important structures can be inspected. We designate this as *standard view #1* (Fig. 4a). After the roots and trunks are visualized in oblique cross-section, a longitudinal coronal view can be performed (Fig. 4b). This view

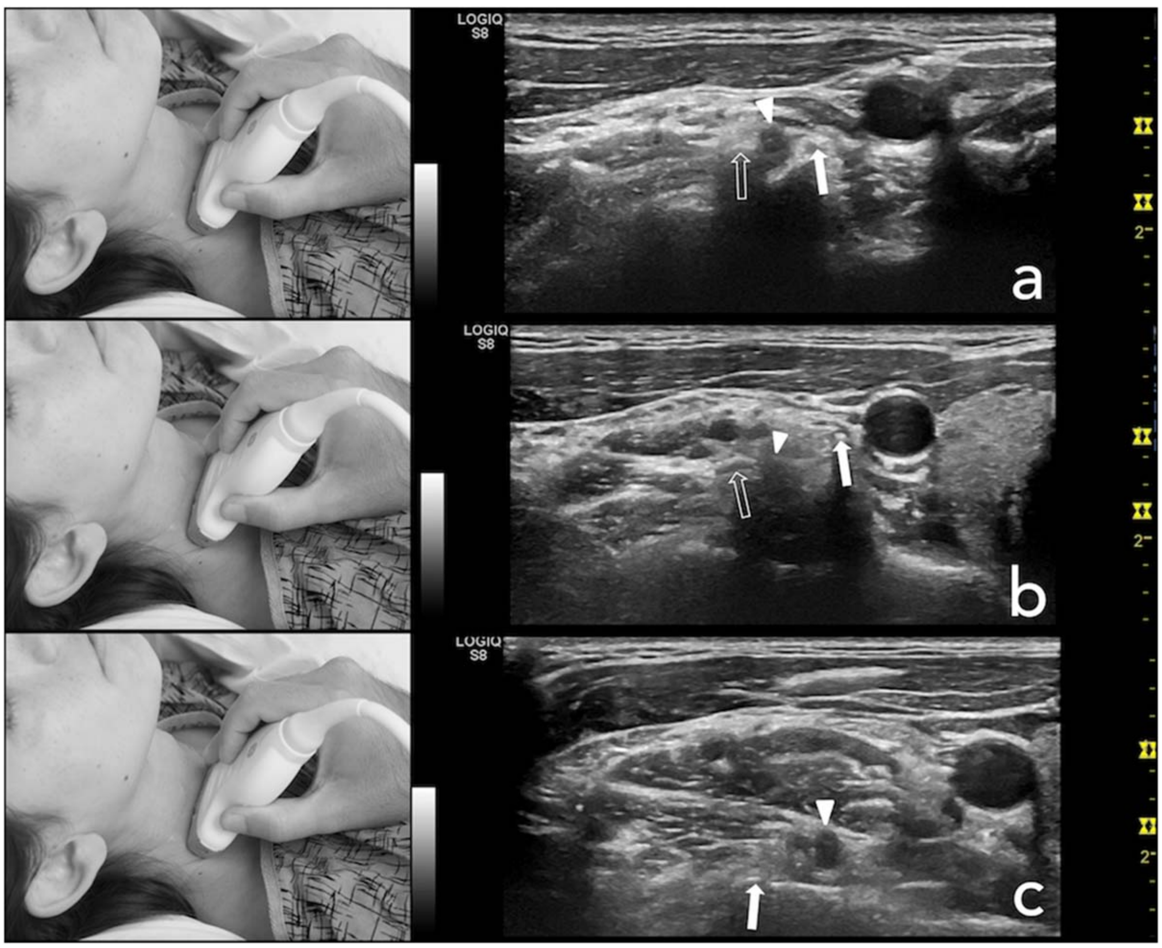

FIGURE 3. (a) The left panel demonstrates the transducer placement for imaging the cervical roots. The right panel shows the C5 nerve root (arrowhead). The anterior (solid arrow) and posterior tubercles (open arrow) are approximately the same size. **(b)** The left panel demonstrates the transducer placement for imaging the cervical roots. The right panel shows the C6 nerve root (arrowhead). The anterior tubercle (solid arrow) is much more prominent than the posterior tubercle (open arrow). **(c)** The left panel demonstrates the transducer placement for imaging the cervical roots. The right panel shows the C7 nerve root (arrowhead). The anterior tubercle is absent and there is only a posterior tubercle (arrow).

