MR Imaging of Brachial Plexus

Michael Todd, MD, Gaurang V. Shah, MD, and Suresh K. Mukherji, MD

Abstract: The brachial plexus is a complex anatomic component originating from ventral rami of the lower cervical nerve roots from C5 to C8 and upper thoracic spinal nerve roots from T1, providing sensory and motor innervation to the upper extremities. As it is inaccessible to palpation, clinical evaluation of the brachial plexus is very challenging and localizing lesions along its course is very difficult. The gamut of pathologic conditions involving the brachial plexus includes primary tumor, direct extension of adjacent tumor, metastasis, trauma, or an inflammatory condition. MR imaging provides superior diagnostic ability due to its ability of multiplanar imaging and greater soft tissue contrast.

This article discusses MR imaging findings in a variety of pathologic conditions, with special emphasis on neoplastic process.

Kew Words: Brachial plexus, tumor, trauma, neoplasm, MR imaging

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The brachial plexus provides sensory and motor innervation to the upper extremities. The brachial plexus is frequently involved by primary tumor, direct extension of adjacent tumor, metastasis, trauma, or an inflammatory disease process.[1] Symptoms of a brachial plexopathy are commonly nonlocalizing.

The spectrum of etiologic factors for brachial plexopathy includes traumatic injuries, involvement by primary or secondary tumors, and inflammatory processes. Clinically evaluating the brachial plexus is very challenging because it is inaccessible to palpation, and localizing lesions along its course is difficult.[2] Imaging of the brachial plexus can be complicated and confusing because of the complex local anatomy and the nonspecific symptoms associated with a brachial plexopathy. These factors make the proper localization of the inciting lesion difficult.

NORMAL ANATOMY

The brachial plexus originates from ventral rami of the lower cervical nerve roots from C5 to C8 and upper thoracic spinal nerve roots from T1. It courses between the anterior and middle scalene muscles adjacent to the subclavian artery. The brachial plexus provides sensory and motor innervation to the upper extremity and is formed by the union of the anterior (ventral) rami of the spinal nerves of C5 to T1.[2] Occasional variations in innervation are encountered. When C4 replaces T1 as a dominant contributor, a "pre-fixed" brachial plexus occurs. Similarly, when brachial plexus receives contributions from C6–T2, a "post-fixed" plexus is present. While these variations in innervation have been described in the literature, they appear to have little clinical significance. The distribution of the innervation to the upper limb follows a similar pattern regardless of the specific roots that comprise the brachial plexus.[3]

The brachial plexus is comprised of nerve roots, trunks, divisions, cords, and branches (Figure 1).[3] When trainees are challenged with the task of memorizing the successive progression of the brachial plexus structures, they often find the mnemonic "Radiology Techs Drink Cold Beverages" to be helpful.[3]

In the majority of individuals, the brachial plexus is formed by the ventral rami of the spinal nerves of C5–T1 in the posterior triangle of the neck, forming the roots of the plexus. Passing between the anterior and middle scalene muscles adjacent to the subclavian artery, the roots combine to form the three trunks (upper, middle, lower) of the plexus. C5 and C6 combine to form the upper trunk, while the roots of C8 and T1 combine to form the lower trunk. The C7 root is the sole contributor of the middle trunk.[2–4]

The trunks course superior and posterior to the subclavian artery and through the supraclavicular fossa. Then they bifurcate into anterior and posterior divisions. At the level of the first rib, the six divisions combine to form the three cords of the brachial plexus. The cords of the brachial plexus are named (posterior, lateral, medial) according to their relationship to the adjacent subclavian artery. The anterior divisions of the upper and middle trunks unite to form the lateral cord, while the anterior division of the lower trunk is the sole contributor of the medial cord. The posterior divisions of the all three trunks combine to form the posterior cord.[3–5]

Just lateral to the pectoralis minor muscle, the cords of the brachial plexus divide into five terminal branches, which supply motor and sensory innervation to the upper extremity as the median, ulnar, musculocutaneous, axillary, and radial

From the University of Michigan, Ann Arbor, MI.
Reprints: Gaurang V. Shah, MD, B1G308, Department of Radiology, University of Michigan Hospitals, 1500E Medical Center Drive, Ann Arbor, MI 48109 (e-mail: gvshah@med.umich.edu).

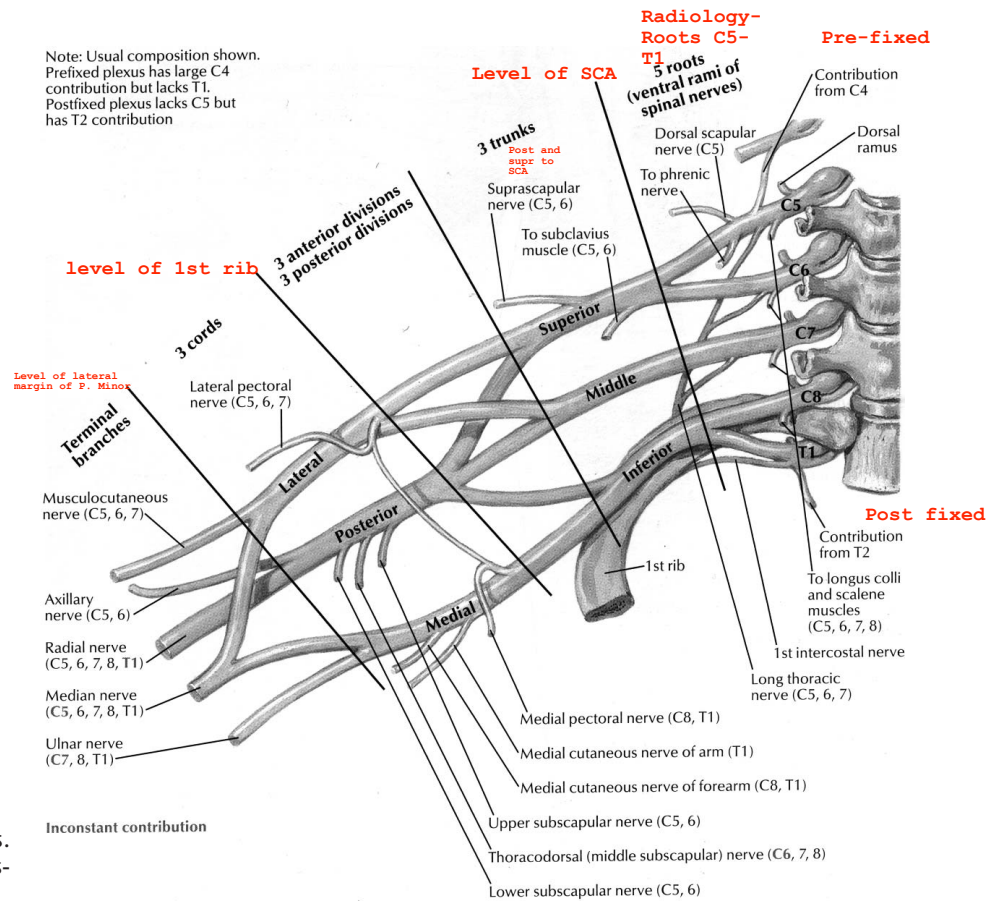

FIGURE 1. Anatomy of Brachial plexus. (With permission from Icon Learning Systems.)

nerves. However, several nerves arise directly from higher locations along the brachial plexus. Arising from the upper trunk of the brachial plexus, the suprascapular nerve innervates the supraspinatus and infraspinatus muscles. The posterior cord gives rise to the thoracodorsal nerve, which innervates the latissimus dorsi muscle, and the subscapular nerve, which innervates the subscapularis and teres major muscles. The lateral cord gives origin to the lateral pectoral nerve, which supplies the pectoralis major muscle. Finally, the medial cord gives rise to the medial pectoral nerve (innervating the pectoralis major muscle) as well as two sensory branches: the medial brachial cutaneous and medial antebrachial cutaneous nerves.[3–5]

