Peripheral nerve tumors may be of neuroectodermal origin, derived from the neural sheath, or of non-neural sheath origin. Benign peripheral nerve sheath tumors (BPNSTs) include neurofibromas and schwannomas, which collectively constitute 10%–12% of benign soft-tissue neoplasms.19,28,29 Malignant PNSTs (MPNSTs) represent 5%–10% of all soft-tissue sarcomas and occur in 0.001% of the general population.12,30

Both BPNSTs and MPNSTs may occur sporadically, or in association with autosomal dominant neurofibromatosis (NFs). Sixty percent of patients with neurofibromatosis Type 1 (NF1)—the most common NF—will develop solitary, diffuse, or plexiform benign neurofibromas, the latter two occurring almost exclusively in patients with NF1.11,26 NF1-associated neurofibromas and schwannomas have an estimated 10%–15% risk of malignant transformation, with internal plexiform tumors at the highest risk of conversion.32 MPNSTs occur in up to 10% of NF1 patients over their lifetimes; conversely, half of all MPNSTs are seen in NF1 patients.5 Peripheral schwannomas are typically sporadic, although...
up to 10% are associated with NF Type 2 (NF2). Rarely, patients may present with schwannomatosis, a largely sporadic disorder that is predisposed to nonvestibular nonintradermal schwannomas. Surgical excision remains the primary treatment modality for BPNTs. Similar techniques are used for intraneural schwannomas, which arise from a single fascicle, and neurofibromas, which often have multiple thicker fascicles entering and exiting the tumor capsule. MPNTs are treated best with wide surgical margins, followed by chemotherapy and local radiation; unfortunately, metastases are common, with poor long-term survival.

Here, we present a series of 201 benign and malignant BPNTs treated surgically over 17 years at Toronto Western Hospital. This represents one of the largest surgical series of BPNTs in the literature, which was collected over a relatively short period and predominantly treated by a single surgeon (A.G.) at a multidisciplinary institution with electrophysiologists, neurologists, and radiation and medical oncologists. The aim of the study is to identify predictors of neurological deficit, tumor recurrence, and extent of resection using multivariate analyses, as well as the impact of genetic predisposition syndromes on tumor location and frequency.

Methods

The charts of all patients with BPNTs who were treated surgically at the Division of Neurosurgery at Toronto Western Hospital between 1993 and 2010 were reviewed retrospectively. One hundred seventy-five patients with 201 primary tumors had adequate follow-up data for analysis. The mean follow-up time for all patients was 29.5 months. Institutional research ethics board approval was obtained from the University Health Network.

Preoperative Workup

All patients had their full medical histories evaluated (including family histories) and underwent general physical and neurological examinations, as well as screening for the signs of NF. Patients with the clinical findings of NF1 or NF2 were referred to a multidisciplinary NF clinic for screening neuroimaging, genetic testing, and counseling. MRI was performed on all cases. In patients with benign-appearing lesions on imaging, excisional biopsy was typically recommended for symptomatic lesions, lesions with interval growth during follow-up, or any lesions in NF1 patients that changed in size. In patients with suspected malignancy, which was often based on rapid clinical growth, irregular margins, and/or heterogeneous gadolinium enhancement on MR imaging, a preoperative needle or open biopsy was sometimes performed or intraoperative pathology was obtained to determine the need for wide excision.

Surgical Technique

Intraoperative nerve stimulation with electromyography recording was used in all procedures. Surgery for BPNTs was performed according to established microsurgical principles. For schwannomas, fascicles adherent to the capsule were bluntly dissected off. One or sometimes 2 fascicles were typically seen entering and leaving the tumor, and these were sectioned following electrophysiological confirmation of a lack of motor activity. The tumor was then removed en bloc. Larger tumors were enucleated via intracapsular dissection, followed by removal of the capsule if it was not densely adherent to the surrounding fascicles. Neurofibromas typically had 2 or more entering and exiting fascicles and required more careful dissection, but with the same principles as for schwannoma resection.

