Aberrant Peripheral Nerves and Neuromas in Normal and Injured Spinal Cords

JOO HO SUNG, M.D., ANGELINE R. MASTRI, M.D., AND KARL T. K. CHEN, M.D.

Abstract. Spinal cords from 20 patients (13–78 years of age) were studied for the occurrence of peripheral nerve fibers within the cord. Peripheral nerve fibers were observed in all but two younger patients, 13 and 24 years old, respectively, but all the spinal cords were otherwise normal. The nerve fibers were thin and predominantly myelinated. They were seen in two forms, small parallel bundles resembling normal nerve fascicles and larger interlacing bundles or whorled masses indistinguishable from traumatic neuromas. They almost always occurred in the perivascular spaces of the major parenchymal branches of the anterior sulcal artery and/or in the anterior median sulcus. The neuromas in the otherwise normal cords were identical with those occurring in the cord with old traumatic injury in three patients studied, but they were few in the former, while numerous and widespread in the injured segments of the latter.

Accumulating evidence suggests 1. that most, if not all, of the parallel nerve bundles about the anterior sulcal artery in otherwise normal spinal cords represent aberrant, regenerated nerve fibers originating from ventral spinal nerve roots which are severed by clinically occult injuries in adult life, and 2. that the regenerated nerve fibers continue to grow into the anterior median sulcus and perivascular spaces and may become entangled or return upon themselves, forming neuromas as their way is blocked by the pia-glial barrier.

Key Words: Neuromas, Peripheral nerves, Spinal cord.

INTRODUCTION

Fine myelinated peripheral nerve fibers in interlacing bundles and intertwined or whorled masses have often been observed within the spinal cord in conjunction with a variety of pathological conditions such as syringomyelia (1, 2), compression by herniated intervertebral discs or tumors (1, 2), long-standing traumatic injury (2, 3, 4, 5) and others (2, 6, 7, 8). The reports by early workers were reviewed in detail by Koeppen et al. (7). The occurrence of similar peripheral nerve bundles in otherwise normal spinal cords has also been reported (8, 9, 10). Although the nerve fiber bundles and masses resemble traumatic peripheral neuromas, they have been variously referred to as aberrant or regenerated nerve fibers (1, 2, 7), Schwann cell proliferation or Schwannosis (8, 9), heterotopic peripheral nerve inclusions or malformations (11, 12), or neuromas (3, 5). In spite of the general agreement as to their

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peripheral nerve nature, there has been no unanimity of opinion as to their origin or pathogenesis. Some (3, 5, 8, 10) viewed them as regenerative growths of existing vascular nerves, while others (1, 2, 5, 7) regarded them as aberrant peripheral nerve fibers originating from severed dorsal or ventral spinal nerve roots. The present study was undertaken 1. to assess the nature and distribution of the peripheral nerve bundles in otherwise normal spinal cords, 2. to compare them with neuromatous lesions occurring in the spinal cord in conjunction with old traumatic injury, and 3. to elucidate the pathogenesis of the nerve bundles or neuromatous lesions occurring in otherwise normal spinal cords.

MATERIALS AND METHODS

The spinal cord was studied in two groups of patients. Group 1 (Table 1) consisted of 20 patients of varying ages (13–78 years), who died from various, mostly non-neurological, diseases. They were selected from routine autopsies on the basis that they had no clinical or pathological abnormalities of the spinal cord. Group 2 (Table 2)