The posterior cord terminates in the axillary and radial nerves. The lateral cord terminates as the musculocutaneous nerve (innervating the biceps and coracobrachialis muscles) and contributes to the median nerve. The medial cord terminates as the ulnar nerve and the medial cord contribution to the median nerve.[4]

The description of surgical anatomy of the brachial plexus depends on the anatomic structures surrounding its classic anatomic features. The surgical classification divides the brachial plexus into supraclavicular, retroclavicular, and infraclavicular segments, based upon its relationship to the clavicle. The supraclavicular brachial plexus contains the roots and trunks and is situated in the posterior triangle of the neck between the anterior and middle scalene muscles. The divisions are formed as the plexus passes posterior to the clavicle, adjacent to the subclavian artery, comprising the retroclavicular plexus. The infraclavicular plexus also courses adjacent to the subclavian artery and contains the cords and portions of the branches of the brachial plexus.[1,4]

While no standard imaging techniques are universally accepted, the brachial plexus is best imaged with MRI or CT, with MRI providing superior diagnostic ability, based upon its provision of tissue signal characteristics (Figures 2, 3). Ultrasound can also play a complementary role in evaluating the brachial plexus, as the supraclavicular and infraclavicular portions of the plexus can be demonstrated. However, the nerve roots within the neural foramina and epidural space cannot be evaluated.[6] Radiographic imaging of the brachial plexus is complex. However, the successful radiologist can identify the key portions of the brachial plexus based on its location in relation to easily identified anatomic structures. The fascial plane between the anterior and middle scalene muscles contains the roots and cords of the brachial plexus. Plexus divisions are formed as the trunks pass posterior to the clavicle, in the retroclavicular plexus. The cords, in turn, are formed at the lateral border of the first rib. Plexus divisions course posterior

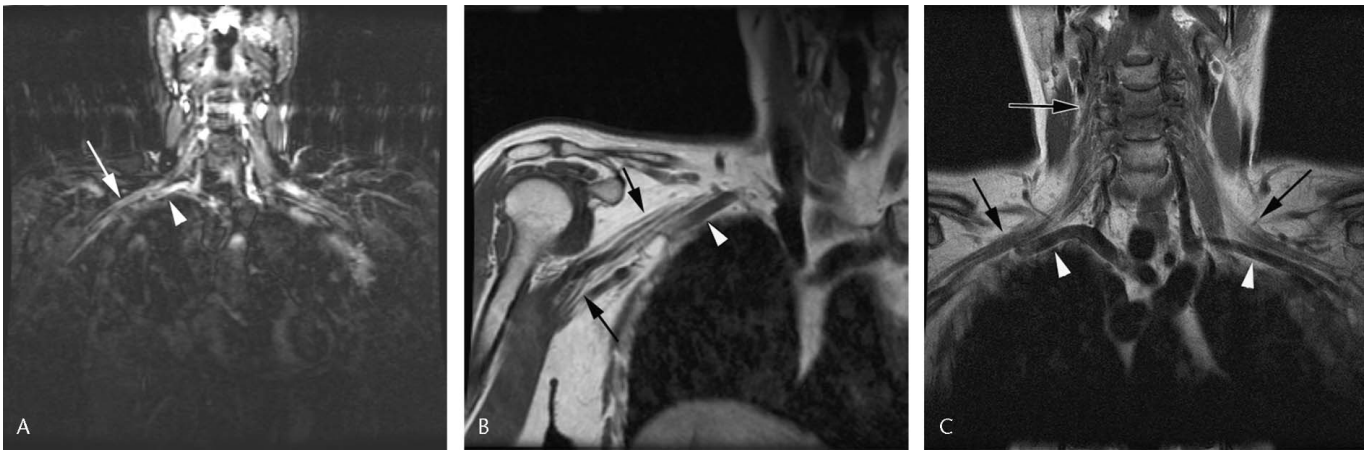

FIGURE 2. Coronal MRI imaging of the normal brachial plexus. A, T2-weighted STIR image demonstrates the brachial plexus divisions (*arrow*) in relation to the subclavian artery (*arrowhead*). B and C, T1-weighted images demonstrating normal anatomy of plexus roots, trunks and divisions (*arrows*) in relation to the bony landmarks of the neck and the subclavian artery (*arrowheads*).

and superior to the subclavian artery. Brachial plexus cords travel laterally, posteriorly, and medially, as the nomenclature indicates. Thus, any lesion that is adjacent to the subclavian artery is in close proximity to the divisions and cords of the brachial plexus. Unfortunately, the branches of the brachial plexus are difficult to identify individually on imaging studies. However, it may be safely assumed that a lesion in the axillary region is likely to involve the terminal branches of the cords.[1]

MR IMAGING

Myelography, ultrasonography, computed tomography (CT), post-myelography CT, and magnetic resonance imaging (MRI) can be used to image the brachial plexus. Ultrasound is capable of imaging brachial plexus in multiple directions.[6] However, it is not possible to image the entire course of the plexus because of numerous intervening bony landmarks. It is also dependent somewhat on the operator. Spiral CT has capabilities of multiplanar reconstructions and had some success in imaging brachial plexus.[7] Only direct axial imaging and beam-hardening artifacts at the level of thoracic inlet are some of the major disadvantages of conventional CT. MRI, on the other hand, has the capability for multiplanar imaging, better tissue contrast, and relative paucity of artifact and can directly visualize nerves and blood vessels. This is especially true on T1-weighted images, where the contrast differences between the nerves and high T1-signal fat lend the brachial plexus to better interpretation. Various studies in the past have concluded that MRI is the imaging method of first choice for evaluation of suspected brachial plexopathy.[4,8–12]

At our institute, the MRI protocol used for the study of brachial plexus includes the following sequences:

1. Coronal Short T1 Inversion Recovery Sequence (STIR) with fast spin-echo inversion recovery technique with TR of 3000 milliseconds, TE of 34 milliseconds, and imaging time of 3.25 minutes with 2 acquisitions.
2. Sagittal fat-saturated fast spin-echo proton-density with TR of 5000 milliseconds, TE of 40 milliseconds, and imaging time of 4.40 minutes with 2 acquisitions.
3. Axial three-dimensional FIESTA with 4 acquisitions and imaging time of 4.36 minutes.
4. Axial T1 spin-echo with TR of 700 milliseconds and imaging time of 4.40 minutes with single acquisition.
5. Coronal T1 spin-echo with TR of 700 milliseconds and imaging time of 4.40 minutes with single acquisition.
6. Coronal post-gadolinium T1 coronal spin-echo with TR of 700 milliseconds and imaging time of 4.40 minutes with single acquisition.
7. Axial post-gadolinium T1 spin-echo with TR of 700 milliseconds and imaging time of 4.36 minutes with double acquisitions.

This is a comprehensive protocol to evaluate a broad range of possible brachial plexopathies. It combines relatively large fields of view with high spatial and temporal resolution. It is possible to visualize the nerve roots, trunks, divisions, and sometimes cords in a single coronal plane. Comparison with contralateral brachial plexus is possible in coronal and axial imaging. Sagittal plane imaging allows the delineation of brachial plexus with relation to blood vessels, especially the subclavian artery.