Surgical management of MPNTs generally involved local excision with wide margins. Amputation was performed in 1 case, following intraoperative histological confirmation of the malignancy with negative preoperative workup for systemic metastases.

Data Collection

The impact of sex, age, NF diagnosis, tumor location, tumor size, and extent of resection on the recurrence of BPNTs was explored. Along with these parameters, the impact of preoperative motor or sensory deficits or neuropathic pain on the patients’ respective postoperative outcomes was assessed. Tumor location was categorized as either the extremity (upper or lower) or paraspinal plexus (brachial, thoracic, or lumbosacral). Preoperative tumor size was volumetrically approximated as a cylinder based on the maximal in-plane dimensions. The extent of resection was classified as gross-total (GTR) resection or subtotal resection (STR) based on the intraoperative findings. For BPNTs, GTR implied complete removal of the tumor capsule and parent fascicles; for MPNTs, STR was signified by negative surgical margins on frozen section and permanent pathology. Neuropathic pain was identified based on the patient reporting lancinating or dysesthetic pain in an identifiable nerve distribution. Postoperative motor/sensory/neuropathic pain scores were dichotomized as either stable/improved or worse relative to the preoperative status based on objective confrontational testing of motor function and patient self-reporting of sensory function and neuropathic pain.

All patients were followed up at 4–6 weeks for incision inspection and the first follow-up gadolinium-enhanced MRI at 3 months. The frequency of the subsequent MRI studies was variable, depending on the extent of resection and NF status. Tumor recurrence was defined as evidence of a new contrast-enhancing lesion on postoperative T1-weighted MR images.

Statistical Analysis

Statistical comparison of the continuous variables was performed using the Student t-test; categorical variables were compared using the chi-square or Fisher’s exact tests, as appropriate. Multiple logistic regression models were used to identify predictors of tumor recurrence, worsened postoperative motor/sensory/pain outcomes, as well as STR, with appropriate odds ratios and confidence intervals computed for each. Explanatory variables were incorporated into the model with forward stepwise progression; nonsignificant interaction terms were dropped to create the final models. The significance levels for all tests were
set at $p < 0.05$. All statistical analyses were conducted using SPSS version 21 (IBM Corp.).

**Results**

**Patient and Tumor Characteristics**

In our cohort of 175 patients, the mean age at presentation was 45.2 years, and the patients with neurofibroma or MPNST were younger than the patients with schwannoma ($p < 0.001$). In total, 54.9% of patients were male, with no difference in the sex distribution across tumor histopathologies (Table 1). Of the 201 tumors in our cohort, there were 49 neurofibromas, 133 schwannomas, and 19 MPNSTs. Twenty-six of the 49 neurofibromas were associated with NF1, and 21 schwannomas were associated with NF Type 3 (NF3) (Table 2). Sixteen of 19 MPNSTs in our series were in patients diagnosed with NF1. The tumor size at diagnosis was available for 57 schwannomas and 20 neurofibromas in our series, with average sizes of 3.86 $\times$ 4.89 $\times$ 3.54 cm and 4.12 $\times$ 6.00 $\times$ 3.98 cm, respectively (Table 1). The difference in the volumetric preoperative size between schwannomas and neurofibromas was not statistically significant ($p = 0.336$).

The anatomical locations of all benign tumors in our cohort are shown in Table 2. Schwannomas were found most commonly in the brachial plexus, lower extremity, and lumbosacral plexus. Neurofibromas showed a similar localization, but with significantly fewer tumors located in the upper extremity. Twelve of the 49 neurofibromas in our series were plexiform. Four of the 19 MPNSTs were in the lower extremity. Twelve of the 49 neurofibromas in our series were in patients diagnosed with NF1. The tumor size at diagnosis was available for 57 schwannomas and 20 neurofibromas in our series, with average sizes of 3.86 $\times$ 4.89 $\times$ 3.54 cm and 4.12 $\times$ 6.00 $\times$ 3.98 cm, respectively (Table 1). The difference in the volumetric preoperative size between schwannomas and neurofibromas was not statistically significant ($p = 0.336$).

