Diagnosis of the level of intradural rupture of the rootlets in traction lesions of the brachial plexus

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The precise point of intradural rupture in preganglionic traction injuries to the brachial plexus has been a subject of controversy. In this study of avulsed roots we have shown that rupture occurs at varying levels. True avulsion of the root with attached spinal cord tissue was seen in two cases and in the remainder rupture was peripheral to the central-peripheral transition zone. We have further shown that corpora amylacea marked the boundary between tissue of the central and peripheral nervous systems. This observation provides a basis for renewed work towards the direct repair of intradural ruptures of the ventral and dorsal roots.

There are two types of traction injury in the brachial plexus. The first is preganglionic rupture of the spinal nerve, peripheral to the dorsal-root ganglion (DRG), which can be repaired. The second is preganglionic rupture which affects the spinal rootlets central to the DRG. This is the more common injury; analysis of 300 consecutive explorations of the brachial plexus revealed 826 preganglionic lesions, 290 postganglionic ruptures and 394 intact spinal nerves. The preganglionic lesion has long been considered to be an injury of the central nervous system and therefore irreparable. Experiments in animals, however, have shown that anterior horn cells can regenerate into peripheral nerve tissue implanted into the spinal cord and this was the basis of reimplantation of avulsed ventral roots via nerve grafts into the cord of patients after a preganglionic traction lesion of the brachial plexus.

Direct inspection of the spinal cord at hemilaminectomy has shown that there are two patterns of preganglionic lesion. In the first, the roots are ruptured in their intradural course, leaving small central stumps of variable length. The term peripheral intradural rupture has been proposed for this lesion. Jamieson described it in the human spinal cord, in the course of an operation to repair ruptured dorsal rootlets: "It was clear that the rupture had taken place just distal to the surface of the cord: little stumps of the rootlets were visible. This observation may be of particular importance." This peripheral intradural rupture has also been described in rats. In the second type of injury, the roots are torn directly from the cord, central nervous tissue is attached to the tip of the avulsed root, and there is a defect in the cord. This is the more serious intradural injury since it leads to rapid retrograde death in a high proportion of the motor neurones of the anterior horn. Reimplantation of ventral roots into the cord prevents such loss of motor neurones in animals. In the central avulsion lesion reimplantation is the only practical way of securing direct reconnection between the spinal cord and the avulsed spinal nerve. Direct repair of the peripheral intradural rupture, peripheral to the transitional zone, has been done for the dorsal roots. We know of no case in which it has been undertaken for the ventral roots because of the difficulty in securing safe access to the anterior face of the spinal cord; this remains a theoretical possibility.

Our study sought a simple means of identification of central avulsions without exposure of the cord. Excision of the tips of avulsed rootlets is a necessary part of the repair of the brachial plexus, by reimplantation or nerve transfer. The excised material was available for morphological assessment by light and transmission electron microscopy in a prospective study on patients with traction injury to the brachial plexus. The unique microanatomy of the transitional zone between the spinal rootlets and the entry zone of the cord has been described, but little is known about the morphological features in this area after preganglionic traction injury in the human brachial plexus. Our aim was to establish morphological criteria which would allow the histological differentiation between central avulsions and peripheral intradural preganglionic ruptures.

Patients and Methods

Between December 1997 and March 1998, we carried out primary exploration for traction injury of the brachial plexus...
us on 12 patients at the Royal National Orthopaedic Hospital.

All the patients gave informed consent to exploration of the brachial plexus and, for research purposes, to the study of material which would otherwise be discarded. Excision of the tips of the avulsed rootlets is an integral part of nerve repair, whether by grafts from adjacent postganglionic ruptures, or by nerve transfer. The nerve biopsies did not alter the surgical procedure nor were patients randomised into different treatment groups. Approval of the study was given by our Ethical Committee.

Preoperative clinical assessment included a detailed neurological examination and assessment using Baker’s injury severity score (ISS).\(^1\)\(^2\) Intraoperatively, each of the spinal nerves forming the plexus was classified as ‘intact’, ‘stretched’, ‘ruptured’ or ‘avulsed’. ‘Avulsion’ was defined by the display of spinal ventral and dorsal rootlets attached to the DRG, which had been pulled into the posterior triangle of the neck. These were seen between the posterior margin of scalenus anterior and the superior margin of the clavicle. Biopsies 3 to 15 mm in length were taken from the tips of the avulsed rootlets and fixed in 4% glutaraldehyde in 0.1M sodium cacodylate buffer. After fixation for 48 hours transverse and longitudinal sections were cut from the tips of the avulsed rootlets, reimmersed in fixative and postfixed two hours later in 1% osmium tetroxide. Stepwise dehydration in alcohol was followed by infiltration of the specimens in Spurr’s hard resin.

Tissue from the cervical spinal cord of a 25-year-old patient who had died from cystic fibrosis was taken at postmortem and fixed and processed by the same method. Transverse sections were taken from the C5 to T1 segments.

Sections for light microscopy (LM) 0.5 \(\mu\)m thick were cut on a microtome and stained with 1% Toluidine Blue in borax. Ultrathin sections were cut with glass knives on the microtome for transmission electron microscopy (TEM). These were stained with 2% uranyl nitrate and lead citrate and examined by a Philips CM-12 electron microscope.

**Results**

**Clinical.** Root avulsions were identified at operation in nine of the 12 patients. The delay between injury and exploration ranged from four days to one year. Age, gender, mode of injury, the ISS and the type of lesion for individual spinal nerves are given in Table I. Injuries associated with the traction injury consisted mostly of injuries to the limbs, but life-threatening chest or head injuries were present in three patients.