PATHOLOGIC CONDITIONS

Clinical features of a brachial plexopathy are often vague and nonspecific. Patients vary in their presentation depending upon the extent, degree, and duration of injury. Symptoms include motor, sensory, and, sometimes, autonomic disturbances of the supraclavicular region, shoulder, and upper

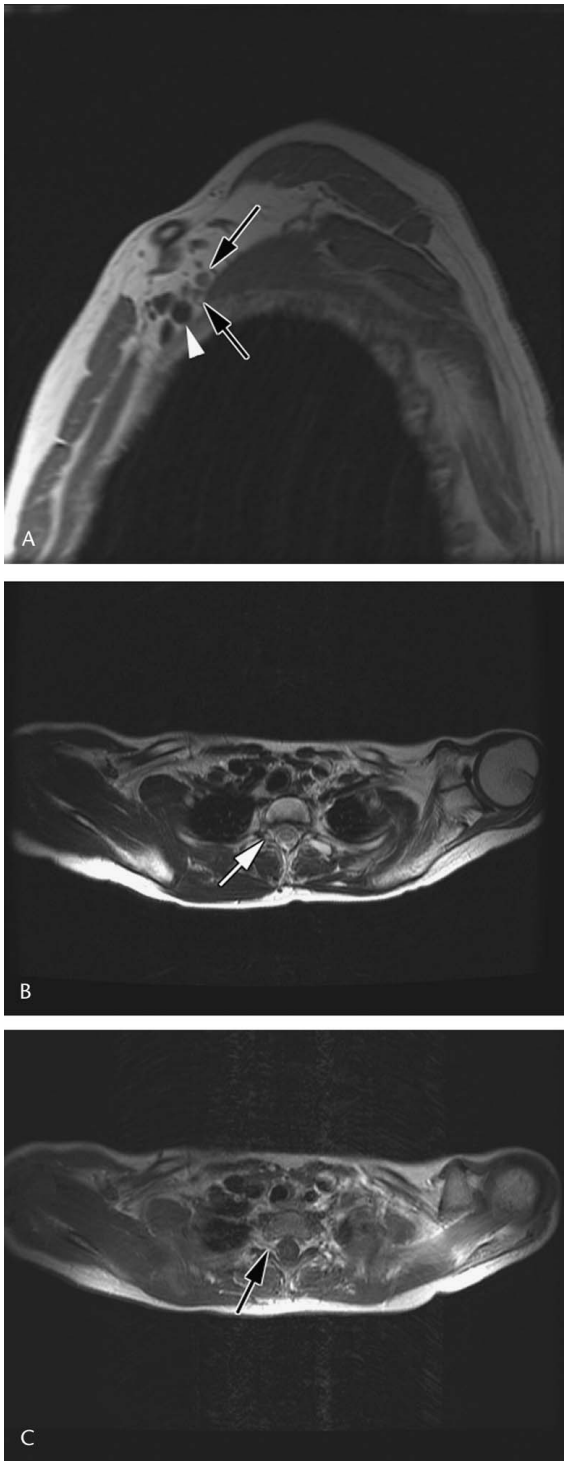

FIGURE 3. Sagittal and axial MRI imaging of the normal brachial plexus. A, Sagittal T1-weighted image demonstrating brachial plexus divisions (*arrows*) adjacent to the subclavian artery (*arrowhead*). B, T2-weighted image demonstration the nerve roots exiting the neural foramen and divisions adjacent to subclavian artery. C, T1-weighted image demonstration the nerve roots (arrow) exiting the neural foramen and divisions with relation to subclavian artery

extremity.[8] The patients may present with pain and numbness in the upper extremities. The etiologic factors can include neoplastic, traumatic, or inflammatory conditions.

Sensory deficits with patchy and incomplete distribution are more common with neoplastic or radiation induced plexopathies, while motor weakness is primarily seen in traumatic conditions associated with avulsions of anterior roots. The neoplastic plexopathies tend to be rapidly progressive and more painful. The rapid clinical course and growth of tumor are associated with neurofibromatosis type 1 (NF-1).[13] Clinical findings in patients with primary neoplasm of brachial plexus include paraesthesia, pain, muscle weakness, and wasting.[14–16] Classic presentation of malignant mass is pain at rest, which may be resistant to opiates and prevent the patient from sleeping and leading to progressive loss of neurologic function.[13]

The anatomic plane and orientation of the mass allow differentiation of the tumors associated with brachial plexus from other anterior neck masses.[1]

Primary tumors arising from the roots lie between anterior and middle scalene muscles and are either oblique or horizontal in orientation.

NEOPLASMS

Benign

Neurogenic Tumors

Approximately 20% of peripheral nerve sheath tumors arise in brachial plexus.[14] Primary neurogenic tumors of the brachial plexus are relatively uncommon but are usually treatable and associated with positive outcomes.[14,15] Benign primary tumors include neurofibroma, plexiform neurofibroma, and schwannoma. Neurofibroma is the most common neurogenic tumor of the brachial plexus, while schwannoma is the second most common.[14,15,17] About a third of the patients with neurofibromas have localized or plexiform neurofibromatosis and are associated with von Recklinghausen's disease (NF-1). By definition, a solitary neurofibroma occurs in a patient who does not have von Recklinghausen's disease (Figure 4).[12] Histologically, these lesions are unencapsulated tumors that are felt to arise from the nerve fascicles. Because of the diffuse penetration of tumor cells in the nerve fascicles, resection of the tumor is associated with neurologic deficit.[15] One third of these lesions occur in patients with NF-1, while two thirds of cases are sporadic. Neurofibromas arising in patients with NF-1 occur with equal incidence in males and females. These tumors are characteristically multiple and plexiform in appearance with diffuse involvement of the brachial plexus (Figure 5). Sporadic neurofibromas are typically solitary and more common in supraclavicular region. They are more commonly seen in females (3:1 female-to-male ratio).

Schwannomas are the second most common neural tumor involving the brachial plexus (Figure 6). Histologically, it

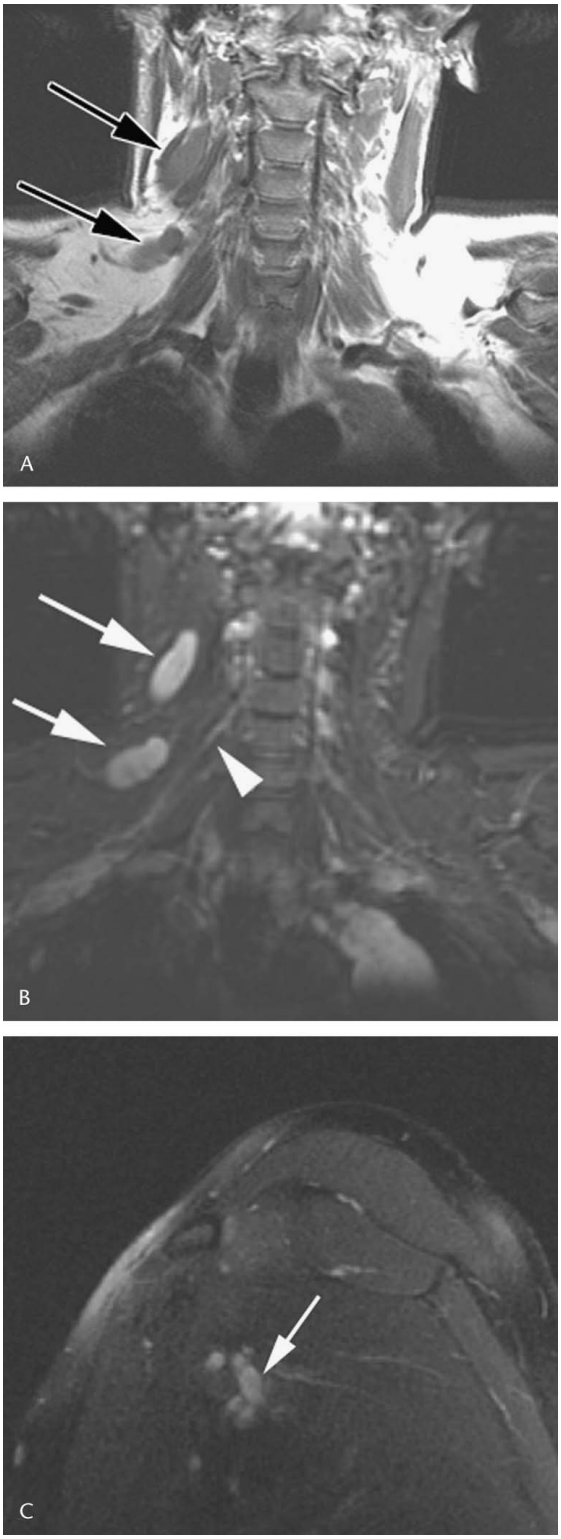

FIGURE 4. NF-1. A, Coronal T1-weighted image shows enlargement of brachial plexus components. B, Coronal T2-weighted image demonstrating the same (*arrows*) adjacent to normal nerves (*arrowhead*). C, Sagittal T2-weighted images demonstrating enlargement of the of the brachial plexus cords.