The symptomatic presentation of all 201 tumors in our series is summarized in Table 3. In total, 12.8% of cases of schwannoma, 30.6% of cases of neurofibroma, and 36.8% of cases of MPNST presented with a preoperative motor deficits attributable to their PNST. Of these, all patients with schwannomas or neurofibromas remained stable or improved postoperatively, with permanent worsening seen in 2 of 7 MPNST patients (Fig. 1). New motor deficits were seen in 12 schwannoma patients (6 permanent) and 4 neurofibroma patients (3 permanent). Among the patients with a preoperative motor deficit, a diagnosis of MPNST was associated with an increased likelihood of worsened postoperative motor function relative to a diagnosis of BPNST (OR 29.55; 95% CI 1.24–702.69; $p = 0.028$); this association did not reach statistical significance for the entire cohort. In the univariate analyses, among BPNSTs, GTR (OR 4.01, 95% CI 1.21–13.22; $p = 0.023$) and the presence of a preoperative motor deficit (OR 8.06, 95% CI 4.65–17.59; $p = 0.038$) were associated with an increased likelihood of stable/improved postoperative motor function. Only GTR was an independent predictor of stable/improved postoperative motor function in the multivariate analysis. Age, sex, tumor histopathology, NF status, location and tumor size were not significant predictors of postoperative motor outcome.

In total, 30.1% of patients with schwannomas, 44.9% of patients with neurofibromas, and 26.3% of patients with MPNSTs presented with paresthesia or numbness in a distribution relevant to their resected PNST. In total, 59.2% had a positive Tinel’s sign in the relevant nerve distribution. Postoperatively, the worsening of preexisting sensory disturbances was seen in 3 patients with schwannoma (1 permanent) and 2 patients with neurofibroma (both permanent). New sensory deficits were seen in 12 schwannoma patients (7 permanent), 1 neurofibroma patient (0 permanent), and 1 MPNST patient (permanent) (Fig. 1). In both the univariate and multivariate analyses, there were no significant predictors among our collected parameters that were associated with worsened postoperative sensory outcomes.

Pain was reported for 57.9% of schwannomas, 75.5% of neurofibromas, and 68.4% of MPNSTs. This pain was neuropathic in character and in the distribution of the affected nerve in 39.8%, 42.9%, and 42.1% of schwannomas,
neurofibromas, and MPNSTs, respectively. No patient with preoperative neuropathic pain reported worsening pain postoperatively. New postoperative neuropathic pain, in or adjacent to the distribution affected by the resected tumor, was reported by 2 patients with schwannoma (1 permanent), 2 patients with neurofibroma (1 permanent), and 2 patients with MPNST (1 permanent). None of our collected parameters, including tumor histopathology, were associated with worsened postoperative pain scores.

Tumor Recurrence

Among BPNSTs, the overall recurrence rates in our cohort were 5.3% for schwannomas and 8.2% for neurofibromas. Patients with recurrent schwannoma presented to neurosurgical attention on average 49.6 months after their index procedure, while patients with recurrent neurofibromas presented slightly earlier at 41.2 months. In the univariate analyses, a diagnosis of NF3 was associated with increased recurrence risk for schwannomas (OR 4.29, 95% CI 1.05–20.80; p = 0.048), with a recurrence rate of 14.3% in our cohort; a diagnosis of NF1 was associated with increased recurrence for neurofibromas (OR 1.18, 95% CI 1.003–1.39; p = 0.022), with a recurrence rate of 15.4% in our cohort. In the multivariate analyses, STR