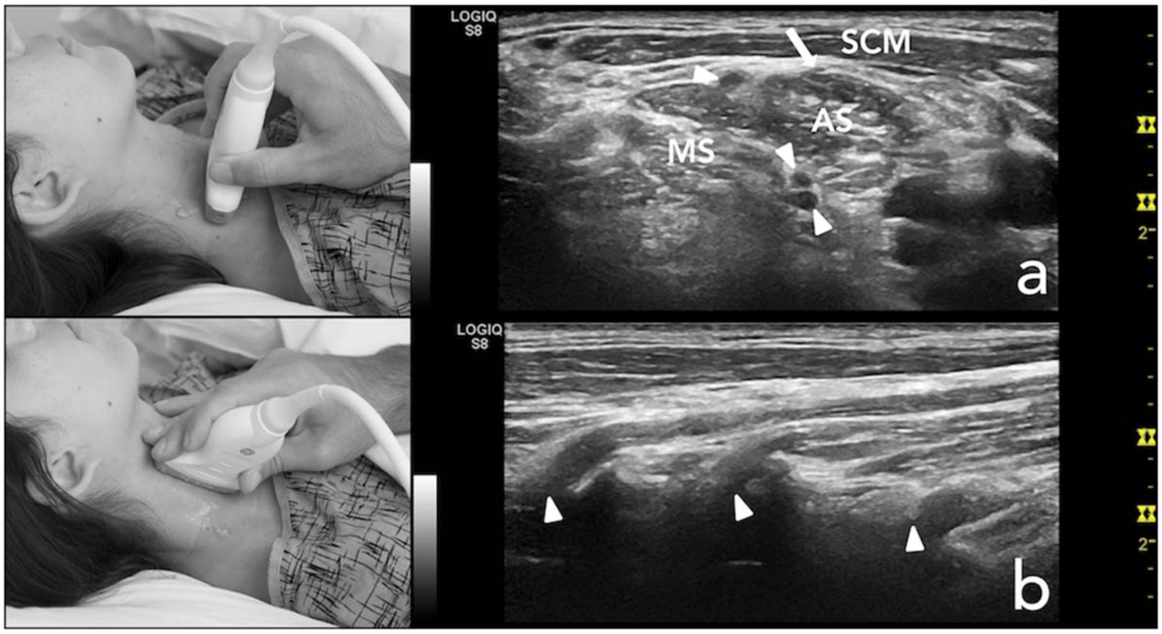

FIGURE 4. (a) This is standard view #1. The left panel demonstrates the transducer placement over the lateral neck to visualize the interscalene brachial plexus. The right panel shows the anterior scalene (AS), middle scalene (MS), trunks of the brachial plexus (arrowheads), and sternocleidomastoid (SCM). The phrenic nerve can be seen superficial to the anterior scalene muscle (arrow). **(b)** The left panel demonstrates the transducer placement over the lateral neck to visualize the interscalene brachial plexus. This is the same site as Figure 5, however, the transducer has been rotated 90 degrees to provide a longitudinal coronal view of the brachial plexus roots. In the right panel, the left side of the image is proximal and superior, and the C5, C6, and C7 roots (arrowheads) can be seen entering the foramina formed by the transverse processes.

shows C5, C6, and C7 nerve roots running parallel to each other and entering their respective foramina. Including longitudinal views of the roots to evaluate for root avulsion is important especially in traumatic plexopathies.

The vasculature in the supraclavicular space can be readily identified and is useful for orientation of the surrounding anatomy. Medial to the origin of the brachial plexus, the common carotid artery is easily visualized with pulsatile flow. The compressible internal jugular vein is lateral to the carotid artery. The subclavian artery traverses between the anterior and medial scalenes. When one scans back from the supraclavicular region toward the foramina, the C8 and T1 root will disappear below the subclavian artery, while the middle and upper trunk segments go superficial to the vessel, back to the interscalene groove. The C8 and T1 trunk elements are the "eight-ball in the corner pocket" with respect to the subclavian artery. The subclavian vein is superficial to the anterior scalene. The dorsal scapular artery branches from the transverse cervical branch of the subclavian artery and travels between the middle and lower trunks of the brachial plexus, eventually paralleling the dorsal scapular nerve (Fig. 5).

