CONTINUING EDUCATION PROGRAM: FOCUS…

Imaging of the non-traumatic brachial plexus

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Abstract The first line imaging of the non-traumatic brachial plexus is by MRI. Knowledge of the anatomy and commonest variants is essential. Three Tesla imaging offers the possibility of 3D isotropic sequences with excellent spatial and contrast enhancement resolutions, which leads to time saving and quality boosting. The most commonly seen conditions are benign tumor lesions and radiation damage. Gadolinium is required to assess inflammatory or tumour plexopathy. MRI data should be correlated with FDG-PET if tumor recurrence is suspected.

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The main function of the brachial plexus is the sensorimotor innervation of the arm. The problem with the clinical examination and suboptimal electromyography is that these only very rarely establish the type and precise site of the lesion [1]. MRI is the reference investigation for identifying and studying a variety of plexus problems because of its excellent spatial and tissue resolution [2–5].

After reviewing the normal anatomy of the BP and its MRI appearances, we will describe the technical findings and limitations of MRI. We will then describe the features of the main neoplastic and inflammatory diseases and those seen in the thoracic (Q2) outlet syndrome.

Anatomy

The pulmonary apical region is complex and contains vascular, neuronal, lymph nodes and muscle structures.

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The brachial plexus arises from the cervical spinal cord and extends to the axillary region [6,7]. The roots of the plexus are formed by the union of the anterior branches of the last four cervical nerves (C5 to C8) and the first thoracic nerve (T1). These roots then cross the thoracic (interscalene) outlet, which is triangular in shape and formed anteriorly by the anterior scalene muscle, posteriorly by the middle and posterior scalene muscles and inferiorly by the subclavian artery and the dome of the apex of the lung.

Three trunks are then formed in the lower part of the neck: the superior trunk formed by the joining of the C5 and C6 nerve roots, the middle trunk which is a continuation of the C7 nerve root and the inferior trunk formed by the union of the C8 and T1 nerve roots.

These trunks pass behind the clavicle and subclavian muscle and cross the cervicoaxillary canal. Each then divides into anterior and posterior branches. The group of six branches form three bundles which are named according to their relationship with the axillary artery: the posterior bundle formed from the union of the posterior divisions of the three trunks, the lateral bundle formed by the union of the anterior divisions of the superior and middle trunks and the medial bundle which extends the anterior division of the inferior trunk.

The collateral and terminal branches of the brachial plexus divide into supraclavicular and infraclavicular parts: the supraclavicular branches stem from the ventral roots of the spinal nerves and the trunks of the brachial plexus and are formed from the dorsal scapular nerve, the long thoracic nerve, the subclavian muscle nerve and the suprascapular nerve. The infraclavicular branches of the plexus arise from the three bundles. The posterior bundle divides into the radial nerve and the axillary nerve. The lateral bundle divides into the lateral pectoral nerve, musculocutaneous nerve and lateral root of the median nerve whereas the medial bundle divides into the ulnar nerve, the median root of the median nerve, the median pectoral nerve, the median cutaneous nerve of the upper arm and the medial cutaneous nerve of the forearm (Fig. 1).

The anterior scalene muscle is an important anatomical landmark in imaging for the purposes of analysing the brachial plexus. Coronally, this muscle separates two, internal and external, regions. The internal lateral vertebral space principally contains the roots and trunks of the brachial plexus. Outside of the scalene area, the bundles pass around the dome of the apex of the lung. The plexus structures lie in a coronal or oblique coronal plane posterior to the plane of the subclavian artery. The middle and posterior scalene muscles are found behind the plane of the plexus. On a sagittal view the anterior scalene muscle delineates two regions. The most anterior, prescalene plane contains the subclavian vein and small lymph nodes. Behind the anterior scalene muscle, above its insertion onto the upper edge of the first rib, known as the Lisfranc tubercle, the pre-plexus subclavian artery lies anterior and superior to the dome of the apex of the lung.