<table>
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<tr>
<th>TABLE 2. Anatomical locations of 182 BPNSTs</th>
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<td>Location</td>
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</tr>
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<td>Upper extremity</td>
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<td>Axillary nerve</td>
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<td>Wrist</td>
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<td>Radial nerve</td>
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<td>PIN</td>
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<td>Brachial plexus</td>
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<td>Supraventricular</td>
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<td>Infraclavicular</td>
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<tr>
<td>Thoracic paraspinal plexus</td>
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<td>Lower extremity</td>
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<td>Femoral nerve</td>
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<tr>
<td>Common sciatic nerve</td>
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<td>Tibial nerve</td>
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<td>Peroneal nerve</td>
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<td>Plantar nerve</td>
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<td>Sural nerve</td>
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<tr>
<td>Lumbosacral plexus</td>
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<td>Occipital nerve</td>
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<td>Vagus nerve</td>
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<td>Total</td>
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PIN = posterior interosseous nerve.

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<th>TABLE 3. Symptomatic presentation of 201 tumors</th>
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<td>Tumor Type</td>
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<td>Schwannoma</td>
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<tr>
<td>Neurofibroma</td>
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<td>MPNST</td>
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All values reported as the number of tumors (%).
was independently associated with increased recurrence for all BPNSTs (OR 13.16, 95% CI 2.04–83.33; p = 0.007). Age, sex, tumor location, and tumor volume were not significant predictors of recurrence for BPNSTs.

The MPNSTs in our series showed a recurrence rate of 21%, though a lack of neurosurgical follow-up may have diminished the true rate.

**Postoperative Complications**

New postoperative neurological deficits and neuropathic pain are summarized in Fig. 1. Among other complications, wound infections occurred in 4 of 175 patients: 3 superficial infections requiring only oral antibiotics, and 1 deeper infection necessitating surgical washout. In 1 patient, a painful neuroma following resection of a schwannoma of the radial nerve at the elbow required resection at 1 year following the initial procedure. One patient with a plexiform neurofibroma of the brachial plexus experienced significant intraoperative bleeding, for which packing material was left in situ and removed during a second procedure. Dysphagia requiring temporary nasogastric tube feeding was seen in 1 patient following uni-
lateral vagus nerve sacrifice during resection of a brachial plexus neurofibroma. One patient experienced a CSF leak following resection of an infraclavicular brachial plexus neurofibroma, which resolved with lumbar drainage and over-sewing of the wound.

**Decision Algorithm**

Based on our, as well as other, large series, a surgical decision algorithm for PNSTs is proposed (Fig. 2). In our series, patients with a confirmed diagnosis of NF1, based on clinical and/or genetic criteria, were typically recommended for surgical excision of even asymptomatic benign-appearing PNSTs, with some variability based on lesion size.

**Discussion**

We present one of the largest single-institution series of symptomatic, surgically treated PNSTs. We aimed to identify predictors of tumor recurrence, extent of resection, and postoperative functional outcomes using multivariate analyses to identify independently associated parameters. To the best of our knowledge, this is only the second large series to explore predictors of outcome using multivariate statistical modeling.

Schwannomas and neurofibromas have a benign histology but may recur locally. The recurrence rates for BPNSTs range from 1.3% to 35.9% in the literature and up to 44% for pediatric plexiform neurofibromas. The recurrence rates for the schwannomas and neurofibromas in our series were 5.3% and 8.2%, respectively. STR has been the most consistently identified predictor of recurrence and was independently and significantly associated with recurrence for both BPMSTs and MPNSTs in our series.

Other clinical, radiographic, and surgical parameters have been variably associated with recurrence or extent of resection. A diagnosis of NF1 has been associated with increased recurrence for neurofibromas in some series and STR of neurofibromas in others. Tumor histopathology has been shown to impact recurrence and extent of resection in some series. Artico et al. showed increased local recurrence in neurofibromas compared with schwannomas, and, in the largest reported series to date, Kim et al. demonstrated decreased GTR rates for neurofibromas, predominantly in their plexiform variants. Vetrano et al., however, found that patients with neurofibromas were at increased risk of postoperative neurological deficits but not recurrence; in their series, increased recurrence of BPNSTs was most associated with longer duration of symptoms prior to resection. Larger tumor size at diagnosis has also been associated with increased recurrence, though primarily in series of malignant PNSTs.