The characteristic muscle pattern in the supraclavicular space also helps provide localization of the nerve structures. The anterior and middle scalenes form walls around the roots and trunks of

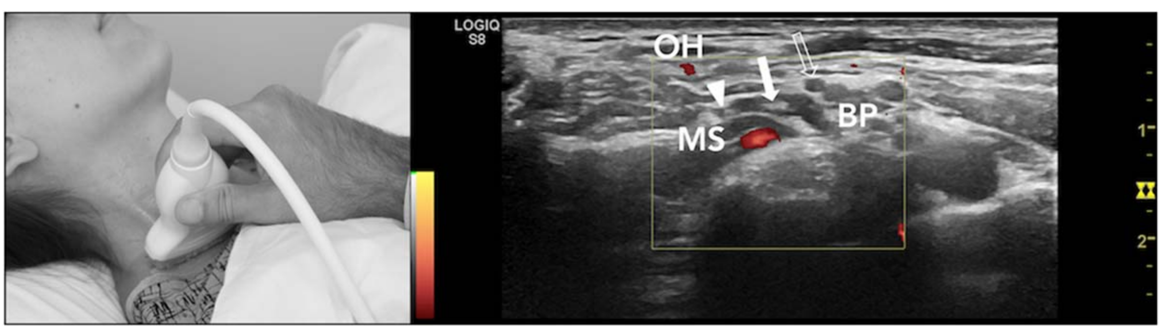

FIGURE 5. The left panel demonstrates the transducer placement for imaging nerve branches as they exit the proximal brachial plexus. The right panel shows the dorsal scapular nerve (arrowhead) (adjacent to the dorsal scapular artery, which has Doppler signal) and long thoracic nerve (solid arrow), both of which travel within the middle scalene muscle (MS). Also demonstrated are the suprascapular nerve (open arrow), omohyoid muscle (OH), and brachial plexus (BP). Images obtained using power Doppler.

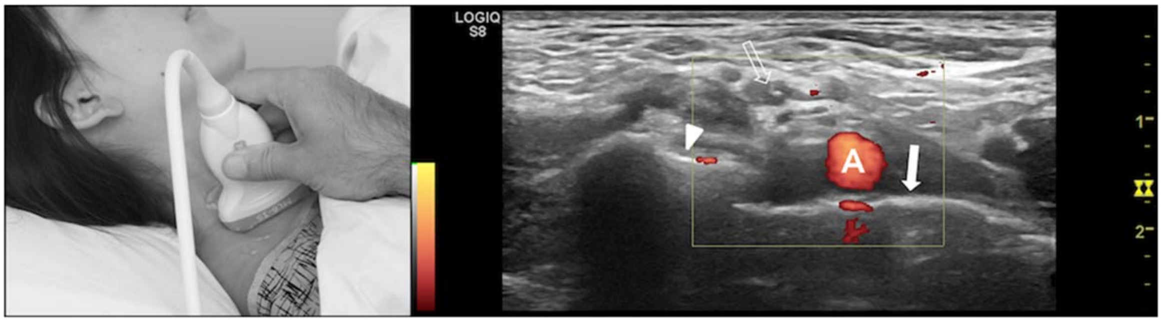

FIGURE 6. This is standard view #2. The left panel demonstrates the transducer placement for imaging the divisions of the brachial plexus, at the supraclavicular level. The right panel shows the subclavian artery (A), first rib (arrowhead), lung (solid arrow), and divisions of the brachial plexus (open arrow). Images obtained using power Doppler.

the brachial plexus and are larger near their more distal insertions. The sternocleidomastoid provides a thin "roof" over the scalenes superficially. The trapezius attaches at three differently locations laterally The upper trapezius has descending fibers that attach to the posterolateral clavicle, the middle trapezius has fibers that attach to the medial margin of the acromion, and the lower trapezius has ascending fibers that attach to the spine of the scapula. The omohyoid is part of the carotid triangle and overlies the jugular vein. It is located deep to the sternocleidomastoid and superficial to the scalenes.

The brachial plexus gives rise to many nerves that deserve consideration. The phrenic nerve traverses superficial to the anterior scalene in an inferior and medial direction (Fig. 4a). Both the dorsal scapular and long thoracic nerves pierce the middle scalene, with the dorsal scapular nerve traveling superficial to the long thoracic nerve. These two hyperechoic structures reside in the center of the body of the middle scalene (Fig. 5). The spinal accessory nerve traverses through the trapezius. The suprascapular nerve diverges from the C5 root and traverses laterally under the omohyoid. It is always the most dorsal plexus element, and can be visualized as a small black dot that runs away from the main structure in the posterior direction.

With further lateral movement of the transducer, the plexus will appear as a large "bundle of grapes" adjacent to the subclavian artery as the divisions emerge from the trunks. (Fig. 6). We designate this as *standard view #2*. Of note, the division level cannot be fully visualized with ultrasound due to the overlying clavicle and first rib.

Measuring individual nerve elements of the brachial plexus may be attempted by measuring the supraclavicular cross-sectional area while trying to avoid non peripheral nerve elements such as connective tissue structures. Side to side comparisons may be helpful.