Anatomical variants are common. The brachial plexus can receive the anterior branches of C4 or T2 then forming a "prefixing" (C4 to C8) or "post-fixing" (C5 to T2) plexus. In the second of these variants, the inferior trunk may then be compressed by the first rib. Variations in the formation of trunks, dividing branches and bundles and in the anatomical relationships with the axillary artery or scalene muscles are also found, although the anatomy of the terminal branches generally remains unchanged. Variants such as supernumerary scalene muscles, fibrous bands from the cervical ribs or an enlarged C7 transverse process can cause thoracic outlet syndrome.

MRI protocol and normal appearances

It is not possible to establish a standard protocol applicable to all investigations and so the choice of sequences and parameters depends on the indication, technical capacity of the instruments and patient constraints.

The protocol we use in our establishment is summarized in Table 1.

Using a double antenna for the neuro-cervical area [8] and the upper part of the chest compensates for the lack of signal from the shoulders. The patient is positioned lying on his/her back, arm lying along the length of the body. Images are taken in slow, shallow respiration. Cardiac and respiratory synchronization methods have been described in the literature although they are not performed routinely because they increase the acquisition times [8]. In addition, respiratory and cardiac artifacts are very troublesome.

The appearances of the brachial plexus at 1.5 and 3 Tesla have been described in several studies [9–12]. High magnetic fields offer a better signal to noise ratio and excellent spatial and contrast enhancement resolutions. A good signal to noise ratio is always required, as is correction of the field inconsistencies, which are more common with 3 Tesla instruments. Presaturation bands, adjustment of field homogeneity (Q4) and correct choice of the phase direction are needed.

Sequences can be programmed as follows: when the cervical spine has not been examined before the investigation an initial T2 weighted sagittal sequence on the whole cervical column is useful, combined with transverse sections
### Table 1  The set of sequences used for MRI investigation of the BP.

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Orientation</th>
<th>FOV (mm)</th>
<th>Section thickness (mm)</th>
<th>Matrix</th>
<th>RT (ms)</th>
<th>ET (ms)</th>
<th>Acquisition time</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2D</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1 TSE (± FS)</td>
<td>3 planes</td>
<td>300*195</td>
<td>3</td>
<td>512*310</td>
<td>575</td>
<td>11</td>
<td>3 min 09</td>
</tr>
<tr>
<td>T2 TSE (± FS)</td>
<td>3 planes</td>
<td>300*195</td>
<td>3</td>
<td>512*310</td>
<td>3000</td>
<td>100</td>
<td>3 min 12</td>
</tr>
<tr>
<td>T2 TSE STIR</td>
<td>Coronal</td>
<td>250*250</td>
<td>3</td>
<td>448*269</td>
<td>4600</td>
<td>99</td>
<td>3 min 33</td>
</tr>
<tr>
<td><strong>3D</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2 Space TSE</td>
<td>Coronal (+ reconstructions)</td>
<td>380*380</td>
<td>0.9</td>
<td>448*448</td>
<td>1500</td>
<td>182</td>
<td>6 min 54</td>
</tr>
<tr>
<td>T2 Space TSE STIR</td>
<td>Coronal (+ reconstructions in the plane of the plexus)</td>
<td>240*240</td>
<td>3</td>
<td>384*350</td>
<td>4000</td>
<td>249</td>
<td>4 min 50</td>
</tr>
<tr>
<td>Vibe GRE</td>
<td>Coronal (+ reconstructions)</td>
<td>300*300</td>
<td>1.2</td>
<td>256*256</td>
<td>12.2</td>
<td>4.4</td>
<td>2 min 27</td>
</tr>
<tr>
<td>T2 Space TSE STIR ISO</td>
<td>Coronal (+ reconstructions in the plane of the plexus)</td>
<td>380*380</td>
<td>0.9</td>
<td>384*384</td>
<td>3000</td>
<td>176</td>
<td>12 min 38</td>
</tr>
<tr>
<td>T1 Space</td>
<td>Coronal (+ reconstructions in the plane of the plexus)</td>
<td>310*310</td>
<td>1.2</td>
<td>256*256</td>
<td>664</td>
<td>10</td>
<td>6 min 54</td>
</tr>
<tr>
<td>CISS</td>
<td>Sagittal (reconstructions)</td>
<td>145*145</td>
<td>0.5</td>
<td>320*320</td>
<td>6.54</td>
<td>2.94</td>
<td>9 min 13</td>
</tr>
</tbody>
</table>
perpendicular to the axis of the spinal cord if any abnormalities are present in order to identify somatic disc or spinal lesions.

