SMS-RESOLVE Tractography for Surgical Management of Brachial Plexus Trauma

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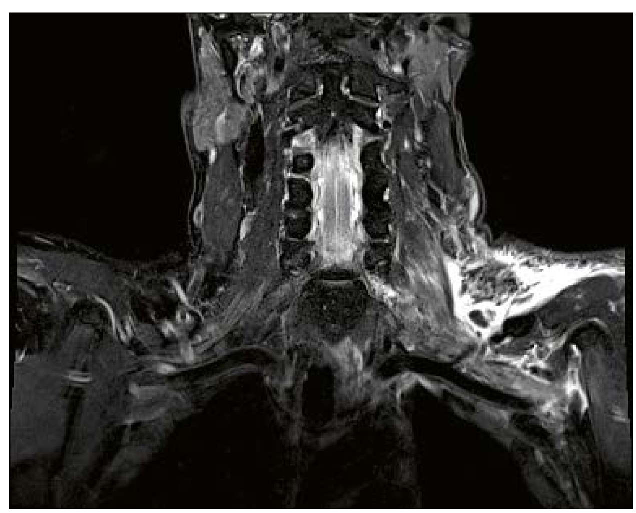
Introduction

Traumatic injury to the brachial plexus is devastating, resulting in significant loss of function and disability. Surgical management is complex, drawing on several surgical techniques ranging from nerve repair to grafting and nerve transfers. Free functioning muscle transfer may also be considered in order to restore stability and function to the upper limb. Surgical reanimation focuses first on restoring elbow flexion and shoulder stabilisation as functional priorities. Grade 3/5 (against gravity) or 4/5 (against resistance) is an expected outcome for these functional groups because intra- and extra-plexus donors are generally available, and the regeneration distances are short. Prior to consideration of any of these procedures, it is important to establish the level of the neurological lesion accurately.

The diagnosis of brachial plexus injuries presents a clinical dilemma due to both complex anatomy and varied symptomology [1]. Imaging with CT myelography and MRI have both been utilised in the evaluation of nerve injuries involving the brachial plexus, with a focus on the identification of preganglionic injuries. In the hyperacute phase post injury, imaging is targeted towards identifying other injuries that may require urgent management such as vascular and orthopaedic injuries. MRI is preferable in many cases thanks to the absence of ionizing radiation, however MR imaging in the hyperacute phase is typically compromised by extensive surrounding oedema and haematoma.

High resolution T2-weighted MR images with fat saturation has been a workhorse in aiding diagnosis and treatment assessment throughout the course of clinical care. Specifically, STIR-prepared 3D SPACE images, and the multiplanar maximum intensity projection (MIP) reconstructions, enable evaluation of the plexus anatomically. Diffusion tensor imaging and tractography have been used in probing the integrity of nerves which can potentially inform surgical planning. However, imaging the brachial plexus with DTI is technically challenging and presents barriers to implementation [8]. Specific limitations include the small size of the brachial plexus relative to the field-of-view, close proximity to physiological motion, and field inhomogeneities [14].



1 Coronal T2 fat-saturated acquisition on day one post injury (performed at an outside institution). There is significant oedema in the supraclavicular fossa. The extent of this oedema obscures the visualisation of any neural injury making a confident diagnosis extremely difficult. We have found that scanning of the acute post-traumatic plexus is best performed 8–10 weeks post injury to best demonstrate the pathology, following the resolution of the acute post-traumatic oedema. Scanning performed at a later time point also depicts the pathology however many surgical treatments are best instituted early and therefore the 8–10 weeks' time frame is best in our experience.

- The small size of the involved nerves can lead to partial volume and mis-registration artifacts. The plane of acquisition is also important. Sagittal imaging is the ideal plane for visualising the spinal cord. However, given that the brachial plexus runs nearly orthogonal to the plane of the cord, the ideal acquisition for the plexus is axial or axial oblique. Our patient's data was acquired axially.
- Motion can occur as a result of pulsation of the CSF, supra-aortic vessels, and respiratory motion. This leads to misregistration of DTI tractography relative to the anatomical overlay images, resulting in the white matter tracts to project away from their true course [10].
- DTI has historically been based on echo-planar imaging. Although rapid in image acquisition, EPI suffers from image distortions as phase-encoding lines of *k*-space are collected immediately after a single radiofrequency pulse. Geometric distortions occur where there is poor magnetic field homogeneity and susceptibility changes from nearby tissue interfaces [2, 10–12].