Segment 2: Infraclavicular View (Cords). With the transducer inferior to the clavicle in a sagittal orientation and slightly medial to the coracoid process, the sub-pectoral axillary artery can imaged. We designate this *standard view #3* (Fig. 7). The collapsible axillary vein is medial to the artery. The three cords are generally triangularly opposed around the axillary artery. While variability exists, there are common locations for the cords of the brachial plexus that can be described using the axillary artery as a clock face. The lateral cord is most prominent and easiest to visualize residing between 10 and 11 o'clock. Often "hiding" within the shadow of posterior acoustic enhancement

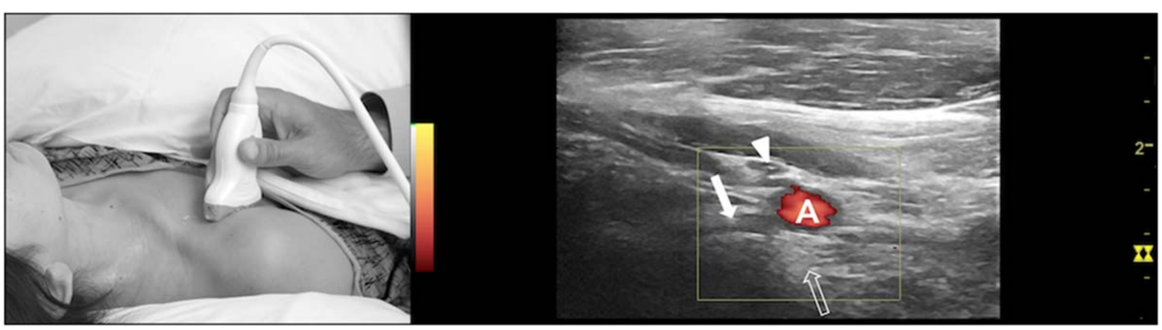

FIGURE 7. This is standard view #3. The left panel demonstrates the transducer placement for imaging the cords of the brachial plexus, at the infraclavicular level. The right panel shows the axillary artery (A) and the cords surrounding the axillary artery. The lateral cord (arrowhead) is at the 11 o'clock position, posterior cord (solid arrow) at the 9 o'clock position, and medial cord (open arrow) at the 6 o'clock positions. Images obtained using power Doppler.

deep to the axillary artery, the posterior cord lies between 5 and 9 o'clock. Lastly, the medial cord is found in the space between the axillary artery and vein between the 2 and 6 o'clock regions.

Muscles in the sub-pectoral space overlying the 2nd rib include the superficial pectoralis major and its deeper neighbor the pectoralis minor. One can follow the pectoralis major to its insertion on the humerus and the pectoralis minor to its insertion on the coracoid process to confirm identification. The medial and lateral pectoral nerves, with their accompanying vessels, can also be identified at this level between the fascial planes of the pectoralis major and minor.

Segment 3: Axillary View (Branches). The transducer is placed in the axilla, and the first structure to identify is the pulsatile brachial artery. We designate this *standard view #4* (Fig. 8). Using light pressure, the brachial vein can be visualized adjacent to the brachial artery. Variability at the terminal branch level requires expanded surveillance to localize the neural structures. The radial nerve can be found posterior to the vascular bundle moving deep toward the humerus as one scans distally down the arm. The ulnar nerve is seen medial to the artery, deep to the fascial plane of the triceps brachii. The median nerve is located lateral to the brachial artery, close to the biceps brachii.

Of note, there are known anatomical variations with regards to the relationship of these nerves to the brachial artery. The more lateral musculocutaneous nerve penetrates the coracobrachialis and appears as a hyperechoic structure adjacent to the biceps brachii. The combination of the brachial artery and median, radial, and ulnar nerves resembles a "dog paw" with the brachial artery as the bigger pad surrounded by the smaller digital pads (radial, ulnar, and median nerves). An alternative approach is to identify the terminal branches, starting the evaluation of each branch distally in the arm, and scanning proximally to the axillary space. The entire course of the axillary nerve is frequently difficult to visualize from the axillary view of the distal brachial plexus. It can be approached from the posterior position near the posterior axillary line where a small portion of the axillary nerve can be seen adjacent to the circumflex artery.

REPRESENTATIVE CASE

A previously healthy 13-year-old right-handed girl presented with progressive right hand weakness, clumsiness, numbness, and paresthesias in digits 1 through 5. These symptoms started after a fall several months earlier, at which time she first noticed an inability to snap the fingers of her right hand, and she eventually became unable to hold a pencil. She had marked thenar atrophy with weakness of all intrinsic hand muscles. There was mild hypesthesia across the palmar surface of the hand. The biceps and brachioradialis reflexes were normal.