Myelography sequences (BALANCE FFE [Philips], CISS [Siemens], FIESTA [GE]) are usually required for injuries and are therefore not considered in this article.

Once the cervical spine has been examined, a T1 weighted sequence without fat saturation centered on the pathological region of the plexus should be organized. It is sometimes helpful to carry out this sequence initially on the unaffected side to use it as a reference, as abnormalities are occasionally difficult to confirm. On 3 Tesla imaging, 3D SPACE isotropic sequences can achieve voxels of 0.9 mm$^3$ with reconstructions in all spatial planes. In order to save time, the image can be recorded on a coronal view, with strict or oblique axial and sagittal reconstructions performed secondarily.

This "anatomical" or morphological sequence is essential and allows the different components of the thoracic outlet and related abnormalities to be examined. Nerve fibers are hypointense compared to the adjacent hyperintense fat and are isointense compared to muscle structures (Fig. 2).

2D or 3D T2 weighted STIR sequences can be used to delineate plexus structures because of the homogeneous fat saturation. Hyperintense nerve fibers are clearly distinguished from the hypointense muscle and saturated fat (Fig. 3). These sequences are useful for detecting peripheral

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**Figure 2.** Normal appearances of the brachial plexus — sagittal sections from inside outwards on T1 weighted MRI. Oblique sagittal TSE showing the different components of the brachial plexus. a: at the emergence of the roots: anterior scalene muscle (AS), middle scalene muscle (MS), subclavian artery (A) and clavicle (C); b: within the interscalene triangle: superior trunk (ST), middle trunk (MT) and inferior trunk (IT); c: in the costoclavicular groove: lateral bundle (LB), posterior bundle (PB) and medial bundle (MB); d: in the pectoralis minor muscle (PM).
nerve abnormalities. A wide FOV allows the two brachial plexus to be compared from their origins to their peripheries allowing any signal or morphological abnormality to be easily identified. Multiplanar isotropic resolution reconstructions can be performed in a T2 weighted 3D STIR SPACE sequence. Maximum intensity projection (MIP) or reverse MIP processing can show the whole plexus over one to two sections (Fig. 4).

T1 weighted gadolinium sequences are needed to assess inflammatory or neoplastic plexopathies and can be performed with fat saturation using 2D or 3D acquisitions.

Additional sagittal or coronal sequences with the arms raised and MRI angiographic sequences can be useful in thoracic outlet syndrome.

Tractography diffusion tensor imaging is currently being used within a research context but may certainly prove useful, particularly in neoplastic pathology in terms of planning surgery.

**Pathological appearances**

**Neoplastic diseases [13—19]**

Neoplastic disease in the brachial plexus can be intrinsic or extrinsic and may be benign or malignant.

The most common benign intrinsic lesions are Schwannomas and neurofibromas [17]. Schwannomas are benign tumors arising from Schwann cells and are usually solitary, well demarcated, encapsulated, slow going and painless. Symptoms are rare and are secondary to compression of the nerve with large tumors. These tumors have the particular feature of growing extrinsically and asymmetrically enabling them to be excised surgically. Neurofibromas are unencapsulated tumors arising from the nerve bundles, which infiltrate the nerve from which they originate and therefore have poorer surgical results. Both tumors appear as fusiform lesions lying parallel to the long axis of the nerve,

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**Figure 3.** T2 weighted 3D STIR MRI. The plexus structures are hyperintense and clearly differentiated from the hypointense muscle components. Planar reconstruction: a: oblique para-coronal; b: oblique axial.