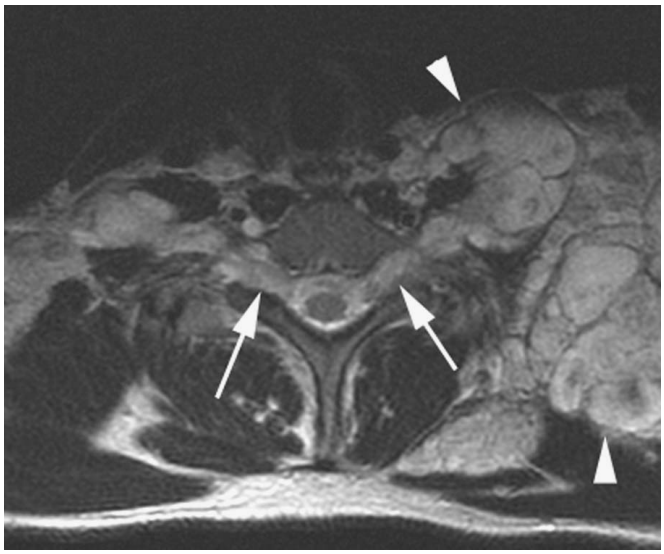

FIGURE 5. NF-1. Axial T2-weighted image demonstrates extensive plexiform neurofibromas involving the bilateral brachial plexi (*arrows*), axilla (*arrowhead*), and left chest wall (*arrowhead*).

is an encapsulated eccentric nerve sheath tumor that arises from Schwann cells and displaces the nerve fascicles instead of invading them. Surgical excision of these tumors is not associated with a high level of neurologic deficits.[14,15] A majority of schwannomas are solitary and are slightly more common in the upper brachial plexus. Tumors arising from lower roots of brachial plexus can sometimes appear as an apical lung mass.[18]

Only positive findings on plain radiography are foraminal enlargement and well-defined bony erosion; however, this is not obvious until late stage. Ultrasound can demonstrate well-defined oval hypoechoic masses with posterior acoustic enhancement.[19–21] The lack of central echogenic hilum differentiates these lesions from cervical lymph nodes.[21] On CT, these lesions have similar attenuation to muscle and enhance variably with contrast. Both tumors may be associated with bony remodeling.

On MRI, schwannomas and neurofibromas appear iso signal to muscle on T1-weighted images and show increased signal on proton-density images. High signal on T2-weighted images is a characteristic finding. Sometimes, a central area of low signal is also seen within this area with high T2-signal, giving the appearance of a "target" sign.[2,22,23] The target sign is attributed to distribution of Antoni type A and type B areas within the tumor.[1] Central distribution of fibrocollagenous tissue is responsible for low signal, while peripheral distribution of myxoid tissue gives rise to a high T2 signal.[23,24] Symmetric palisades cell nuclei are seen in denser Antoni type A tissues. Both the types of tumor enhance intensely following intravenous gadolinium contrast. Less commonly, schwannomas and neurofibromas appear mildly hypointense or hyperintense to

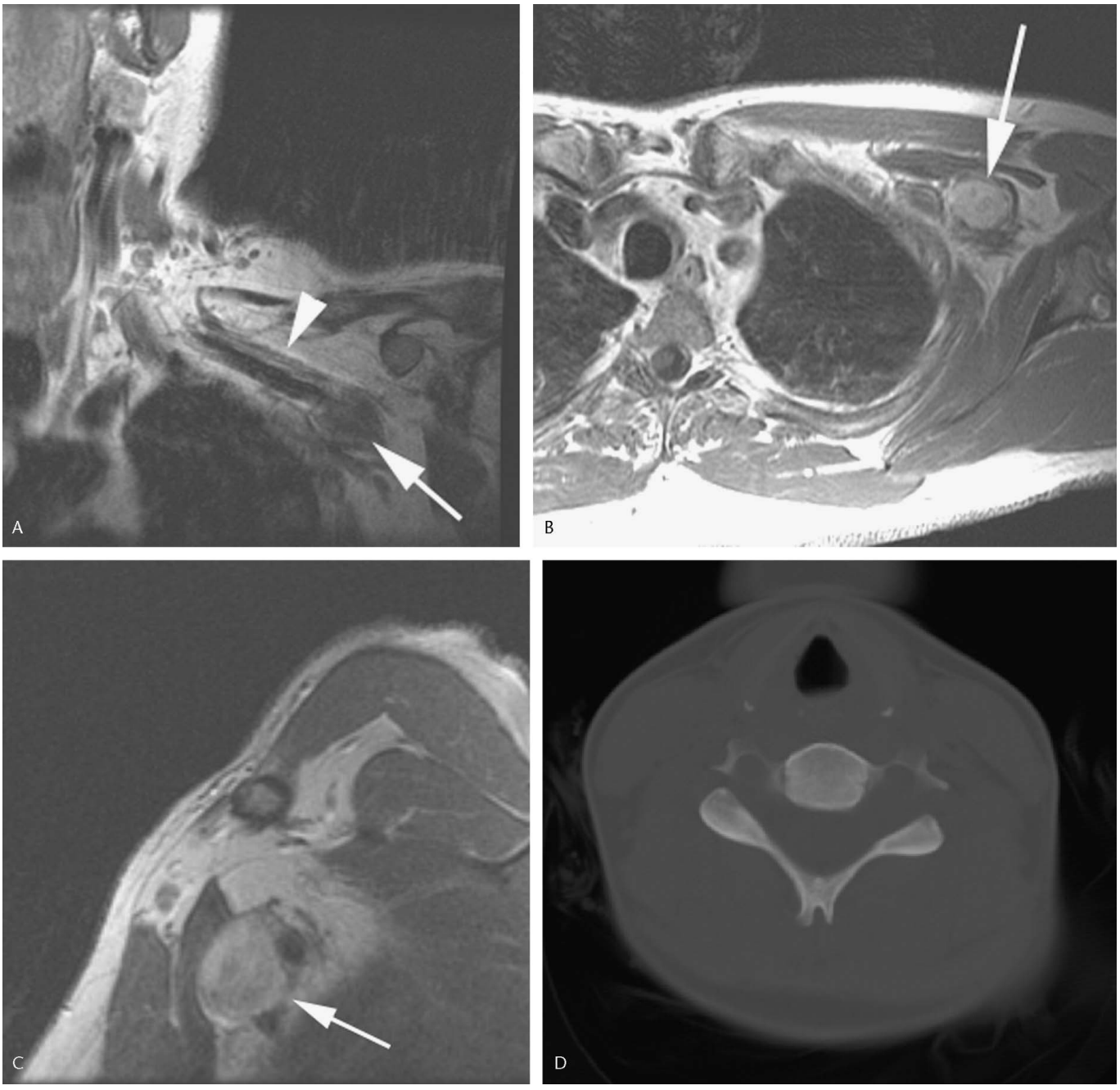

FIGURE 6. Schwannoma in two patients. A, Coronal precontrast T1-weighted image shows tumor (*arrow*) adjacent to the brachial plexus cords (*arrowhead*). B, Axial postcontrast T1-weighted image shows enhancement of same mass. C, Sagittal postcontrast T1-weighted image shows enhancement of same mass. D, Axial CT image of another patient shows expansion of the left neural foramina by schwannoma.

muscles on T1-weighted images and exhibit patchy nonuniform postcontrast enhancement.[19,22–26] The tumors generally have sharply defined margins, are oval or fusiform in shape, and in many cases the involved nerve can be seen entering and leaving the tumor.[12] This sign can be useful to differentiate a neurofibroma from a schwannoma. In case of neurofibroma, the nerve passes through the center of the tumor, while in case of schwannoma, it enters eccentric to the tumor.[27] No amount of edema is seen surrounding either a neurofibroma or a schwannoma of brachial plexus.[25] Cystic necrosis is more common in schwannoma,[22] while mild muscle atrophy distal to the tumor is seen both in neurofibroma and schwannoma.[28]