### TABLE 1
Summary of Clinical Features and Incidence of the Parallel Bundles and Neuromas in Group 1

<table>
<thead>
<tr>
<th>Case</th>
<th>Age</th>
<th>Sex</th>
<th>Diagnosis</th>
<th>Parallel bundles</th>
<th>Neuromas</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13</td>
<td>F</td>
<td>Head trauma</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>24</td>
<td>F</td>
<td>Leukemia</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>69</td>
<td>M</td>
<td>Progressive supra-nuclear palsy</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>4</td>
<td>31</td>
<td>M</td>
<td>Hodgkin's disease</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>5</td>
<td>58</td>
<td>M</td>
<td>Carcinoma of larynx</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>6</td>
<td>53</td>
<td>F</td>
<td>Polycystic kidney, renal transplant</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>35</td>
<td>M</td>
<td>Pancreatitis, pancreatic transplant</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>8</td>
<td>36</td>
<td>M</td>
<td>Leukemia</td>
<td>++</td>
<td>+</td>
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<tr>
<td>9</td>
<td>67</td>
<td>F</td>
<td>Arteriosclerosis, myocardial infarct</td>
<td>++</td>
<td>+++</td>
</tr>
<tr>
<td>10</td>
<td>28</td>
<td>F</td>
<td>Diabetes mellitus</td>
<td>+++</td>
<td>+</td>
</tr>
<tr>
<td>11</td>
<td>48</td>
<td>F</td>
<td>Ovarian carcinoma</td>
<td>+++</td>
<td>+</td>
</tr>
<tr>
<td>12</td>
<td>64</td>
<td>M</td>
<td>Hemochromatosis</td>
<td>+++</td>
<td>+</td>
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<tr>
<td>13</td>
<td>69</td>
<td>M</td>
<td>Carcinoma of mouth</td>
<td>+++</td>
<td>+++</td>
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<td>14</td>
<td>68</td>
<td>F</td>
<td>Carcinoma of breast</td>
<td>+++</td>
<td>+</td>
</tr>
<tr>
<td>15</td>
<td>68</td>
<td>M</td>
<td>Liver cirrhosis</td>
<td>+++</td>
<td>+</td>
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<tr>
<td>16</td>
<td>70</td>
<td>M</td>
<td>Sepsis</td>
<td>+++</td>
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</tr>
<tr>
<td>17</td>
<td>72</td>
<td>M</td>
<td>Silicosis of lung</td>
<td>+++</td>
<td>+</td>
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<tr>
<td>18</td>
<td>74</td>
<td>M</td>
<td>Arteriosclerotic heart disease</td>
<td>+++</td>
<td>+</td>
</tr>
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<td>19</td>
<td>77</td>
<td>M</td>
<td>Subdural hematoma</td>
<td>+++</td>
<td>+</td>
</tr>
<tr>
<td>20</td>
<td>78</td>
<td>M</td>
<td>Glioblastoma</td>
<td>+++</td>
<td>-</td>
</tr>
</tbody>
</table>

-, +, ++, and +++ indicate the number of affected spinal segments, 0, 1–2, 3–4, and 5 or more, respectively.
consisted of three patients who had sustained spinal cord trauma and lived for many years following the trauma.

In Group 1, the spinal cords were carefully removed with the nerve roots and dura attached and were fixed in 10% formalin in a long plastic container for two weeks. Each spinal segment below the 7th cervical segment was identified by means of the spinal nerve roots and was sectioned at every 2- to 3-mm interval. All the sections of each segment were embedded in paraffin and five serial 8-micron-thick sections were made from each paraffin block. In Group 2, each spinal segment could not be precisely determined, and many sections were sampled from the traumatized segments, as well as from the segments above and below the region of maximum injury. The specimens were fixed in formalin and embedded in paraffin in the same manner as in Group 1. Histological sections in both groups were routinely stained with hematoxylin and eosin (H&E). Additional stains applied included Luxol fast blue-periodic acid Schiff's (LFB-PAS), Bielschowsky's silver, Laidlaw's silver, and azocarmine methods for myelin, axons, reticulum, and fibrous tissue, respectively. Central and peripheral types of myelin sheaths were distinguished by LFB-PAS stain according to the difference in color between the two, light blue-green for the former and dark blue for the latter (13).

