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The diagnostic accuracy of 1.5T magnetic resonance imaging for detecting root avulsions in traumatic adult brachial plexus injuries

Abstract

Identification of root avulsions is of critical importance in traumatic brachial plexus injuries because it alters the reconstruction and prognosis. Preoperative magnetic resonance imaging is gaining popularity but there is limited and conflicting data on its diagnostic accuracy for root avulsion. This cohort study describes consecutive patients requiring brachial plexus exploration following trauma between 2008 and 2016. The index test was magnetic resonance imaging at 1.5 Tesla and the reference test was operative exploration of the supraclavicular plexus. Complete data from 29 males was available. The diagnostic accuracy of MRI for root avulsion(s) of C5-T1 was 79%. The diagnostic accuracy of a pseudomeningocoele as a surrogate marker of root avulsion(s) of C5-T1 was 68%. We conclude that pseudomeningocoles were not a reliable sign of root avulsion and MRI has modest diagnostic accuracy for root avulsions in the context of adult traumatic brachial plexus injuries.

Level of Evidence: III

Introduction

Traumatic brachial plexus injuries affect up to 1% of adults involved in road traffic collisions who are triaged in regional trauma centres (Midha, 1997). Optimal management relies upon differentiating pre-ganglionic and post-ganglionic injuries because the reconstruction and prognosis is different. Post-ganglionic nerve injuries (ruptures or attenuations) have a more favourable prognosis because the damaged nerve may be repaired or grafted if treated in a timely fashion. Conversely, pre-ganglionic nerve injuries (root avulsions) warrant nerve transfers from intra-plexal or extra-plexal donors, as re-implantation remains of uncertain value (Eggers et al., 2016; Fournier et al., 2005). Therefore, the identification of root avulsion(s) is critical as it alters the operative plan and prognosis.

Currently, operative exploration of the supraclavicular brachial plexus is the most reliable method of identifying root avulsion(s). As the exploratory surgery has an uncertain outcome, pre-operative imaging and neurophysiological tests (O'Shea et al., 2011) are obtained to help the surgeons and patients to better prepare for the possibility of nerve repairs, grafting, or transfers and rehabilitation. Magnetic resonance imaging (MRI) is gaining popularity owing to its multi-planar capabilities and unparalleled soft-tissue contrast (Vargas et al., 2010). However, few studies have specifically considered the diagnostic accuracy of MRI for root avulsions (Hayashi et al., 1998; Yoshikawa et al., 2006). The overall reported accuracy of MRI for traumatic root avulsion ranges from 52-88% with technical issues limiting improvements. Some studies investigating the accuracy of MRI for root avulsion use a reference standard of clinical follow up, ie. reanimation of the limb (Tagliafico et al., 2012) or electrophysiological studies (Tsai et al., 2006; Yoshikawa et al., 2006) as surrogate markers of root avulsion. A few studies report operative exploration as the reference standard (Penkert et al., 1999; Hems et al., 1999; Disawal and Taori, 2012; Doi et al., 2002; Carvalho et al., 1997; Yang et al., 2013; Chanlalit et al., 2005; Nakamura et al., 1997; Qin et al., 2016), but most have important methodological flaws, used outdated MRI technologies or pulse sequences which are now obsolete and fail to report their data in accordance with the Standards for Reporting Diagnostic accuracy studies (STARD, Smidt et al., 2005; Bossuyt et al., 2015), Therefore, there is a lack of reliable data on the diagnostic accuracy of MRI for root avulsion in adult brachial plexus injuries.

We present a study on the diagnostic accuracy of MRI in traumatic adult brachial plexus injury. Our hypothesis was that 1.5T MRI of the brachial plexus (the index test) could not correctly classify patients with traumatic root avulsions, as compared with the reference standard of operative exploration.

Methods

This report was written in accordance with the STARD guidance (Smidt et al., 2005; Bossuyt et al., 2015) and Cochrane Handbook for Reviews of Diagnostic Test Accuracy (The Cochrane Collaboration, 2016).

Design

This retrospective cohort study evaluated the diagnostic accuracy of MRI at 1.5 Tesla (T) performed on a consecutive series of adult males who sustained non-penetrating traumatic brachial plexus injuries. Participants were managed in the host institution between January 2008 and July 2016.