Despite multiple studies in the past, it is not possible to differentiate between a schwannoma, a neurofibroma, or a malignant schwannoma based on MRI findings.[4,24,28] Even the target sign is not specific for differentiating neurofibroma and schwannoma.[22] It is widely accepted, however, that detection of primary neurogenic tumors of brachial plexus has really increased with increasing utilization of MRI.[4,8–12,28–30]

Non-neurogenic Tumors

Rare non-neurogenic benign tumors involving the brachial plexus include desmoid tumor, lipoma, and perineuroma. Also known as aggressive fibromatosis, desmoid tumor is the commonest non-neurogenic benign tumor of brachial plexus and has severe clinical presentation with pain and neurologic dysfunction in upper arms.[31] It is locally aggressive and has infiltrative margins. It is isointense to muscles on T1-weighted images with inhomogeneous T2 signal and intense postcontrast enhancement. Areas of signal void on T2-weighted images are characteristic.[32–34] The second commonest benign non-neurogenic tumor is lipoma, which has a characteristic high T1 and low T2 signal. However, differentiating a lipoma from a well-marginated liposarcoma is not possible by imaging criteria.[35] Perineuroma is a rare tumor-like lesion resulting from hypertrophic neuropathy producing slowly progressive weakness in the distribution of the nerve, which can also involve brachial plexus.[36,37] MRI shows fusiform thickening of the affected nerve, which appears mildly hyperintense on T2-weighted images. Lymphangioma, myoblastoma, osteochondroma, and ganglioneuroma are some of the rare non-neurogenic benign tumors of brachial plexus.

Malignant

Malignant Peripheral Nerve Sheath Tumor (MPNST)

Malignant neural tumors are relatively less common and consist mostly of fibrosarcomas[15,38,39] and neurogenic sarcomas (malignant neurofibromas). About 3% to 13% of the patients with NF-1 develop malignant peripheral nerve sheath tumor (MPNST),[17] especially after radiation therapy.[38,40] Synovial sarcoma, lymphoma, and neuroblastoma are some of the less common malignant brachial plexus tumors. The imaging features of malignant neural tumors are similar to their benign counterparts, which makes it difficult to differentiate benign from malignant tumors. The diagnosis of a malignant nerve sheath tumor may be suggested by a progressively enlarging mass in a patient with NF-1.[8] It is suggested that lack of target sign is a sign of malignancy.[22–24] However, in Antoni type B schwannomas with predominant myxoid tissue and cystic degeneration, this sign would be absent. Presence of bone destruction[27] and poorly defined margins also help to define a tumor as malignant.[1] Heterogeneous contrast enhancement is also proposed as sign of malignancy; however, it can also be seen in Antoni type B schwannomas. Diffusion-weighted MRI[41] and [^{18}F] fluorodeoxyglucose positron emission tomography (^{18}FDG PET) have been used with some success for evaluating malignant change in plexiform neurofibromas.[42] However, biopsy should always be performed whenever there is concern for malignant change within a brachial plexus neoplasm.[43]

Pancoast Tumor

Primary lung cancers arising in pulmonary apex can invade structures, such as the lower part of brachial plexus and subclavian vessels. An uncommon lung cancer arising from superior pulmonary sulcus limited to upper apical segment but invading the para-apical structures causes Pancoast's syndrome.[44] Pancoast suggested that tumor originates from an embryonal rest in superior pulmonary sulcus, better known as subclavian artery groove in cupola of the pleura.[44] However, now it is widely accepted that the tumor originates from the lung[45] and is pathologically identical to other primary malignant tumors of the lung: adenocarcinoma, squamous cell carcinoma, or large cell or small cell carcinoma (Figure 7).[46]

The Pancoast syndrome consists of pain around the shoulder and in the arm in the eighth cervical and first and second thoracic root distribution, Horner's syndrome, muscle atrophy of the hand, and radiologic evidence of a shadow at the pulmonary apex with rib destruction and often with vertebral body involvement. Shoulder pain is the commonest initial symptom, produced by neoplastic involvement of brachial plexus.[47] The pain can radiate up to head and neck. Horner's syndrome is produced in 20% of the patients[17] and consists of ipsilateral ptosis, miosis, and anhydrosis and is caused by invasion of the paravertebral sympathetic chain and the inferior cervical ganglion.[44]

The use of MRI has markedly improved the visualization of pulmonary apical mass and shows the relationship between the brachial plexus and the tumor very well.[9,48–50] The extent of disease is also better depicted with MRI than with CT.[30,51] The coronal and sagittal planes are helpful to evaluate the extent of the tumor in all orthogonal planes and to evaluate its relationship with the brachial plexus and subclavian artery. The imaging findings include asymmetry of apical region, apical mass, and bone destruction.[5] Presurgical radiotherapy followed by extended surgical resection is the most common treatment.[47,52,53]

Metastatic Tumors

Metastatic lymphadenopathy of supraclavicular or axillary region is quite common, especially in cases of carcinoma of breast, because one of the major routes of lymphatic drainage is through apex of axilla.[2] However, true hematogenous metastases to brachial plexus are rare.[54] Involvement of neurovascular bundle and brachial plexus can lead to vascular or neural compromise.[55] The clinical symptoms include neck, shoulder, or arm pain, muscle weakness, paresthesia, tingling