**Histological findings.** We were able to differentiate three different histological patterns in the LM sections of the tips of the avulsed roots (Figs 1 to 3). Biopsies taken from patients at four weeks or longer after injury consistently showed abundant fibrosis at the zone of rupture (Fig. 1) so that it was not possible to distinguish between central avulsion and peripheral intradural rupture.

LM sections of biopsies taken within one week of injury showed two different histological patterns. Most of the spinal nerves were ruptured peripheral to the transitional zone, shown by the uniform nerve structure at the tip of the root in Figure 2. A different tissue structure was demonstrated in the centre of the tip of the spinal rootlet in Figure 3. It had undergone post-traumatic lytic changes, but corpora amylacea (CA) were identified at the periphery of this area. CA are round and homogeneously staining bodies 15 to 50 \(\mu\)m in diameter; they are a consistent finding in the subpial zone of the spinal cord in postmortem material (Fig. 4).\(^1\)\(^6\) Since they were named by Virchow in 1854 (Greek: amylon = starch), CA have not been associated with dis-

<table>
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<tr>
<th>Case</th>
<th>Age (yr)</th>
<th>Mode of injury</th>
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<th>Interval between injury and exploration</th>
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<td>R</td>
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<td>Motorcycle</td>
<td>9</td>
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<td>8 days</td>
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<td>31</td>
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<td>Motorcycle</td>
<td>19</td>
<td>12 months</td>
<td>R</td>
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</table>

* the maximum possible score is 75 and indicates a lethal outcome
† I, intact; IC, lesion in continuity; R, extradural rupture; A, avulsion (intradural injury), ?, diagnosis likely but unproven
‡ bold type indicates a biopsied avulsion
ease, but more recent findings link their increased incidence to a number of neurodegenerative disorders. We found them at the tips of two of ten examined roots, namely the dorsal root of C6 and the dorsal root of C8 (cases 2 and 3).

Identification of the central part of the central-peripheral transition zone. Central glial cells in the postmortem material underwent early lytic changes similar to those of the cells at the tip of the avulsed root after preganglionic traction injury. The foot processes of the astrocytes which are characteristic features of CNS tissue in TEM sections could not be clearly identified, although several profiles of astrocytic glial filaments were seen (Fig. 5). Lytic changes affect the CNS at a different rate. Figure 5 shows the early signs of breakdown of the myelin sheaths, but the external lamina of the Schwann cell can be seen to be intact in a different section of spinal cord tissue (Fig. 6). This is a characteristic feature of peripheral nerve tissue, but was seen here extending into central nervous tissue. CA were not affected by lytic changes in biopsies taken within one week from injury, or in the postmortem specimens (Figs 3 and 4).

Discussion

Our study has shown that rupture in preganglionic traction injury to the brachial plexus occurs at different levels. That central to the central-peripheral transition zone was found in two out of ten examined roots, but rupture peripheral to the transition zone was more common. Histological differentiation between the two types of preganglionic rupture is possible in biopsies studied within a week from injury. Fibrosis prevents the diagnosis of the level of rupture in later cases.

Which morphological criterion is best used to distinguish the central from the peripheral part of the transitional zone (TZ) in avulsed human roots? Astrocytes are found in clusters just on the central side of the TZ and can be identified by their foot processes in TEM sections of animals perfused in vivo. These degenerate extremely quickly, however, within six hours in the postmortem cases, and this morphological criterion is not useful clinically. The minimum interval between injury and exploration is rarely less than 24 hours and can be much longer in patients with associated life-threatening injuries.

A striking characteristic of the microanatomy of the TZ is the protrusion of central nervous tissue into the root in a
A dome-shaped extension up to 400 µm in depth. This applies mainly to the dorsal roots of rats but variations of this pattern have been described in ventral roots and in roots of other animals and in man. Our observation that the external lamina of the Schwann cell extended into the spinal cord adds further to this irregularity of the microarchitecture of the TZ. The presence of the external lamina cannot be used as a reliable indicator of peripheral nervous tissue at the tip of avulsed nerves.

CA can be easily identified at the tip of avulsed roots and there is recent evidence which supports the use of CA as a sensitive and specific marker for CNS tissue in central avulsions. In a series of 24 postmortems, CA were shown to be present in the subpial area of the spinal cord. They were not seen in a seven-month-old child and their numbers increase with age. Studies of freshly-fixed nerve tissue in 23 patients undergoing extirpation of the vestibular nerve showed that CA were consistently found on the central side of the TZ in all examined specimens.

The distinction between avulsion, central to the TZ, and rupture, peripheral to it, is important for several reasons. First, central avulsion leads to the rapid death of the motoneurones of the anterior horn and this may be mitigated or even prevented by the early reimplantation of ventral roots. Therefore, intraoperative histological identification of central avulsions is an indication for hemilami-
nection and reimplantation, if the early positive results of this procedure are confirmed. Secondly, central avulsions are true CNS lesions leading to the formation of a characteristic scar, which contains astrocyte processes, laminin and collagen, and expresses receptors for nerve growth factors. This CNS scar is known to have potentially beneficial effects on regenerating fibres. This reaction is absent in peripheral intradural ruptures, which may prove amenable to direct reconnection between their proximal stumps and the periphery. It is clear that more work needs to be done to establish the necessary length of intradural stumps required to allow direct reconnection and avoid reimplantation.

We continue to study the proportion of central avulsions in preganglionic traction injuries using CA as markers in a larger number of patients. We will confirm whether the identification of CA is a useful tool for the intraoperative histological differentiation of preganglionic injuries by frozen section during explorations on the brachial plexus.

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References