The recently developed RESOLVE technique [2] aims to address some of the above-mentioned challenges. RESOLVE is a diffusion-weighted sequence based on multi-shot multi-slice 2D echo-planar imaging. With each excitation the sequence acquires a segment of the data in the readout direction, providing significantly shorter echo spacing compared to the single-shot technique. This in turn reduces susceptibility and blurring effects, as well as making high resolution diffusion imaging possible. However, the multi-shot nature of the sequence exacerbates physiological motion during diffusion preparation. To this end, a navigator echo of the centre *k*-space is acquired at each shot to provide data for phase correction or to trigger a re-acquisition in the case of severe phase errors [3–5].

Segmenting the acquisitions into multiple shots, the RESOLVE technique is significantly slower than the single-shot counterpart, limiting the number of slices and/or diffusion directions that can be acquired in a practical imaging time. To combat this limitation, a blipped-CAIPIRINHA technique is implemented to drastically accelerate RESOLVE technique by simultaneous excitations and acquisitions of multiple slices [6]. These slices are then separated in the reconstruction facilitated by the sensitivity profiles of the multi-channel receive coil [7]. The blipped-CAIPIRINHA technique enhances the separability by introducing an in-plane shift of the simultaneous slices with additional blips in the slice direction applied along with phase-encoding blips. In the following section, we describe the benefit of the addition of such an advanced imaging technique to the anatomic assessment of the traumatic plexus with a pertinent clinical case.

Case Study

Acute care

The patient was a 46-year-old male who sustained a severe upper brachial plexus injury following a downhill mountain bicycle injury. Clinically he presented with left arm pain and clinical signs consistent with an upper plexus injury, including absent sensation in the C5 and 6 dermatomes, 0/5 power in the C5 and 6 myotomes with reduced power in some C7 myotomes and some preservation of C8 and T1 innervation. In particular, he was noted to have weakness of the wrist and fingers. Following initial trauma management according to ATLS principles, his brachial plexus was imaged with anatomical MRI, day one post injury. The initial imaging (Fig. 1) demonstrated a C7 nerve root avulsion and extensive oedema within the supraclavicular fossa which precluded further assessment of the constituent components of the plexus.

His initial surgical management comprised an Oberlin I and II nerve transfer to restore elbow flexion four months after injury. Specifically, redundant fascicles of the ulnar nerve to Flexor Carpi Ulnaris (FCU) were transferred to the biceps branch of the musculocutaneous nerve and redundant fascicles of the median nerve to Flexor Carpi Radialis (FCR) were transferred to the brachialis branch of the musculocutaneous nerve. He subsequently underwent a spinal accessory to suprascapular nerve transfer six months after injury.

Follow-up

The patient did not achieve any recovery of elbow flexion four months after surgery and was referred to the brachial plexus clinic at our institution for an assessment. At that time, the patient's hand function had improved substantially from the initial presentation, but elbow flexion was absent, and the shoulder was unstable. He was referred to the radiology department for imaging of his brachial plexus. He gave informed consent to partake in a research examination of his plexus, which granted access to a prototype sequence SMS-RESOLVE.

The anatomical imaging demonstrated a pseudo-meningocele at the C7 level, consistent with the earlier MRI findings of C7 avulsion (Fig. 2A). There was also hyperintensity and a nodular fusiform appearance to the C5 and C6 nerve roots, not shown, consistent with axonotmesis and neuroma in continuity. The C8 and T1 nerve roots appeared normal on anatomic MRI.