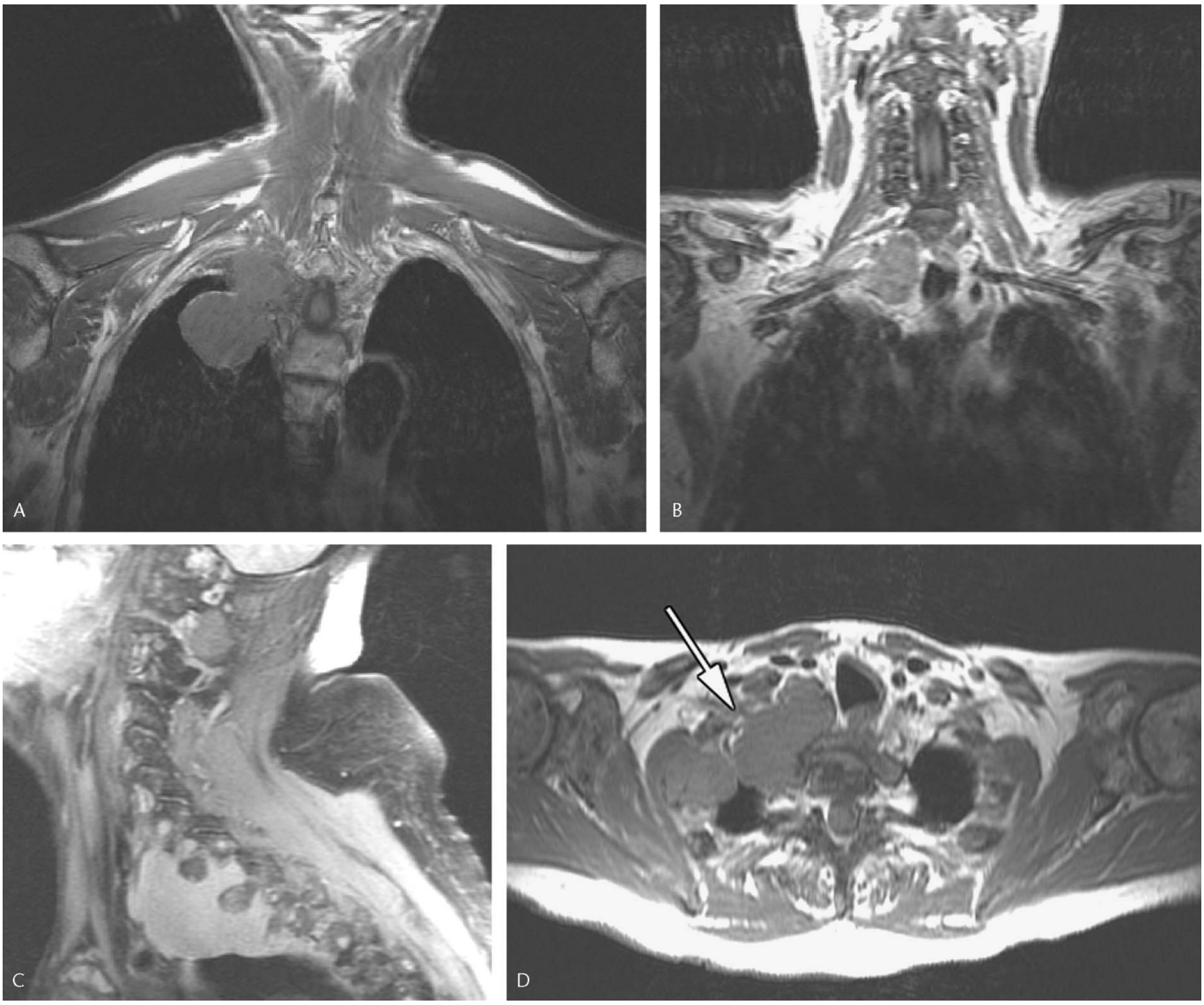

FIGURE 7. Direct extension of primary lung cancer in two patients. A, Coronal T1-weighted image demonstrates right apical lung mass with extension to the brachial plexus. B, Coronal T1-weighted image in second patient demonstrates a right apical lung mass (*arrow*) with extension to the brachial plexus (*arrowhead*) in a second patient. C, Sagittal T2-weighted image shows same mass as in second patient. D, Axial T1-weighted image shows same apical lung mass as in second patient.

sensation in fingers, or painful supraclavicular mass.[5] Metastasis from a bronchial carcinoma to brachial plexus is also known.[17] Differentiation between brachial plexopathy caused by metastatic disease and radiation therapy is a clinical and radiologic challenge, especially in carcinoma of breast.[56,57]

With its multiplanar imaging capability and better tissue contrast, MRI can be very helpful to differentiate between a metastatic tumor and radiation fibrosis.[4,12,30,58,59] Tumors exhibit low T1 signal, high T2 signal and show enhancement with gadolinium administration (Figure 8).[5,60] Radiation fibrosis exhibits a low signal intensity on both T1-weighted and T2-weighted images but can have high signal intensity on T2-weighted images.[59,61,62] Radiation fibrosis can also enhance following gadolinium contrast administration.[61] The distinction between metastatic mass and radiation-induced fibrosis can thus be a diagnostic challenge. The most reliable radiologic sign to differentiate tumor from radiation fibrosis is the presence of a soft tissue mass.[60,63]

Metastatic deposits from lymphoma, sarcoma, bladder, gastrointestinal primaries, thyroid, testis, melanoma (Figure 9), bone tumors, and head and neck masses can also involve the brachial plexus.[4,8,12,15,30]

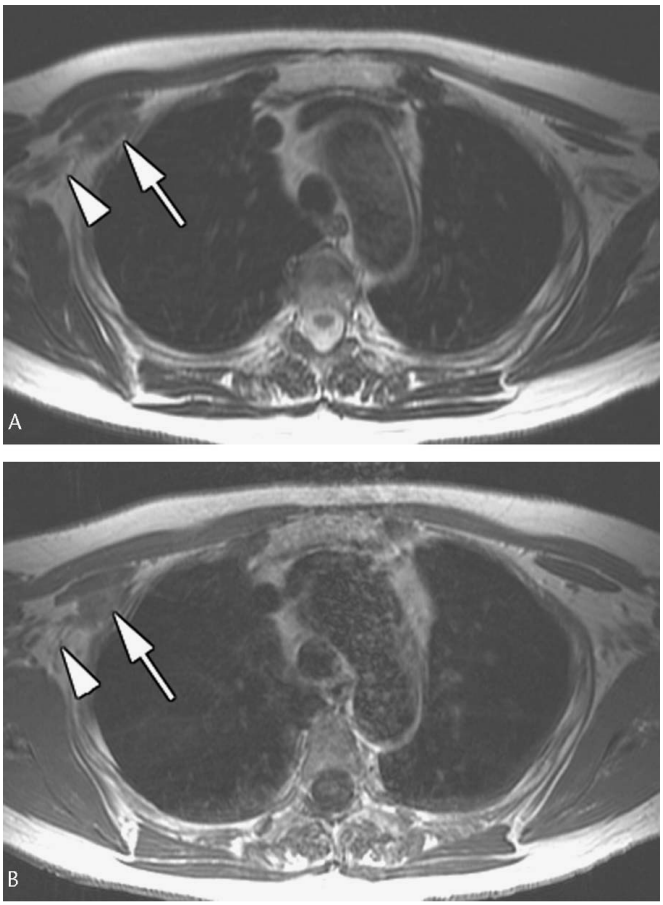

FIGURE 8. Metastatic involvement by breast cancer. A, Axial precontrast T1-weighted image shows tumor (*arrow*) adjacent to the brachial plexus cords (*arrowhead*). B, Axial postcontrast T1-weighted image demonstrates enhancement of tumor (*arrow*) adjacent to the brachial plexus cords (*arrowhead*).

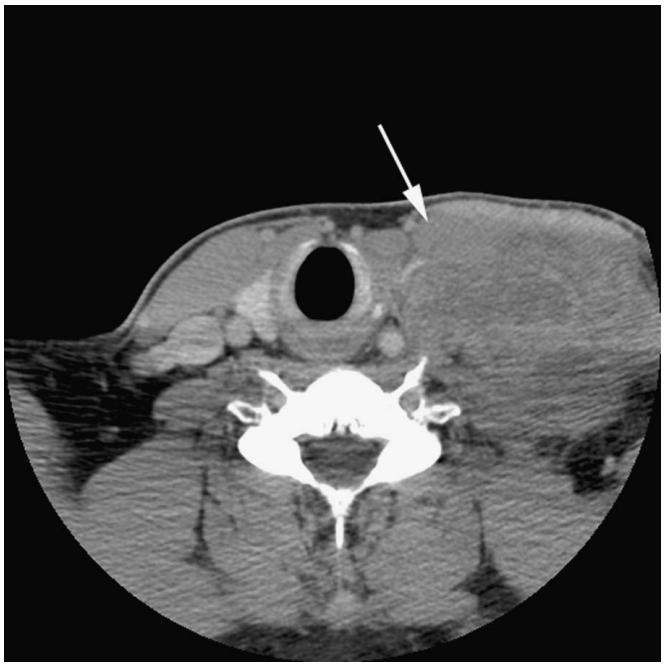

FIGURE 9. Metastatic involvement by melanoma. Axial contrast-enhanced CT image demonstrating a large tumor between the anterior (*arrow*) and obliterated middle scalene muscles, likely affecting the brachial plexus trunks.

Trauma

Brachial plexus injury represents a severe traumatic event that is difficult to handle. The spectrum of injuries can be grouped in to closed versus open injuries and direct versus stretch injuries.[64] The closed injuries include motorcycle accidents, automobile accidents, pedestrian accidents, fall from height, and sports-related accidents. By far the commonest cause in adults is motorcycle injuries.[64,65] The incidence and severity of lesions and number of patients with brachial plexus injuries have increased since the 1980s because of progress in life-saving emergency measures and compulsory helmet use for motorcyclists.[66] Open injuries include gunshot wounds, other penetrating objects like glass or metal, and stab wounds.

Depending on the site of injury, the traumatic lesions may be preganglionic or postganglionic.[12] This subdivision is important for anatomic surgical decision making to repair the brachial plexus injury by a combination of graft repair, neurolysis, and neurotization.