RESULTS

Fine nerve fibers, which were usually ensheathed by peripheral myelin and Schwann cells, were observed in two forms, although rigid distinction between the two was not always feasible. In the first form (Fig. 1A), the nerve fibers assumed small, regular, parallel bundles which were in no way different from ordinary peripheral nerve fascicles. In the second form (Figs. 1B, C, and D), the nerve fibers were in interlacing bundles or intertwined or whorled masses (depending upon the plane of section) which were usually larger than the first form. By virtue of the disarrayed arrangement of the nerve fibers (Fig. 1D) and numerous Schwann cells (Figs. 1B and C) and abundant reticulin fibers, the second form closely resembled traumatic peripheral neuromas. The two forms of the nerve fibers are herein referred to as "parallel bundles and neuromas," according to their similarity to normal nerves and traumatic neuromas, respectively.

Parallel nerve bundles and neuromas in Group 1 (Table 1): The parallel bundles and neuromas were observed in the anterior median sulcus and/or within the cord (Figs. 2A and C). In the anterior median sulcus, both the parallel bundles and neuromas were usually about the anterior sulcal artery. The sulcal arteries at various spinal levels were only occasionally cut in a longitudinal plane, mainly in the C8–T1 and lumbosacral segments, but were almost always
Fig. 1. A. Fine myelinated nerve fibers in small parallel bundles (arrows) about the anterior sulcal artery. B. An interlacing nerve fiber bundle in the perivascular space about a major parenchymal branch (arrow) of the anterior sulcal artery. C and D. A whorled nerve fiber mass in the anterior median sulcus shows numerous Schwann cells (C) and abundant axons (D). H&E (A, B, and C) and Bielschowsky's (D) stains. ×300 (A and B) and ×120 (C and D).

cut in a transverse or oblique plane in the thoracic segments. The parallel bundles and interlacing bundles in the sulcus in various spinal segments were also sectioned in a similar manner. This suggested that the nerve bundles, too, run either rostrally or caudally in most segments, much as the anterior sulcal arteries. The parallel bundles and neuromas within the cord were invariably located in the perivascular spaces of the two major parenchymal branches of the anterior sulcal artery on either or both sides of the anterior commissure (Figs. 2A and C). On serial sections, the parallel bundles and neuromas within the cord could often be traced to the similar structures in the anterior median sulcus.

The parallel bundles were encountered in 17 (85%) of the 20 patients: within the cord in 17 (85%), in the anterior median sulcus in 15 (75%), and in both in the same segment in 15 (75%). The neuromas were observed in 16 (80%) of the 20 patients: within the cord in 12 (60%), in the sulcus in 11 (55%), and in both in the same segment (Figs. 2A and C), in 7 (35%). Their incidence and the extent of involvement varied from one patient to another (Table 1). Neither the parallel bundles nor the neuromas were seen in two younger female patients, aged 13
Fig. 2. A. Neuromas in both the anterior median sulcus (see also Fig. 1C) and the perivascular space in a thoracic segment. B and C. Sacral cord of a 69-year-old man with oral carcinoma. Interlacing nerve fiber bundles extend from the dorsal root to the dorsal horn along perforating blood vessels (B); the nerve bundles about the anterior sulcal artery ramify along its branches within the cord (C). LFB-PAS stain. × 50 (A and B) and ×30 (C).
and 24 years, who died of acute head trauma and leukemia, respectively. In two patients, a 53-year-old woman who had renal transplants for polycystic kidney and a 78-year-old man who died of glioblastoma, only the parallel bundles were observed. In a 69-year-old man who died of progressive supranuclear palsy, only a neuroma in the sacral cord was found. In the remaining 15 patients, both the parallel bundles and neuromas were observed together in the same segment or separately in different segments. Of the 17 patients with the parallel bundles (Table 1), the bundles were observed in one or two segments in 3 (18%), in three or four segments in 3 (18%), and in five or more segments in 11 (65%). Of the 16 patients with the neuromas (Table 1), the neuromas were seen in one or two spinal segments in 9 (56%), in three or four segments in 5 (31%), and in five or more segments in 2 (13%).