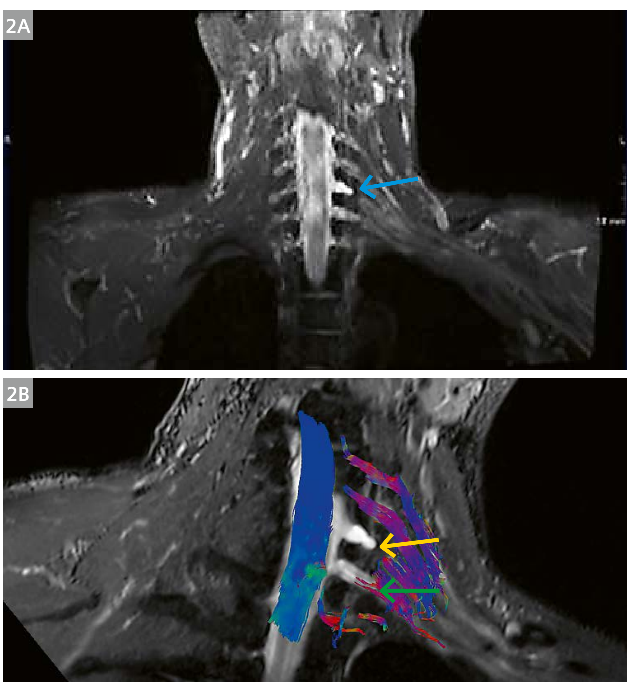
Tractography with 20 directions was also performed using the above-mentioned SMS-RESOLVE DTI technique and overlayed on the anatomical information (Fig. 2B). This demonstrated lack of fiber continuity proximally at the C7 nerve root as expected but also demonstrated a lack of proximal fiber continuity at the C8 level (green arrow

Fig. 2B) – this finding was not expected and served as a potential explanation for the failure of the previous surgical procedure given the nerve fibers transferred to aid elbow flexion (fascicle to FCU) are innervated primarily by C8. Had the proximal injury to C8 been recognised pre-operatively, a different treatment strategy may have been pursued.

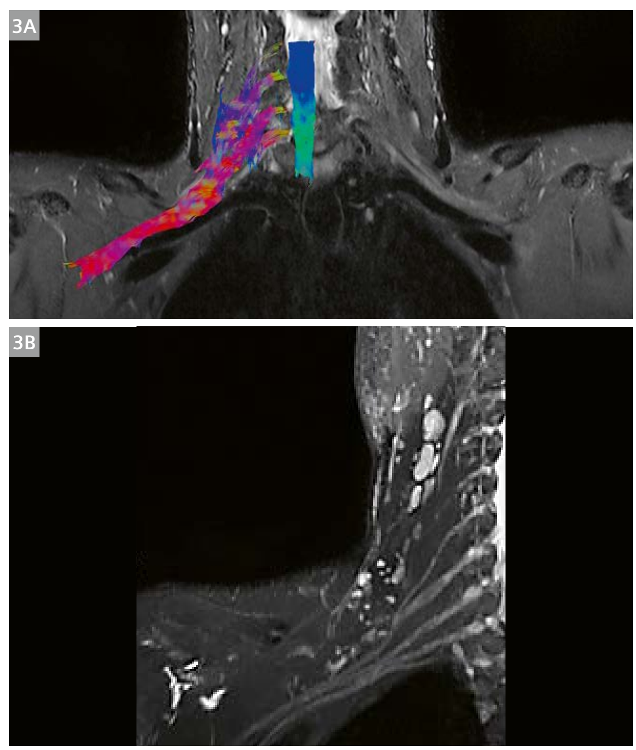
The patient is currently considering the option of free functioning muscle transfer (gracilis) using the phrenic nerve as a donor.

Discussion

MRI DTI tractography is an established neuroimaging technique in determining the location of important fiber tracts and in order to better plan surgical and radiation oncology procedures. It utilises the directional constraints to free water movement (diffusivity) to resolve the directionality of fibers in the CNS [16]. As alluded to in the introduction, the SMS-RESOLVE technique is uniquely suited to tackle the challenges faced with brachial plexus DTI. The read-out segmented EPI aids in providing high resolution scans with reduced susceptibility and blurring effects. Additionally, the shot-by-shot navigators and corresponding phase correction/re-acquisition help reduce the effects of physiological motion including, the small fibres relative to the field-of-view, physiological motions. The SMS technique has also demonstrated the capacity to reduce the imaging time.