Nerve root avulsions occur when there is simultaneous traction of the arm and throwing of the head to the opposite side, separating the arm from the shoulder (Figure 10).[67,68] This may result in stretching and subsequent tearing of fibrous attachments, which extend from the nerves to their respective transverse processes. Pseudo-meningoceles arise from tears of the dura and arachnoid membranes caused by the root sleeves being pulled out into the intervertebral foramen (Figures 11, 12). Finally, nerve root avulsion takes place if the traction forces exceed the elastic tolerance of the nerve root.[67,68] Spinal cord injury may also occur from direct contusion or by avulsion of the nerve root if the mechanical forces are excessive. Thus, it is possible to have post-traumatic pseudo-meningoceles without a coexistent nerve root avulsion[69,70] and nerve root avulsion without traumatic meningoceles.[71] Approximately 20% of cervical nerve root avulsions are not associated with a pseudo-meningocele.[72]

The initial imaging evaluation in patients with a post-traumatic brachial plexopathy should consist of plain films of the cervical spine, shoulder, clavicle, and chest. These plain films should be assessed for fractures or subluxations, which could account for the acute neurologic deficit.[8]

Both CT myelography and MRI may be used to evaluate patients with post-traumatic brachial plexopathies. The characteristic findings in a post-traumatic brachial plexus stretch injury are pseudo-meningoceles, which may be detected by

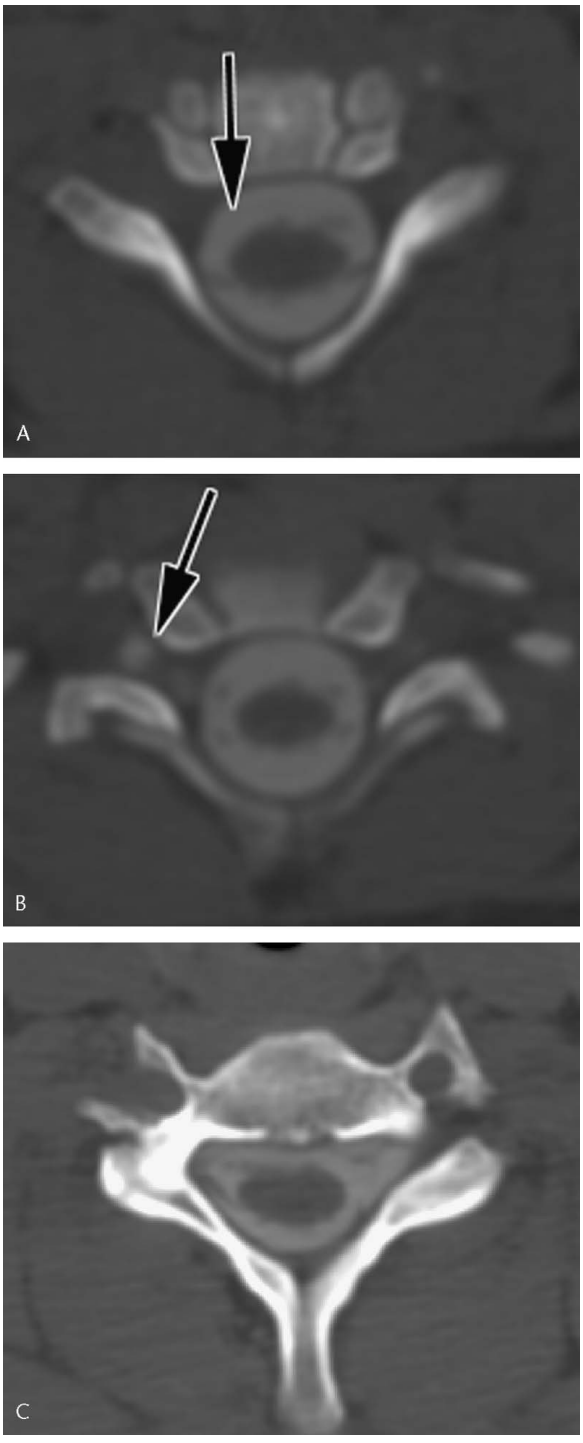

FIGURE 10. Nerve root avulsions in two patients. A, Axial image from a CT myelogram demonstrates right ventral nerve root avulsion in a newborn, status post birth trauma (*arrow*, expected location of the right ventral nerve root at this level). B, An additional image from the same study demonstrates resultant pseudo-meningocele. C, Axial image from a CT myelogram from an adult demonstrates post-traumatic ventral and dorsal nerve root avulsions on the left.

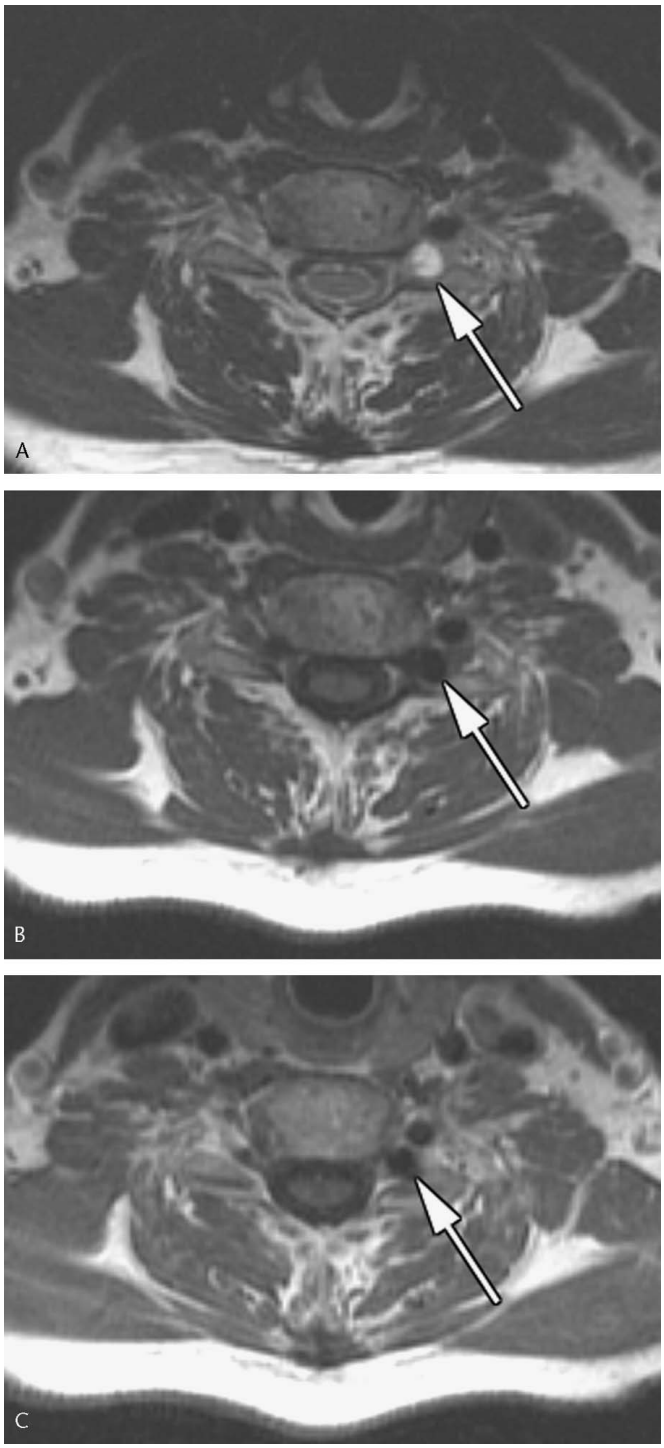

FIGURE 11. Perineural cyst (indicated by arrows). A, Axial T2-weighted image shows extension of cerebrospinal fluid into the left neural foramina, consistent with perineural cyst. B, Axial precontrast T1-weighted image shows the same. C, Axial postcontrast T1-weighted image demonstrates no enhancement.