Eligibility Criteria

Our institution is a specialist centre for adult and paediatric brachial plexus pathology, both congenital and acquired. Potential cases were identified from operative logbooks (electronic and paper based) containing keywords pertaining to brachial plexus exploration. We included consecutive adults who underwent exploration of the supraclavicular brachial plexus during the study period. Exclusion criteria are shown in Figure 1.

Outcomes

The primary outcome was the diagnostic accuracy of MRI for detecting a root avulsion of the brachial plexus as compared to the reference standard of operative exploration. Secondarily, we sought to investigate the accuracy of pseudomeningocoeles visualised on MRI as a surrogate marker of root avulsion, as compared to the reference standard.

Prior tests

As part of their clinical care in the context of major trauma, all patients were routinely examined and imaged by plain radiography and contrast-enhanced computed tomography (CT). These images were typically reported by two radiologists (a trainee and consultant) and findings were coded in binary. Vascular injury was defined by any flow abnormality or extravasation affecting the subclavian or axillary vessels. Hemicord oedema/haemorrhage was defined by asymmetrical high signal intensity at multiple levels of the hemicord on fluid weighted images.

<u>Index Test</u>

The index test was MRI of the brachial plexus. Clinically, this test is used to attempt to diagnose the type of nerve injury. All participants were scanned using a MRI scanner (Siemens Avanto 1.5T system, Siemans Healthcare, Erlangen, Germany) acquiring sagittal T1-weighted (280mm FOV, 3mm slice thickness, TR 6020, TE 102 and 384 matrix) and T2-weighted turbo-spin echo (280mm FOV sequences, 3mm slice thickness, TR 500, TE 9.7 and matrix 384), axial T2 turbo-spin echo (TSE; 220mm FOV sequences, 3mm slice thickness, TR 4180, TE 104 and matrix 320), coronal short-tau inversion recovery (STIR; 3mm slice thickness, 5960 TR, 83 TE and 320 matrix) and constructive interference steady state (CISS; 0.7mm slice thickness, 11.48 TR, 5.74 TE and 320 matrix) sequences. No intravenous contrast was used. All scans were performed pre-operatively and so the results of the reference standard were not known to the assessor. All images were reviewed at the time of imaging by one experienced musculoskeletal radiologist (JJR, a highly experienced Consultant Radiologist) with access to examination findings and prior test results; reports were not revised for this research. The MR image was considered “positive” for root avulsion when there was a lack of continuity or absence of the nerve root between the spinal cord and the exit foramen, or if there was abnormal contour of the nerve root with a more horizontal orientation, suggesting that the avulsed nerve root was lying caudal to the level of the normal attachment. A pseudomeningocoele was defined by expansion of the space containing the nerve root and cerebrospinal fluid (CSF) within the foramen, associated with an abnormal contour of the dura within the spinal canal, which is the site where dural leaks occur. Occasionally, the leak of CSF extended beyond the foramen into a cystic collection lying in the paraspinal soft tissues and this too was defined as a pseudomeningocoele.

<u>Reference Standard</u>

The reference standard for a diagnosing root avulsion of the brachial plexus was operative exploration. In our institution, exploratory surgery is preferentially performed acutely for brachial plexus injuries in the context of major trauma. We defined avulsion as a binary outcome with implicit threshold. In early exploration, if the spinal foramina was empty (ie. there was no identifiable nerve) then avulsion was diagnosed; equally, if there was a neural structure in the foramen but it was easily pulled away then a concealed avulsion was diagnosed. If exploration was delayed, the avulsion was defined by a combination of: the absence of the nerve roots in the foramina; relaxation, attenuation and displacement of the scarred proximal nerve trunks or dorsal root ganglion; no identifiable nerve fascicles on exploration of the nerve root; empty proximal nerve sheaths; and the absence of any muscle activity on electrical stimulation of the nerve. Somatosensory Evoked Potentials were not used. The C4 to T1 roots were explored in all participants.