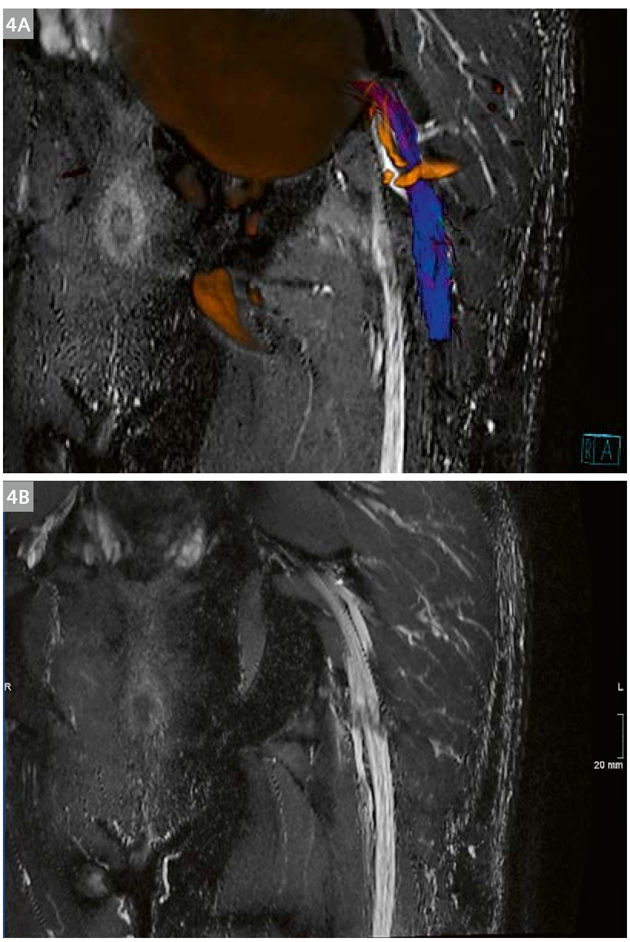
2 **(2A)** Coronal MIP reconstruction of a 3D STIR space MRI demonstrating a pseudomeningocele of the C7 nerve root on the left (blue arrow), consistent with a preganglionic avulsion injury of the C7 nerve root. The remainder of the nerve roots appear intact. **(2B)** Coronal oblique MIP reconstruction of a 3D STIR space MRI with overlayed DTI tractography, depicting lack of continuity of the proximal fibers of C7 with the source anatomic imaging showing a corresponding pseudomengocele (yellow arrow). In addition, a feature not seen on the anatomic imaging is an absence of proximal continuity of the C8 nerve root (green arrow).



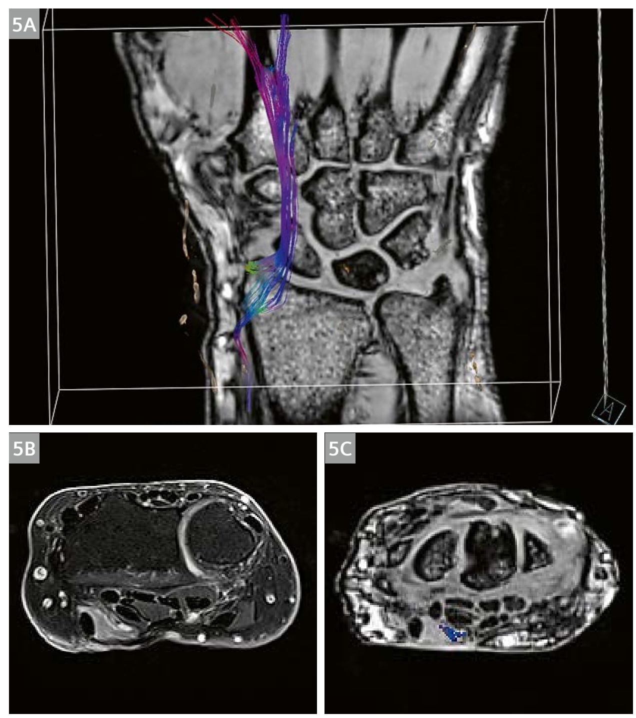
3 **(3A)** DTI tractography overlayed on a STIR SPACE anatomic acquisition in a 45-year-old male volunteer. The images depict robust tracks extending from the nerve roots to the proximal aspect of the distal branches. Combined with high resolution anatomic images and clinical correlation regarding neurology, we feel this technique shows significant promise in improving the evaluation of plexus trauma. **(3B)** Coronal oblique MIP reconstruction from a STIR SPACE acquisition. The proximal components of the Brachial plexus are demonstrated. The upper trunk is formed by the union of the C5 and C6 nerve roots, the lower trunk is similarly formed by the junction of the C8 and T1 nerve roots. The middle trunk represents the continuation of the C7 nerve root.