The incidence of the parallel bundles and neuromas varied considerably from one spinal segment to another (Fig. 3). The parallel bundles were observed very frequently in T₄–T₁₁ (40–60%), less frequently in C₈–T₃ (15–35%) and T₁₂–L₂ (20–40%), and least frequently in L₃–S₃ (5–10%). They were encountered more frequently in the anterior median sulcus than in the parenchyma in most segments in C₈–L₂, while they were infrequent in both locations in L₃–S₅. The neuromas were also more frequent in T₄–T₁₁ (10–35%) than in T₁₂–L₂ and S₁–S₃ (5–10%), and were absent in C₈–T₃ and L₃–L₅ segments. In contrast to the parallel bundles, the neuromas were usually more frequent within the parenchyma than in the anterior median sulcus in most spinal segments (Fig. 3). The parallel bundles and neuromas were most frequently encountered in the T₃: the parallel bundles were observed within the cord in 10 (50%), in the sulcus in 9 (45%), and in either one or both locations in 12 (60%); the neuromas were encountered within the cord in 6 (30%), in the sulcus in 4 (20%), and in either one or both locations in 7 (35%); the parallel bundles and/or neuromas occurred

![Graph](http://jnen.oxfordjournals.org/)

**Fig. 3.** Incidence of parallel bundles and neuromas in the anterior median sulcus (□) and within the cord (■) at each segment (N = 20).
within the cord in 12 (60%), in the sulcus in 12 (60%), and in either one or both locations in 14 (70%) of the cases.

In two patients, there were numerous neuromas in the pia and subarachnoid space about the sacral spinal cord, in addition to frequent parallel bundles and neuromas in the sulcus and/or parenchyma in other spinal segments like those in the other cases. In a 69-year-old man who had carcinoma of the mouth with multiple distant metastasis and chemotherapy, the neuromas were numerous in the pia-arachnoid over the dorsal and ventromedial aspects and anterior median sulcus of the sacral cord (Figs. 2B and C). Some of them had penetrated into the parenchyma along blood vessels in both dorsal horns (Fig. 2B) and along the branches of the anterior sulcal arteries (Fig. 2C). Myelin sheaths could be demonstrated in none of them by LFB-PAS stain, but they contained numerous Schwann cells and abundant reticulin fibers, much as the myelinated neuromas. In the other 68-year-old man who died of liver cirrhosis, similar unmyelinated neuromas were numerous only over the dorsal aspect of the sacral cord; a few of them had also penetrated into the parenchyma along several blood vessels in the dorsal horns. In both patients, some of the neuromas in the pia-arachnoid could be traced to the dorsal roots, which also contained neuromatous lesions. The neuromas occurring in the dorsal aspects of the cord in these two patients were unique and were not included in the analysis in Table 1 or Figure 3. Neither patient had had clinical or pathological evidence of cord injury.

Neuromas associated with long-standing traumatic injury in Group 2 (Table 2): In the three patients who had sustained traumatic cord injury, the spinal cords were diffusely attenuated and showed severe collapse at the site of maximum damage in the C₈–T₁ segments in the first, T₁₀–T₁₂ in the second, and lumbosacral segments in the third patient. About the severely damaged segments, the leptomeninges were mildly thickened and the nerve roots were often enlarged. In the C₈–T₁ segments, which were severely collapsed, the anterior and posterior median sulci were no longer discernible and the parenchyma was almost totally replaced by loose fibroglial meshwork and numerous peripheral nerve bundles in the form of neuromas and smaller bundles (Fig. 4A), which were often located about blood vessels ramifying along their branches. They were also numerous in the pia-arachnoid, particularly in the dorsal and ventral aspects (Fig. 4B), and occasionally extended from the pia-arachnoid to the parenchyma along perforating blood vessels. In several areas of the anterior and posterior columns of the severely affected segments, their nerve fibers were ensheathed by peripheral myelin instead of central myelin (Fig. 4B). These nerve fibers were more cellular than the neighboring fibers ensheathed by central myelin, but both were similar insofar as their orientation and distribution were concerned. They, therefore, appeared to be central axons ensheathed by peripheral myelin and Schwann cells. The neuromas and nerve bundles showed varying degrees of myelination although, in the vast majority, their nerve fibers were predominantly myelinated, and Schwann cells and reticulin fibers were abundant (Figs. 5A and C). Schwann cells were generally less numerous in the poorly- or sparsely-myelinated neuromas than the fully-myelinated ones. The neuromas and nerve bundles in the injured cords were,
Fig. 4. C₈–T₁ segments with severe injury. A. Degenerated parenchyma is replaced by numerous myelinated neuromas (Whorled masses and interlacing bundles). B. Many neuromas in the pia-arachnoid and within the cord with the intervening white column, which shows extensive myelination by peripheral myelin (darker). LFB-PAS stain. ×50 (A) and ×30 (B).

