Internal topography of major nerves of the forearm and hand: A current view

Fresh cadaver nerves were examined by serial cross-sections and microdissection with the operating microscope. The findings are compared with those of previous authors, primarily Sydney Sunderland. Our study confirms and amplifies Sunderland's findings: although it is true that funicular plexus formation and interchange takes place in the nerves of the human forearm, these connections are not of such a degree as to preclude operative procedures such as intraneural neurolysis, fascicular nerve repair, and interfascicular nerve grafting. Individual branches and bundles can be identified and traced within the main nerve trunk for considerable distances without significant trauma to conducting fibers. This arrangement lends itself to the application of modern microneurosurgical techniques. Clinical applications of these findings in the repair, lysis, and grafting of the major nerves of the forearm are described. The possibility of using such branches as the dorsal cutaneous branch of the ulnar nerve (if irreparably damaged) as a donor nerve for grafting is noted.

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"Honor those who go first, even if those who come later go further."

—Arabian proverb*

The unpredictable quality of functional recovery which follows nerve repair has stimulated both clinical and basic researchers to continue their investigations of the structure and function of peripheral nerves. In

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1945, Sunderland reviewed 40 years of such research and described his own work with the internal topography of the radial, median, and ulnar nerves. This well known work is often cited by other authors to explain their failure to attain a satisfactory level of function following nerve repair and subsequent axon regeneration. Sunderland pointed out that the cross-sectional arrangement of nerve components changes from level to level and from millimeter to millimeter; histological sections of nerve ends which are examined at different levels will appear to be different. This fact has led some to adopt an attitude of resignation toward accurate alignment of fascicles when gaps of more than a few millimeters exist.

The changing nature of the internal arrangement is
unquestioned. Nevertheless, several clinical observations led us to wonder if other factors known to be involved in peripheral nerve function might not outweigh the handicap of an evolving cross-sectional relationship in determining the quality of a final result. For example, bundles and funiculi of intact nerves can be separated (lysed) with no loss of function and sometimes even with clinical improvement. Similarly, in ulnar nerve transposition operations, the motor branches can be safely separated from the main trunk for some distance. Relatively long nerve gaps can sometimes be overcome with successful restoration of both motor and sensory function either by direct suture or interpositional grafts, suggesting that some measure of effective funicular alignment has been accomplished. Lastly, and most spectacularly, Manktelow and McKee have reported transfer of the gracilis muscle to the forearm by microneurovascular techniques with subsequent recovery of function. Clearly, nerves may have a greater potential for functional recovery than is generally assumed provided circumstances are otherwise favorable.

Definition of terms

A peripheral nerve consists of (1) neural elements which are extensions of motor and sensory cells located in the dorsal ganglia and anterior horns of the spinal cord and (2) non-neural connective tissue which supports, separates, nourishes, protects, and maintains the relative position of the various neural elements. The neural elements, called axons (or fibers), may be afferent, efferent, or sympathetic (sympathetic fibers will be ignored in this discussion). The non-neural elements consist of the epineurium, perineurium, and endoneurium. The epineurium can be subdivided into the epineural sheath (which surrounds the whole nerve) and the epineural connective tissue (which lies between funiculi or bundles). Groups of axons enclosed by perineurium are called funiculi or fasciculi. They are the smallest clinical units with which surgeons might work using current clinical techniques. Sunderland chose to use the term funiculus; we have elected to use this term and its synonym, fascicle (or fasciculus), interchangeably, since both are found frequently in the clinical literature. The term bundle is purely descriptive and will be used to describe a group of fasciculi which appear to be associated topographically within the epineurium, either in photomicrographs or upon clinical or laboratory dissection. It is a clinical term and does not necessarily imply a functional association.

Sir Sydney Sunderland

Sunderland’s study of the intraneural topography of the radial, median, and ulnar nerves clarified the divergent opinions expressed in the literature prior to 1945. He later extended this investigation to other nerves and assembled all his studies in the monumental publication, Nerves and Nerve Injuries. Sunderland found “no constant or characteristic funicular pattern for any nerve,” and he stated that “the funicular pattern was continually modified along the entire length of each
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Ve gaps can be restored by direct suture. Some measure may be achieved by the repeated division, anastomosis, and migration of the bundles. The longest section of any nerve with a constant pattern was 15 mm, although individual fascicles and bundle groups pursued longer courses without change; the average length of constant pattern was only 0.25 to 5.0 mm. Although he discussed resection, repair, and regeneration in sutured nerves, Sunderland made no attempt to correlate his findings with function or clinical results. Nevertheless, his famous three-dimensional reconstruction of the musculocutaneous nerve (Fig. 1) is frequently associated with explanations of suboptimal results following nerve repair. We believe that the hand surgeon’s interpretation of Sunderland’s work is incomplete and unnecessarily pessimistic.

At the time of Sunderland’s study, standard nerve repair was performed by epineurial suture without magnification. Intraneural topography was of some academic interest, but had little clinical importance. Since the introduction of magnifying devices, sophisticated instruments, and microsurgical suture, more and more surgeons have undertaken interfascicular dissection for the purpose of neurolysis, interfascicular grafting, and repair. Because of the increasingly frequent use of these techniques, an accurate understanding of intraneural architecture has become mandatory. To bet-
understand the limits and the usefulness of these technical advances, we have undertaken to perform serial nerve sections in the fashion described by Sunderland and to compare these observations with the findings of interfascicular microdissections of the major nerves of the human forearm.