<u>Analysis</u>

Continuous metrics are skewed so presented as medians with interquartile ranges (IQR) and compared with rank-based methods. Categorical variables are presented as frequencies (with percentages) and compared with Chi Square or Fisher's Exact test as appropriate. To correlate time to scan with the index and reference tests, Spearman's Rho are reported. The agreement between pseudomeningocolele and avulsion counts on MRI, compared to avulsion counts at exploration are represented by Cohen's kappa (k, whereby perfect agreement is k=1 and no agreement is k=0). To investigate the association between other injuries (as binary explanatory variables) and the presence of any avulsion at operation, binary logistic regression models were developed in an iterative manner, with the final reported model in entry mode. As per the Transparent reporting of a multivariable prediction model for individual prognosis or diagnosis statement (Collins et al., 2015), models were internally validated using lossless non-parametric bootstrapping with 1000 iterations (resampling with replacement) as there are no available datasets for external validation. Overall diagnostic accuracy was defined as (TP+TN/total). Significance was set at $p<0.05$. Confidence intervals (CI) were generated to the 95% level.

Results

There were 47 potential participants identified from hospital records of whom 17 were excluded because case notes were missing (n=1), cases were erroneous coded (n=2), there were no preoperative MR images (n=8) or the MR images acquired were unintelligible owing to movement artefact (n=2) or acquired using a pulse sequence which does not visualise the plexus (n=7). Therefore, data from 29 males involved in high energy trauma were available for analysis.

The mechanism of injury included: motorcycle collisions with vehicles (n=22), pedestrians hit by motor vehicles (n=2), bicyclists hit by motor vehicles (n=2), a fall from substantial height (n=2) and an industrial traction injury (Table 1). Horner's syndrome was associated with a T1 root avulsion (sensitivity 67% and specificity 90%, p=0.004), with exploration as the reference standard.

We explored timings to MRI and surgery for patients treated exclusively within our institution versus those initially managed elsewhere and later referred; there was no significant difference in the median time from injury to MRI (16 vs. 97 days, p=0.104) or injury to surgery (53 vs. 157 days, p=0.062).

Overall, the diagnostic accuracy of MRI for root avulsion(s) of C5-T1 was 79% (Table 2), which means that MRI incorrectly classified the injury in approximately one out of four cases. Importantly, the negative predictive value is approximately 81% which means that for every five cases the MRI reports no avulsion, there will be one occult root avulsion. In nine cases (31%), the MRI findings were in perfect agreement with the operative findings.

Table 3 details the diagnostic test accuracy of a pseudomeningocoele as a surrogate marker for root avulsion. The overall diagnostic accuracy for C5-T1 was 68% which means that for one in three cases, MRI incorrectly classified root avulsion based on the presence of a pseudomeningocoele. Again, in nine cases the MRI findings of pseudomeningocoeles agreed with the operative findings of avulsion exactly.

Time from injury to scanning was not associated with the accuracy of root avulsion identification (Figure 1). There was moderate agreement between the frequency of avulsions suspected on MRI and avulsions diagnosed at operation (k=0.4, p<0.001). Data suggests that the longer the time from injury to MRI, the weaker the association between pseudomeningocoeles and true root avulsion, albeit not statistically significant (Figure 2). There was moderate agreement between the frequency of suspected avulsions and pseudomeningocoeles (k=0.3, p=0.001) and no agreement between the presence of a pseudomeningocoele and a true root avulsion (k=0.3, p=0.09), which suggests that pseudomeningocoeles are not a good surrogate radiological marker of root avulsion.

Every case sustained a fracture, namely of the ribs (n=18), sternum (n=2), base of skull (n=3), cervical spine (n=11), thoracic spine (n=8) and lumbar spine (n=3) and the ipsilateral clavicle (n=6), 1st rib (n=9), scapula (n=11) and humerus (n=5). Three males had radiologically paralysed hemidiaphragms. Six participants sustained ipsilateral vascular injuries which were all intimal tears resulting in acute thrombosis. There were 11 haemopneumothoraces.

The only significant predictor of a root avulsion was the suspicion of any root avulsions on MRI (OR 4.1 [95% CI 3.2, 1089], p=0.006). When bootstrapped, the suspicion of any root avulsions on the MRI remained a strong predictor of root avulsion (OR 4.1 [95% CI 1.7, 60], p=0.007) and the presence of an ipsilateral vascular injury (OR 2.7 [95% CI 0.3, 40], p=0.003) and clavicle fracture (OR 2.1 [95% CI 1.7, 38], p=0.048) emerged as further potential predictors.