therefore, identical in nature with those in the otherwise normal cords in the first group of patients, but were numerous, widespread, and often larger in the former. Rarely observed were small neuromas and nerve bundles which completely lacked myelin sheaths. Their Schwann cells were very sparse and their nerve fibers were uniformly delicate, but reticulin fibers were fairly abundant (Figs. 5D, E, and F). These unmyelinated neuromas were, therefore, distinct from the myelinated neuromas in not only the lack of myelination, but also in the paucity of Schwann cells and connective tissue and uniformly delicate nerve fibers. They were, however, closely related to blood vessels, much as the
Fig. 5. Myelinated (A, B, and C) and unmyelinated (D, E, and F) neuromas occurred together in the severely injured C₈–T₁ segments. Myelinated neuroma shows numerous Schwann cells (A), abundant axons of irregular thickness (B), and rich reticulin fibers (C). Unmyelinated neuroma shows a paucity of Schwann cells (D), uniformly delicate axons (E), and rich but loosely arranged reticulin fibers (F). H&E (A and D), Bielschowsky's (B and E), and Laidlaw's (C and F) stains. ×300.
myelinated neuromas. In the segments of less severe damage in the first patient or partial transection in the second and third patients, the neuromas were often observed in the anterior median sulcus and along the intraparenchymal branches of the anterior sulcal artery (Fig. 6A). They were, however, consid-
erably larger, more numerous, and penetrated farther distally to the finer branches of the sulcal artery than those observed in the first group of patients.

The spinal nerve roots about or near the transected segments of the cords showed striking traumatic neuroma formation. Some of the affected nerve roots were largely replaced by numerous interlacing nerve bundles or whorled nerve fiber masses, depending upon the plane of section (Fib. 6B). They were richly myelinated and were identical with those occurring within the cord and in the pia-arachnoid in both groups of patients.

**DISCUSSION**

Peripheral nerve fiber bundles of varying sizes and forms were frequently observed in the otherwise normal spinal cords in the present series of 20 patients, and this generally confirms several previous reports by other investigators (9, 10, 12). In the present report, the nerve bundles were divided into two forms, the parallel bundles and neuromas, according to their arrangement—similar to either normal nerve fascicles or traumatic neuromas. The two forms were analyzed separately, although a clear distinction was not always feasible. No such distinction was, however, made in other reports (10). Both forms of the nerve bundles occurred almost exclusively in the perivascular spaces of the major intramedullary branches of the anterior sulcal artery and/or the anterior median sulcus. They were few in number in a given spinal segment, considerably more frequent in the thoracic than in other regions, and most common in T₁₀. In T₁₀, the parallel bundles and neuromas were observed within the cord in 50% and 30% and in the sulcus in 45% and 20% of cases, respectively. The nerve bundles in either one or both forms were observed in all but two younger female patients, 13 and 24 years of age, respectively.