Electrodiagnostic testing revealed the following results: the right median motor nerve, right ulnar motor nerve, and right radial motor nerve all revealed reduced amplitudes. The right ulnar sensory response was absent, but the right median and radial sensory nerve responses were normal. The right medial antebrachial cutaneous response was absent on a previous study; however, returned to normal on the study being discussed. Needle electromyography of the right upper extremity revealed chronic, severe neurogenic changes in the following muscles without abnormal spontaneous activity: first dorsal interosseous, extensor digitorum communis, flexor polices longus, and flexor digitorum profundus. These findings were consistent with a severe right lower trunk brachial plexopathy.

Neuromuscular ultrasound showed intact median and ulnar nerves with normal cross-sectional areas at the distal wrist crease, forearm, elbow, and arm. When imaging the right brachial plexus, there was a hyperechoic structure adjacent to the plexus trunks at the interscalene level, which prohibited deeper imaging and full visualization of the lower trunk

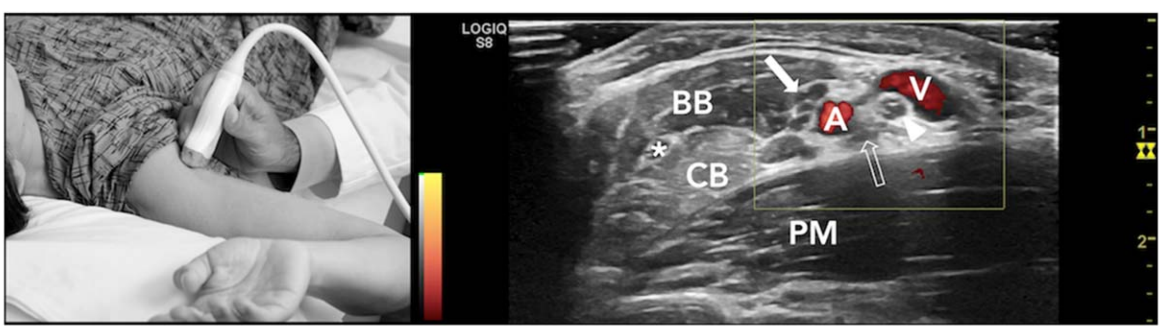

FIGURE 8. This is standard view #4. The left panel demonstrates the transducer placement for imaging the terminal branches of the brachial plexus, at the axillary level. The right panel shows the axillary artery (A) and vein (V), median nerve (solid arrow), ulnar nerve (arrowhead), radial nerve (open arrow), musculocutaneous nerve (*), coracobrachialis (CB), biceps brachii (BB), and pectoralis major (PM). Images obtained using power Doppler.

(Supplementary Fig. S3). This structure was consistent with bone, specifically a cervical rib, given the hyperechoic cortex and deep shadowing. At the site of the cervical rib the trunks of the plexus appeared constricted, particularly the inferior trunk. Chest radiography revealed prominent bilateral cervical ribs.

She underwent surgical exploration of the right supraclavicular brachial plexus. Multiple fibrous bands were found attached to the cervical rib, compressing the brachial plexus; these were released. A large, anomalous muscle inserted on the transverse processes of C7 and T1 and merged with the middle scalene, further compressing the C8 and T1 nerve roots. After myectomy and tenotomy of the anomalous muscle and a portion of the middle scalene, the scalene triangle and subclavicular space were found to be sufficiently open and excision of the cervical rib was deferred. The patient's numbness and paresthesias improved following surgery, but she continues to have residual weakness of the intrinsic hand muscles 1 year after intervention.

Neurogenic thoracic outlet syndrome remains a difficult diagnosis, given its rarity, limitations of the physical exam and potential equivocal findings on imaging.[2] In this patient, neuromuscular ultrasound was informative as it demonstrated the cervical rib adjacent to and constricting the trunks of the brachial plexus.

In conclusion, brachial plexus lesions can be anatomically complex and, therefore, present diagnostic challenges. Ultrasound of the brachial plexus is a relatively new and useful diagnostic tool that, when used in conjunction with electrodiagnosis, may mitigate these diagnostic dilemmas. Accurate and reproducible ultrasound techniques are crucial when challenged with the task of correctly identifying pathology. The techniques described in this study were agreed upon by a multidisciplinary team of clinicians and should provide a systematic diagnostic approach for evaluating pathology in or around the brachial plexus.

Ethical Publication Statement: We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

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