**Figure 4.** Normal appearance of the brachial plexus – T2 weighted 3D STIR MRI. MIP processing provides a view of all of the parts of the plexus in a single section: a: MIP reconstructions; b: reverse MIP reconstruction.
Figure 5. Schwannoma in a 45-year-old patient with right arm dyesthesia. The various sagittal views show a solitary encapsulated eccentric lesion, compressing and displacing the plexus and vascular structures. a: T2 weighted MRI with salt and pepper appearance in the lesion; b: T2 STIR weighted MRI; c: T1 weighted MRI with homogeneous hypointensity; d: T1 weighted MRI with gadolinium showing central enhancement and an unenhanced peripheral line.

which are hypointense on T2 weighted MRI and have a hypointense centre creating a target sign and are isointense or hypointense and homogeneous on T1 weighted MRI enhancing strongly after contrast injection. The T2 weighted salt and pepper appearance described in the literature is not discriminatory [16] (Fig. 5). Heterogeneous appearances with cystic degeneration are usually seen in Schwannomas. Topographic features are useful in characterizing lesions, with an extrinsic growth in Schwannomas and infiltrating disease in neurofibromas. Neurofibromas may be multiple or plexiform when they are pathognomic with type 1 neurofibromatosis (NF1). These then involve a long segment of nerve with a “bag of worms” appearance on MRI. (Fig. 6). Intrinsic neoplastic lesions are rarer and consist mostly of the malignant peripheral nerve sheath tumors usually seen in NF1. The same lesions may be seen after radiotherapy and can develop up to 20 years after treatment [5,20,21].

Although it is not often straightforward to confirm whether these lesions are benign or malignant, some features such as size (over 5 cm), signal heterogeneity or enhancement, extension to adjacent soft or bone tissues and the presence of metastases suggest malignancy. Hypermetabolism on PET-CT can also be a key factor in suggesting whether the lesion is benign or malignant, although low uptake does not definitively exclude malignancy.

Benign and malignant extrinsic tumors can also cause brachial plexopathy. The benign lesions are the desmoids tumors, lipomas, lymphangiomas, hemangiomas and perineuronal cysts. The most common malignant lesions are recurrences of breast cancer, apical lung tumors,
lymphomas, metastatic lymphadenopathy, osteosarcomas and Ewing’s sarcomas (Fig. 7).

The investigation to assess apical lung tumors and [Q5] Pancoast syndrome should include all of the plexus structures including the nerve roots in its report. Posterosuperior or anterosuperior invasion of the plexus structures does not in itself represent a contraindication to surgery. Contrast enhancement in the anterior scalene muscle, which suggests tumor extension, should be looked for routinely [22,23].

Whilst an interface defect is not synonymous with tumor extension, deformity or circling of the subclavian artery are adverse indicators [22,23].

Radiation-induced plexopathy

It can be difficult to distinguish plexus disease due to post-radiation fibrosis from tumor recurrence, particularly in breast carcinomas. Post irradiation plexopathies may occur within 6 months after radiotherapy is started or several months to years after it is finished. It generally develops at doses over 60 Grays [5] and the main MRI findings are diffuse uniform thickening of the radiated segment of the plexus with poorly demarcated fat interfaces. Appearances are hypointense on T1 weighted MRI with moderate to extensive gadolinium enhancement and hyperintense on T2 STIR in the early stage, reflecting the inflammatory changes in the fibrosis, which may persist for several years [24]. FDG-PET CT is certainly useful and shows normal or low radio-tracer uptake [25,26]. Concomitant involvement of the adjacent soft tissues and the presence of a pleural effusion or radiation pneumonia in the apex of the lung support the diagnosis. (Fig. 8). In the chronic stage, radiation plexus fibrosis can appear as a T2 and T1 weighted hypointensity without contrast enhancement although this is a rare finding. If any diagnostic doubt is present, close interval MRI or PET CT monitoring should be offered.

Thoracic outlet syndrome

Thoracic outlet syndrome is due to dynamic compression of the neurovascular bundle in the thoracic outlet, usually when raising the upper limb. Neuronal, arterial and venous structures can be compressed either separately or simultaneously within the interscalene triangle, the costoclavicular space or more occasionally the pectoralis minor tunnel [27–29]. If neurological symptoms are present, electromyography may show delayed nerve conduction speed in the C8 and T1 territories. The clinical diagnosis, however, is difficult and CT or MRI is essential in order to establish the exact causes and precise sites of the compression.