However, brachial plexus DTI using SMS-RESOLVE requires a robust and consistent workflow, including imaging protocols and post-processing techniques. Our imaging department performed numerous scans with volunteers to establish an optimized imaging protocol that balance between, FOV, resolution, SNR, the number of diffusion directions, and overall scan time. Representative volunteer images with DTI tractography and STIR SPACE are shown in Figure 3.

The optimized SMS-RESOLVE based workflow has found wider applications. Figure 4 illustrates a clinical case of a 34-year-old male patient who sustained a stab wound to his buttocks. The anatomic imaging shown on the right demonstrates decreased signal within the sciatic nerve at the site of stabbing injury likely reflecting fibrosis or hemosiderin. While the extent of injury is inconclusive from the anatomical scan alone, the DTI study demonstrates continuity of the nerve fibers, in this case, combined with the clinical findings of relatively mild weakness in the sciatic nerve distribution, negating the need for surgical exploration. In another case, as shown in Figure 5, SMS-RESOLVE tractography provided evaluation of the relationship of a painful lump in the volar aspect of the wrist to the median nerve for a 74-year-old female patient, with a remote history of glass laceration and surgical repair. This evaluation avoided the need for surgical exploration, by demonstrating that the painful lesion was continuous with the median nerve, consistent with a traumatic neuroma, surgery to this could have resulted in significant loss function of the median nerve which was clinically intact.



4 MRI study of a 34-year-old male patient who sustained a stab wound to his left buttocks. **(4A)** Overlay image of a 20 direction DTI acquisition of the sciatic nerve covering the region of a stab injury. The DTI study demonstrates continuity of the nerve fibers, which in combination with the clinical findings negated the need for surgical exploration. **(4B)** Coronal STIR SPACE acquisition of the left sciatic nerve. There is linear hypointensity within the nerve, which corresponded to the site of knife injury, likely reflecting a combination of haemosiderin and fibrosis.



5 **(5A–5C)** DTI tractography of the median nerve in a 74-year-old female with a remote history of glass laceration and surgical repair as a child in another country – details not available. The patient presented with a palpable and painful lump in the volar aspect of the wrist and imaging was requested to evaluate the relationship to the nerve. Anatomic MRI demonstrating a poorly demarcated mass in the expected location of the median nerve. DTI tractography shows the fibers of the median nerve to pass through the lesion indicating the lesion to be of neural origin – likely a neuroma in continuity given the clinical context. The study prevented a surgical exploration of the lesion which could have resulted in damage to the remaining median nerve.

Conclusion

As demonstrated in the above case, we believe that the addition of DTI tractography to the evaluation of traumatic nerve injuries in general and brachial plexus injuries in particular traumatic can improve the diagnostic accuracy and demonstrate additional pathology that is not evident on the purely anatomical imaging. As clearly shown in this case, the selection of the correct treatment option relies on a correct diagnostic assessment of the level and extent of injury. Advanced imaging can aid in correct patient and procedure selection to allow the best chance of meaningful restoration of function in these patients. The technique is not limited to the brachial plexus and we have had success adding useful information in complex clinical cases elsewhere in the body.

In conclusion, we have presented a case that demonstrates how the addition of DTI tractography, using the SMS-RESOLVE sequence, adds valuable information over and above that of standard MR imaging, assisting in the correct management of the complex injuries sustained in traumatic injury of the brachial plexus.

The ability of SMS-RESOLVE to acquire multiple slices simultaneously results in shorter scan times and less motion artifacts. It is therefore able to generate robust tracking of the complex peripheral nervous system and will likely find more applications in complex surgical planning.

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