In our series, tumor size was not significantly associated with recurrence. While the schwannomas on average were smaller at presentation than the neurofibromas in our cohort, this difference did not reach statistical significance and may be attributable to differences in tumor location. Proportionally fewer neurofibromas were located in the
extremities, where they may be expected to be symptomatically or cosmetically noticeable at a smaller size in comparison with neurofibromas in a plexal location, which is consistent with other reports.\textsuperscript{19} We found that NF type was significantly associated with recurrence: NF1 for neurofibromas and schwannomatosis (i.e., NF3) for schwannomas. The increased recurrence risk for NF1-associated neurofibromas persisted when plexiform neurofibromas were excluded. Patients with hereditary predisposition syndromes should therefore be monitored more closely for recurrence. Whether a diagnosis of NF increases the likelihood of an asymptomatic BPNST that would require future resection is also uncertain. This question may be answered by longitudinal follow-up of the entire BPNST cohort. However, follow-up of asymptomatic patients in our cohort was largely relegated to primary care physicians, and hence only surgical outcomes are addressed here.

Interestingly, tumor location influenced the extent of resection only for schwannomas in our series, with schwannomas located in an extremity being more readily resected than plexal tumors likely due to anatomical accessibility. Schwannomas inherently grow extrinsic to their parent fascicles while neurofibromas are intertwined with multiple fascicles of origin and are therefore more difficult to fully resect irrespective of accessibility, which is a possible explanation for this finding. Another possibility is that the impact of tumor location is limited to schwannomas due to the disproportionately greater association of neurofibromas with NF. However, in our cohort 53% of neurofibromas were associated with NF1, which is not significantly different from other series\textsuperscript{2,15,19,23}; moreover, in multivariate modeling, tumor location influenced the extent of resection independently of NF status. Admittedly, our overall cohort of BPNSTs contains a higher number of patients with NF than other large series, largely due to the sizeable subset of schwannomas associated with NF3. However, our finding that NF3+ is associated with the increased recurrence of schwannomas has been echoed in other series.\textsuperscript{13} Overall rates of GTR in our cohort were 44.9% for neurofibromas and 76.7% for schwannomas, which are lower than implied by Kim et al. in their large retrospective series.\textsuperscript{15} All patients in our series received intraoperative neurophysiological monitoring; Levi et al. reported an increase in the residual tumor in patients monitored intraoperatively, perhaps accounting for our lower rates.\textsuperscript{19} Unfortunately preoperative electrodiagnostic data were not available for all patients in our cohort.

Among the BPNSTs in our series, all patients with a preoperative motor deficit remained stable or improved postoperatively. New motor deficits were seen immediately postoperatively in 10.3% of schwannomas and 11.8% of neurofibromas, which were permanent in 5.2% and 8.8%, respectively. Preoperative sensory disturbances were permanently exacerbated in only 1 patient with schwannoma and 2 patients with neurofibroma. New sensory disturbances were seen immediately postoperatively in 12.9% of schwannomas and 3.7% of neurofibromas, which were permanent in 7.5% and 0%, respectively. The rates of postoperative motor deficit in our cohort are largely in keeping with the lower end of the range reported in the literature. In the largest series to date, Kim et al. reported stable or improved motor function in 89% of schwannomas and 85% of solitary neurofibromas;\textsuperscript{15} Levi et al. reported postoperative motor deficits in 8% of schwannomas and 5.9% of neurofibromas.\textsuperscript{19} In smaller series, permanent postoperative sensorimotor deficits have been reported in 11%–36.7% of schwannoma patients.\textsuperscript{16,22,33}