Comparing those with perfect MRI and surgical agreement vs. others, there was no difference in the median time from injury to MRI (23 vs. 24 days, p=0.9) or surgery (48 vs 65 days, p=0.2)

Discussion

Our data shows that cross sectional imaging by MRI at 1.5T using the described pulse sequence and when interpreted by an expert, confers a modest diagnostic test accuracy for root avulsion compared to operative findings in the context of adult traumatic brachial plexus injuries. Accuracy was not affected by the time between injury and scanning. Conversely, we suggest that the presence of a pseudomeningocoele is not a reliable surrogate marker of root avulsion in either a positive or negative predictive fashion.

MRI is believed to be the best indicator of brachial plexus pathology (Vargas et al., 2010) and in the context of trauma, more informative than electrophysiological studies (O'Shea et al., 2011), ultrasonography (Zhu et al., 2014; Mallouhi and Meirer, 2003; Lapegue et al., 2014) and intraoperative somatosensory-evoked potentials (Sureka et al., 2009). Many historical articles report the findings of MRI without a reference standard (Bayaroğullarıi et al., 2013; Chen et al., 2014; Ning et al., 2011; Takahara et al., 2008; Qiu et al., 2014; 2008; Zhang et al., 2008) or use a reference such as CT myelography. A few studies have reported MRI findings against the best available reference standard of operative exploration (Penkert et al., 1999; Hems et al., 1999; Disawal and Taori, 2012; Doi et al., 2002; Carvalho et al., 1997; Yang et al., 2013; Chanlalit et al., 2005; Nakamura et al., 1997; Qin et al., 2016). This is important, because if another reference test is chosen (eg. CT) then the index test can only ever be shown to be as good as the reference. Further, if the index test is better than that chosen reference standard, then this cannot be shown. Our finding of an overall diagnostic accuracy of 79% is consistent with the overall accuracy of 52-88% reported in previous studies comparing MRI to operative exploration. There are numerous potential reasons for differences in accuracy, such as, technical limitations of MRI, improved image fidelity with improved scanner technology, different methods of surgical exploration, varying definitions of avulsion, methods of sample selection, and chance. These factors might be explored further with a systematic review.

Pseudomeningocoeles are described as a surrogate marker of root avulsion because the rupture of the dura mater is believed to correspond to a rupture of the nerve root. This is not always the case (Aralasmak et al., 2010; Vvan Es and Bollen, 2010; Yoshikawa et al., 2006; Sureka et al., 2009; Doi et al., 2002) with pseudomeningocoeles reported to occur without root avulsion in less than15% of cases. However, we detected a pseudomeningocoele in 8% of intact roots, with the agreement varying depending on the root concerned. Further, the literature suggests that 20% of root avulsions have no appreciable pseudomeningocoele on MRI. No pseudomeningocoele was observed in 23% of root avulsions. Our findings may be different to historical figures because better scanners provide a greater ability to detect pathology. We suggest that pseudomeningocoeles are not a reliable sign of avulsion as either a positive or negative predictor.

Seven cases (15%) were excluded because scans performed elsewhere were inadequate. This is unsurprising given that the proprietary brachial plexus imaging sequences in commercially available MRI scanners produce poor images and therefore, substantial sequence customisation is usually needed (Figure 3). We recommend that patients with brachial plexus injuries be promptly referred for investigation and treatment within a specialist centre. This model would allow robust research to be undertaken by experts in nerve injury and medical imaging, and enable_experimentation with diffusion techniques [diffusion tensor imaging tractography (Tagliafico et al., 2011; Chen et al., 2012; Vargas et al., 2010)] and hyperpolarisation methods (Ross et al., 2010) which may futher improve the accuracy of peripheral nerve imaging.

Our study has limitations which must be considered. The sample is small and so all hypothesis tests are at risk of Type 2 error. Unfortunately, the accuracy of the reference standard of surgical exploration of the supraclavicular brachial plexus is not perfect. Therefore, the reported accuracy of any comparison test may be less reliable and cautious interpretation is needed. Partial root injuries cannot be reliably detected and delayed exploration may reduce the identification of true positives. It may be impossible to morphologically differentiate a post-ganglionic rupture which is very proximal from a true root avulsion. In the case of intradural avulsions, when the nerve root is not displaced from the intervertebral foramen, the root may appear normal in the posterior triangle. Better accuracy for the reference standard may be achieved if cervical laminectomy and exploration of the roots within the spinal canal were also performed, but this is rarely justifiable. Our sample could be biased because we selected (albeit consecutive) a series of operatively managed adults from the United Kingdom, imaged with a specific brand and model of MRI scanner using specific pulse sequences and so the inferences cannot necessarily be generalised to other situations.