Adelman and Aronson (9) observed the nerve bundles in the spinal cord, which they referred to as foci of Schwann cell proliferation (Schwannosis), in 174 (25.4%) of 684 patients of varying ages who were autopsied consecutively. However, they must have analyzed the parallel bundles and neuromas together, without making a distinction between them. The nerve bundles were not found in patients who were younger than 16 years. The incidence of the nerve bundles was higher in men than women, and increased progressively with advancing age (43% in men and 26% in women of ages 76 years or older). The incidence was also higher in diabetics (48% and 34% in men and women, respectively) than non-diabetics. Because of the small sample size and difference in the method of examination, a comparison between the incidence of the nerve bundles in the present series and that in the large series of Adelman and Aronson is probably of little value. Nevertheless, the exceptionally high incidence in our series might have been attributed to the fact that the spinal cords were examined by semiserial sections in our series, while Adelman and Aronson examined a few sections randomely sampled from various levels in each spinal cord. Others reported the incidence to be considerably lower in their routine sections: 2% by Staemmiler (10) and less than 10% by Feigin and Ogata (12).
Our observation of the numerous peripheral neuromas in the spinal cords with long-standing trauma in our second group of three patients was in accord with previous reports by many other investigators (2, 3, 4, 5). Similar neuromas were also observed in the brain stem associated with local lesions (11, 14). As observed by many others, myelinated fibers predominated over unmyelinated ones in the vast majority of the neuromas. The fully myelinated neuromas were generally more cellular and less fibrous than sparsely myelinated ones. The unmyelinated neuromas which were observed only occasionally in the severely injured C₈-T₁ segments had, however, very sparse Schwann cells and little connective tissue, but reticulin fibers were fairly abundant. They, therefore, differed not only from the myelinated peripheral neuromas, but also from the "non-myelinated neuromas" described by Feigin and Budzilovich (11), which occurred together with myelinated peripheral neuromas in the brain stem in conjunction with cystic infarcts. We, too, have observed five cases of the "non-myelinated neuromas" in the brain stem or spinal cord, including two patients with spinal cord injury, who are included in the present report. The detailed account of the cases of the "non-myelinated neuromas" is beyond the scope of this report and is presented in another paper (15). In contrast to the unmyelinated neuromas under discussion, the "non-myelinated neuromas" were unrelated to blood vessels and lacked Schwann cells and reticulin fibers. The "non-myelinated neuromas" may, therefore, originate from central nerve fibers, while the unmyelinated neuromas may arise from unmyelinated vascular nerves. Feigin and Budzilovich (11), however, regarded the "non-myelinated neuromas" in the brain stem as originating from unmyelinated vascular nerves, thought to occur rarely.

The occurrence of myelinated and/or unmyelinated peripheral nerve fibers about intracranial and intraspinal arteries and arterioles has been well established in man (16, 17, 18, 19, 20) and in animals (20, 21, 22, 23, 24). Nevertheless, the myelinated or unmyelinated nerve bundles about intraparenchymal vessels are rarely observed in the human central nervous system in routine studies, except for those concerned here in the spinal cord. Since the parallel bundles resembling normal nerve fascicles occur so frequently in otherwise normal cords and always lie close to the anterior sulcal artery, it is tempting to view them as normally-occurring perivascular nerves peculiar to the artery. In cord injuries, the perivascular nerves would be severed along with other structures and react to form neuromas, much as the spinal nerve roots are injured and regenerate, forming neuromas along the roots and/or growing into the damaged cord parenchyma. The evidence for regenerating fibers of the spinal nerve roots to extend into the damaged cord following injury has been observed in both man (2, 5) and animals (25, 26, 27). One can, therefore, reasonably assume, as suggested by others (5), that the intramedullary neuromas in the injured segments of the spinal cord with long-standing trauma represent regenerative growth of either perivascular nerves or spinal nerve roots, or both, following injury, although the severed spinal nerve roots may be the predominant source.