The most common causes are bone and muscle-ligament abnormalities. The bony causes are cervical ribs, enlarged C7 transverse processes and acquired, often post-traumatic, abnormalities. The muscle and ligament causes include congenital or acquired abnormalities of the subclavious or scalene muscles and fibrous bands with or without cervical ribs or enlarged C7 transverse processes (Fig. 9). In addition, some body morphotypes such as bodybuilders and young tall slim women with sagging shoulders are predisposed to the condition [27].

Whilst the bone abnormalities can be confirmed by conventional radiography or CT, muscular and ligament conditions are best identified by the good tissue resolution offered by MRI. Dynamic maneuvers, usually with the arm in abduction and with rotation of the head on the ipsilateral side reduces the size of the outlets and can unmask vascular compression on Doppler ultrasound or MRI angiography, with the best results being obtained with CT angiography.

Other plexopathies [3,12,30,31]

The other inflammatory and infectious problems, which occur in the brachial plexus, include the Parsonage-Turner syndrome, otherwise known as acute brachial plexus neuritis.
Figure 7. 55-year-old patient with left arm pain as a result of recurrence of a tumor 19 years after surgery, radiotherapy and chemotherapy treatment for a left breast ductal carcinoma. a and c: enhanced axial chest CT — tissue infiltration around the left subclavian artery and brachial plexus in the pectoralis minor tunnel. a: FDG-PET showing increased uptake compatible with malignant disease; b: T1 weighted MRI — homogeneous hypointensity in the lesion; e and f: T1 weighted MRI with gadolinium showing pronounced contrast enhancement in the lesion.
Figure 8. Radiation plexopathy in a patient following treatment for invasive ductal carcinoma of her left breast. a: sagittal T2 weighted MRI showing thickening of the three trunks in the interscalene triangle, which is slightly hyperintense with loss of interfaces. Note the neighboring apical pulmonary fibrosis supporting the suspected diagnosis; b and c: T1 weighted MRI with and without gadolinium showing moderate late enhancement of the brachial plexus trunks similar to the apical lung fibrosis.

Radiation plexopathy or neuralgic amyotrophy of the shoulder should also be mentioned. This is a rare syndrome of unknown cause involving inflammation of the nerves of the shoulder, arm or chest. A history of vaccination or recent infection is reported in 25% of cases [30]. Patients present with sudden onset sharp shoulder pain with no history of injury and develop flaccid paralysis, usually of the scapular muscles, a few days later. The most commonly affected muscles are the supraspinous and infraspinousus and the condition is bilateral in a third of cases. The paralysis may last for several months and a complete recovery is generally expected. A change in the denervated muscles may be seen on MRI, with a homogeneous hyperintense signal on T2 weighted fat saturation sequences and amyotrophy with fat infiltration appearing as a hyperintensity on T1 weighted sequences may be seen in the acute stage (Fig. 10).

Charcot-Marie-Tooth disease or hypertrophic neuropathy is a hereditary sensorimotor neuropathy, which can affect the branches of the brachial plexus, although it more commonly involves the peripheral nerves in the arms and legs. It generally affects children or young adults and is characterized by focal or diffuse thickening of one or more peripheral nerves with atrophy of the affected limb. Fusiform thickening of the nerve structures is seen, with T2 weighted hyperintensity and T1 weighted hypointensity and diffuse homogeneous gadolinium enhancement. It is associated with acute or chronic muscle denervation.
Figure 9. Thoracic outlet syndrome with enlarged C7 transverse process in a 40-year-old patient with right arm pain which worsens on abduction. Low dose, unenhanced cervical column CT. a: axial section in the bone window showing an enlarged C7 transverse process on the right; b: volume reconstruction; c: oblique sagittal reconstruction in the soft tissue window. The inferior trunk of the brachial plexus is seen clearly in contact with the right transverse process of C7.
Conclusion

MRI is the reference technique for assessing brachial plexopathies. Advances in 3 T equipment and 3D sequences offer spatial resolution of under a millimeter, which improves diagnostic performance. In the future, diffusion tensor imaging is expected to elicit further indications, which have not yet been defined. It is still always essential to interpret results alongside the clinical findings and other findings from the assessment for all cases. In some situations, PET-CT should be used in addition to MRI, particularly if recurrence of a tumor is suspected.

Disclosure of interest

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