In our series, GTR and the presence of a preoperative motor deficit were predictive of stable or improved postoperative motor function. The latter is perhaps initially counterintuitive; however, patients with preexisting deficits attributable to a compressive lesion also have the potential to improve once their lesion is surgically decompressed. Ujigo et al. identified a preoperative positive Tinel’s sign as predictive of postoperative sensorimotor deficit, but this was not observed in our series.\textsuperscript{33} Surgical technique may also influence postoperative neurological outcomes. Date et al. espoused the practice of intracapsular enucleation rather than extracapsular resection of schwannomas located in an extremity to minimize postoperative deficits.\textsuperscript{7} Levi et al. noted that patients with either schwanna or neurofibroma who had undergone a needle or open biopsy procedure prior to definitive resection were at 2.7-fold higher risk of postoperative neurological deficits than those who underwent a resective procedure up front.\textsuperscript{19} However, we were not able to identify in all records whether a biopsy had been performed at an outside institution.

MPNSTs represent a significant management challenge for peripheral nerve specialists. They occur mostly in the trunk and extremities but have been reported rarely at other sites.\textsuperscript{25,36} Half are associated with NF1, with the remainder arising either de novo (40%) or secondary to prior radiation (10%).\textsuperscript{9,36} While MRI remains the initial workup of choice for all PNSTs, FDG-PET has shown promise for accurately differentiating benign from malignant NF1-associated lesions, potentially avoiding the morbidity associated with surgical biopsy.\textsuperscript{3,30,37}

The primary treatment for MPNST remains wide local resection, though limb amputation in the absence of systemic metastases may be considered. Local recurrence rates may reach up to 65%,\textsuperscript{4,39} 5-year tumor-specific survival ranges from 16% to 52%,\textsuperscript{10,31,41} While NF1-associated MPNSTs have traditionally been associated with a poorer prognosis than sporadic lesions,\textsuperscript{18,39} a recent meta-analysis showed no significant differences in overall survival.\textsuperscript{17} Local recurrence for MPNST in our series was 21%, well below the rates reported in the literature, though this likely reflects a loss of neurosurgical follow-up to oncological specialists. In multiple retrospective series, tumor size (>5 cm), truncal location, incomplete resection, high grade, S100\textsuperscript{b} negativity, and p53 mutations have been associated with worse prognosis.\textsuperscript{9,14,31,34,41} In our limited cohort of MPNSTs without immunohistopathological data available, STR was the only independent predictor of recurrence. MPNSTs have traditionally been resistant to adjuvant chemo- or radiotherapy. Recent studies have demonstrated improved local control with adjuvant external-beam radiation but a negligible effect on overall survival.\textsuperscript{4,14,34} The roles of proton-beam therapy and brachytherapy—the latter is applied widely with good effect on other soft-tissue sarcomas—have yet to be elucidated for MPNSTs. Conventional chemotherapy for MPNSTs has shown poor re-
Multidisciplinary management of peripheral nerve tumors

Conclusions

We present here one of the largest surgical series of PNSTs to date. Functional outcomes are influenced by tumor histopathology, while recurrence rates depend on tumor histopathology, genetic predisposition syndrome, and, as demonstrated uniquely by our group, tumor location for certain subtypes. GTR should be attempted for benign lesions where feasible. MPNST remains a significant challenge, with a poor prognosis despite advances in multimodal therapies.

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Disclosures
The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions
Conception and design: Zadeh, D Guha. Acquisition of data: D Guha, Davidson, Nadi, Fehlings, Gentili, Valiante, Tator, Tymianski. Analysis and interpretation of data: D Guha. Drafting the article: D Guha, Alotaibi. Critically revising the article: Zadeh, D Guha, Davidson, Nadi, Alotaibi. Reviewed submitted version of manuscript: Zadeh, Guha, Davidson, Nadi, Alotaibi, Fehlings, Gentili, Valiante, Tator, Tymianski. Approved the final version of the manuscript on behalf of all authors: Zadeh. Statistical analysis: D Guha. Administrative/technical/material support: Zadeh, Fehlings, Gentili, Valiante, Tator, Tymianski, A Guha. Study supervision: Zadeh.

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