Such an assumption is, however, not logical for the occurrence of the neuromas in otherwise normal spinal cords, as in the first group of patients. Peripheral nerve fibers have to be injured in order to regenerate and form neuromas, and the neuromas are, as a rule, formed at or near the site of severance. The parallel bundles must, therefore, be injured to form the neuromas in the otherwise normal cords, regardless of their origin, but there was no reason to believe that they were selectively injured in the anterior median sulcus or perivascular spaces within the normal cords in the present series. Accumulating evidence also suggests that many, if not all, of the parallel bundles are not normally-occurring perivascular nerves, but abnormal or aberrant nerve fibers derived from spinal nerve roots (1, 2, 7). In support of this, the nerve bundles do not seem to occur in children. The nerve bundles were not observed in two younger patients (13 and 24 years old) in the present series. Adelman and Aronson (9) failed to observe them in individuals under 16 years of age, while Staemmler (10) did not find them in patients under 20 years of age in his series. According to these workers, the incidence of the nerve bundles or neuromas increases progressively with advancing age. Furthermore, the parallel bundles and neuromas are usually myelinated, while perivascular nerves of intraparenchymal vessels are predominantly unmyelinated (18, 20, 21). It seems, therefore, unlikely that the parallel bundles are normally occurring perivascular nerves and the neuromas represent regenerative growth of such vascular nerves, as suggested by Riggs and Clary (8).

If the parallel bundles are not normally-occurring perivascular nerves, they must arise from spinal nerve roots, as suggested by Hughes and Brownell (2), since they are the only other potential source of the peripheral nerve fibers in the cord. The fact that the nerve bundles occur in adult life and in greater frequency in old age (9, 10) and in diabetic patients (6, 9) further suggests that they represent aberrant regenerative growth of spinal nerve root fibers. The nerve root fibers must, therefore, be injured during adult life and, whatever the type of injury may be, it seems to be accelerated by the aging process and diseases affecting peripheral nerves, such as diabetes. In view of the almost exclusive occurrence of the parallel bundles and neuromas along the anterior sulcal artery in normal cords, they must arise more frequently from ventral than dorsal roots near the anterior sulcus or their emergence from the cord, but we have not been able to document the exact site of the nerve root injury or regeneration.

If the parallel bundles are, indeed, regenerated fibers originating from spinal nerve roots, the mechanism by which the neuromas are formed in the absence of injury to the regenerated nerve fibers at or near the site of neuroma formation may be postulated, as previously suggested by other investigators (1, 2, 7). Spinal nerve root fibers severed by clinically occult injury regenerate and may grow along the nerve roots or stray off from them, growing into the anterior median sulcus, for the sulcus provides a comparatively wide space or less resistance. The nerve bundles are then guided by the anterior sulcal artery and enter readily into the perivascular spaces alongside its parenchymal branches.
and extend as far as the spaces are available. They are, however, unable to penetrate the pia-glial barrier and remain entangled in the perivascular spaces or turn themselves around, forming whorled masses or interlacing bundles. The regenerated nerve fibers do not, however, grow indefinitely, and usually remain thinner than the originals unless they reach their proper effector cells (28). This may explain the fact that the nerve fibers are usually thin and the neuromas remain small, usually less than 0.3 mm in diameter. The manner in which some form neuromas while others remain as small parallel bundles may depend on when the nerve fibers happen to encounter the pia-glial barrier in the course of their growth. Some may run into the barrier in the sulcus or perivascular spaces early in the course of regeneration and continue to grow, returning upon themselves to form interlacing bundles and whorled masses in the sulcus or perivascular spaces. Other nerve fibers, on the other hand, may travel rostrally or caudally for considerable distances before they encounter the pia-glial barrier and reach the limit of their growth by the time they run into the barrier and, thus, remain as small parallel bundles. The central question is, then, how the nerve root fibers are injured. We have no direct answer to the question at this time, but may postulate, based on the circumstantial evidence, that the nerve roots are subject to frequent subclinical injuries resulting from minor physical or other insults in adult life, and such injuries may become accelerated by aging and various disease states affecting the peripheral nervous system, e.g., diabetes mellitus.

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