In conclusion, MRI at 1.5T appears to confer a modest diagnostic test accuracy for root avulsions in the context of adult traumatic brachial plexus injuries. Adults with brachial plexus injuries should be promptly transferred to specialist centres to enable high-quality prospective research which may improve diagnostic tests and reconstructive methods. Until the fidelity of diagnostic imaging improves, we recommend that surgical exploration by an experienced surgeon remains the reference standard and MRI be utilised as a supplemental investigation.

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Tables

Table 1. Comparison of patient demographics between two groups

Patient demographics	**Patients with No root avulsions (n=10)**	**Patients with any root avulsion (n=19)**	**p-value**
Median age in years at injury (IQR)	26 (28-34)	32 (26-44)	0.211
Right sided injury (%)	6 (60)	9 (47)	0.700
Median days from injury to MRI (IQR)	16 (7-41)	29 (6-163)	0.769
Median days from injury to operative exploration (IQR)	49 (11-149)	65 (40-164)	0.330

Table 2. MRI diagnostic accuracy for suspected nerve root avulsions.

Location of suspected avulsion on MRI		**Avulsion found at operative exploration** Yes	No	Test sensitivity (%)	Test specificity (%)	Positive Predictive value (%)	Negative Predictive Value (%)
At least one avulsion	Yes	17	2	89	80	89	80
	No	2	8				
C4 root	Yes	1	0	100	93	100	93
	No	2	26				
C5 root	Yes	6	3	67	75	67	75
	No	5	15				
C6 root	Yes	10	1	90	73	91	72
	No	5	13				
C7 root	Yes	9	4	69	81	69	81
	No	3	13				
C8 root	Yes	8	3	73	89	73	89
	No	2	16				
T1 root	Yes	5	2	71	86	71	86
	No	3	19				
Cumulative (per root) suspicion of root avulsion for C5-T1	Yes	38	13	68	85	75	81
	No	18	76				

Table 3. MRI diagnostic accuracy for nerve root avulsions based on pseudomeningocoeles.

Location of the pseudomeningocoele		**Avulsion found at operative exploration** Yes	No	Test sensitivity (%)	Test specificity (%)	Positive Predictive value (%)	Negative Predictive Value (%)
At least one detected	Yes	12	3	63	70	80	50
	No	7	7				
C4 root	Yes	1	0	100	93	100	93
	No	2	26				
C5 root	Yes	2	1	67	75	67	65
	No	9	17				
C6 root	Yes	4	1	91	72	80	54
	No	11	13				
C7 root	Yes	5	5	69	81	50	63
	No	7	12				
C8 root	Yes	6	3	73	89	67	80
	No	4	16				
T1 root	Yes	5	2	71	86	71	86
	No	3	19				
Cumulative (per root) detection of a pseudomeningocoele for C5-T1	Yes	22	12	40	87	65	69
	No	34	77				

Figure Legends

Figure 1. A scatter plot showing the agreement between suspected avulsions on MRI and root avulsions at operation with time to MRI, with linear regression co-efficient (red line) and 95% confidence intervals (green lines). The maximum agreement is six counts (ie. the status of C4-T1 [all 6 roots] were correctly classified by MRI). No agreement is shown by zero counts (ie. all six roots were incorrectly classified by MRI). This shows no evidence that time from injury to MRI is correlated with the accuracy of a suspected root avulsions on MRI.

Figure 2. A scatter plot showing the agreement between pseudomeningocoeles on MRI and root avulsions at operation with time to MRI, with linear regression co-efficient (red line) and 95% confidence intervals (green lines). The maximum agreement is six counts (ie. the status of C4-T1 [all 6 roots] were correctly classified by MRI); no agreement is shown by zero counts (ie. all six roots were incorrectly classified by MRI). A negative correlation between the time from injury and the agreement between pseudomeningocoeles on MRI and a root avulsion at operative exploration is suggested.

Figure 3. An axial T2-weighted image at the level of C7 showing an abnormal contour of the left sided dural sac, indicating a tear and no visualised rootlets crossing the CSF space which is suggestive of root avulsion.