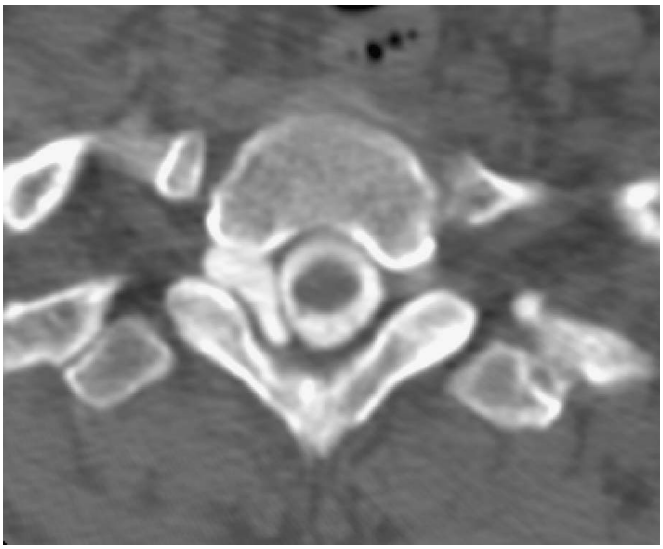

FIGURE 12. Post-traumatic pseudo-meningocele. Axial image from a CT myelogram demonstrates a posttraumatic pseudo-meningocele (*arrow*).

both CT myelography and MRI. Thin section CT myelography (1- to 3-mm-thick sections) allows for consistent visualization of the ventral and dorsal nerve roots within the spinal canal.[73] Absence of a nerve root shadow on CT myelography indicates nerve root avulsion.[67]

MRI is relatively noninvasive and does not require administration of intrathecal contrast material. On MRI, nerve root or dural thickening indicates nerve root avulsion or edema. Traumatic meningoceles are seen as fluid collections extending from the neural foramen and appear isointense to cerebrospinal fluid in all sequences. MRI allows visualization of pseudo-meningoceles which may not fill with contrast on CT myelography but cannot reliably show all the nerve roots.[71,74] Because nerve root avulsions and traumatic meningoceles can be mutually exclusive, it is necessary to image the nerve roots themselves and not only the meningoceles. Another advantage of MRI is visualization of the postganglionic extraforaminal brachial plexus. Edema and fibrosis of brachial plexus can manifest as thickening of the plexus with or without increased T2 signal.[30,75–77] MRI can also demonstrate other causes and sequelae of trauma such as hematoma and fractures, causing compression of the brachial plexus[4,10] as well as possible associated cord injuries like contusion or hematoma of cervical cord. However, presently CT myelography is considered to be the most reliable study for imaging the nerve roots.[78]

Inflammation

The commonest cause for inflammation of brachial plexus is following radiation treatment, most commonly radiation of axillary nodes for breast cancer. The neurologic symptoms manifest 5 to 30 months after radiotherapy, with a peak at 10 to 20 months.[17] The degree of damage is also dependent on the dose of the radiation, with a higher dose more likely to

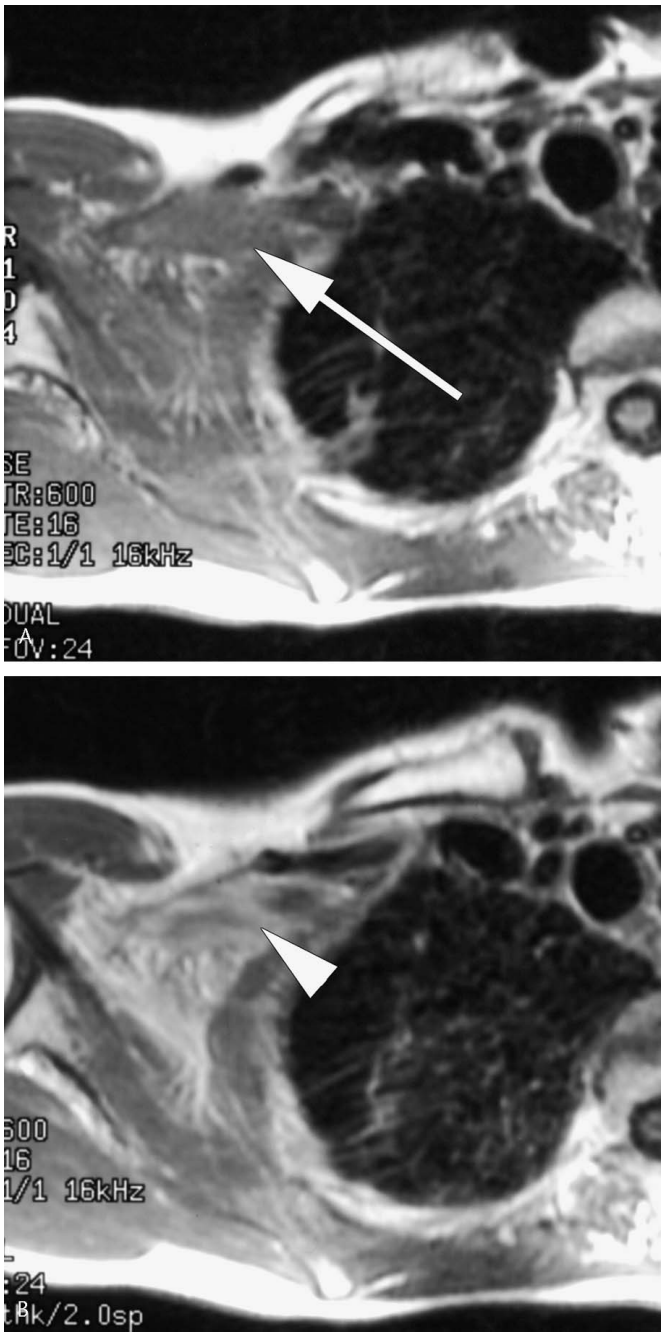

FIGURE 13. Post radiation Fibrosis. A, Axial T1-weighted image shows an irregular area isointense to muscles. B, Axial post-contrast T1-weighted image shows intense enhancement of the area revealing thickened divisions of the brachial plexus without evidence for a focal mass. (Courtesy of Douglas Quint, M.D., University of Michigan, Ann Arbor).

cause symptoms.[55] Three classic syndromes of radiation therapy (RT)-induced brachial plexopathy have been described. The most common form is a delayed progressive radiation fibrosis.[79–81] The remaining two forms of radiation damage are a reversible or transient plexopathy[79,82] and an acute ischemic plexopathy.[79,83] Radiation damage to the brachial plexus appears to be dose related and most likely occurs in patients who have received doses in excess of 6000 cGy.[57] Histologically, in radiation therapy-induced plexopathy, there is dense fibrous tissue encasing the brachial plexus with Wallerian degeneration.[84] Clinical distinction between radiation-induced neuropathy and recurrent or residual disease is difficult. MRI reveals diffuse thickening and enhancement of the brachial plexus without a focal mass[4,79] (Figure 13). The presence of a focal mass in a patient treated with RT is suspicious for recurrent tumor and requires further evaluation, especially in patients treated with doses less than 6000 cGy. Horner's syndrome is rarely caused by RT alone and, when present, is also strongly suggestive of recurrent tumor.

Active inflammation of the brachial plexus, called "brachial neuritis" may be due to a primary viral infection (cytomegalovirus, coxsackie), or complication from prior infection. It can also result as a complication of previous serum vaccine, antibiotic, or other drug administration or can be idiopathic. Patients present between the third and seventh decades of life. MRI shows diffuse thickening, abnormal T2 signal intensity, and abnormal enhancement of the brachial plexus on the gadolinium-enhanced images.[4]

Infectious process of the brachial plexus most commonly involves supraganglionic portion and is most likely due to discitis with associated epidural abscesses.

Miscellaneous

The clinical symptoms of degenerative cervical disc disease may mimic those of a brachial plexopathy. It is prudent to include evaluation of the cervical spine when imaging brachial plexus. Brachial plexopathy may also be caused by cervical ribs, present in approximately 1% of the population and are symptomatic in 10% of affected individuals.[85,86] Occasionally, a cervical rib may be attached to the first rib by a fibrous band. The cervical rib syndrome is thought to result from compression of the lower trunk of the brachial plexus as it crosses over the cervical rib or by compression of the lower trunk by a fibrous band that attaches to the first rib.

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