**Method**

We examined the median, ulnar, and radial nerves of six unfixed human arms by either serial section (three median nerves—one sectioned totally, two partially) or microscopic interfascicular dissection (four median, four ulnar, and two radial nerves). Serial sections were taken between the medial epicondyle of the humerus and the terminal nerve branches in the palm; the microdissections were extended 10 to 12 cm above the medial epicondyle.

**Serial section study.** Three median nerves were studied, all from adult males. The median nerve and its branches were exposed throughout the forearm and hand and left in place. All branches were identified and labeled. The volar (anterior) surface of the nerve was marked with a continuous No. 6-0 silk suture placed within its epineurium and India ink applied to its surface. The length of the nerve and the distance from the radial styloid reference point to each branch was measured in millimeters and recorded. The location of branches on the perimeter of the main trunk was noted. The entire median nerve and its branches were removed from the arm, pinned to a board to maintain correct length and orientation, and fixed in 10% formalin for 7 days.

After adequate tissue fixation the median nerve was cut into 44 separate blocks, either 5 or 10 mm in length. The proximal end of each block was labeled and the distal 2 mm was removed as a separate subblock, processed, and embedded for microtome slicing. The 2 mm block was serially cut into 20-micron-thick sections, which were mounted unstained for examination. (Initially these sections were stained with hematoxylin and eosin, a step later omitted after we learned that we could see adequate detail on unstained preparations.) Each microscopic section was projected and traced on thin paper to document the relative size and location of fasciculi, the amount of epineurium present, and the origin of branches. Branches which could be positively identified were followed in retrograde fashion and their fascicular makeup recorded. Sections were made immediately proximal and distal to all branches to confirm their identity. Additional sections were taken throughout each block when necessary to permit positive identification of bundles and clarification of their changing pattern. Like Sunderland, we examined the nerves in a distal-to-proximal direction to detect changes in number, size, and location of fasciculi. Photographs of appropriate sections were made for permanent recording.
Table I. Median nerve serial sections

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<tr>
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<tr>
<td></td>
<td>First</td>
<td>Total</td>
</tr>
<tr>
<td></td>
<td>interconnection</td>
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</tr>
<tr>
<td>Thenar motor branch</td>
<td>56</td>
<td>112</td>
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<tr>
<td>Sensory</td>
<td>50</td>
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<td>66</td>
<td>81</td>
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<tr>
<td>3rd web space</td>
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<tr>
<td>Palmar cutaneous</td>
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<td></td>
</tr>
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<td>Distal</td>
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<td>99</td>
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<td>62</td>
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<td>4</td>
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<td>32</td>
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<td>83</td>
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<td>53†</td>
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<tr>
<td>Flexor carpi radialis</td>
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<td></td>
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<td>Pronator teres</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Distal</td>
<td>95</td>
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*Internal topography of the median nerve as measured in serial sections. All distances are in millimeters.
†Levels in the upper arm where branches could still be identified but dissection was arbitrarily stopped.

The tables and text provide detailed measurements of various branches of the median nerve, listing distances in millimeters. The measurements are divided into two categories: Sunderland's data and the authors' data. The tables include data for different nerve branches, such as the thenar motor branch, sensory branches, and various cutaneous branches.

Microscopic dissection was performed with the Zeiss OpMI 7 operating microscope at magnifications of 4.5 to 25 times using standard techniques with jeweler's forceps, scalpel, and scissors. Photographs of representative fields were taken through the microscope with a Yashica FL camera and automatic light meter. The films were Kodak Ektachrome, ASA 64, and Tungsten Ektachrome, ASA 160. Three median, ulnar, and radial nerves were examined in fresh autopsy specimens. In addition, numerous observations were made in the operating room on patients undergoing nerve repair or grafting. These latter observations confirmed our opinions but were not included in the data drawn from microdissection.

Terminal branches of the motor and sensory divisions of the median and ulnar nerves were identified in the palm and traced proximally by incising the epineurium and separating the branches from the remaining nerve trunk for as far as they could be identified and easily separated. This was done by gentle scalpel dissection, as very little cutting was necessary. Connections between the branches and other bundles were maintained to form an axial pattern. We ultimately used a system where one 20-micron-thick section out of every five was mounted for viewing and the other four discarded. This was possible because no significant change in funicular pattern was ever noted within a 100-micron length of serially studied nerve. Ten such sections could be mounted on each slide so that one slide represented 1,000 microns or 1.0 millimeter of nerve.

Two figures are listed for each branch: The first interconnection is the level where any connection, regardless of size, was seen. The total measurable distance is the level to which the branch could be traced before intermingling with other bundles.

Terminal branches of the thenar motor and sensory divisions of the median and ulnar nerves were identified in the palm and traced proximally by incising the epineurium and separating the branches from the remaining nerve trunk for as far as they could be identified and easily separated. This was done by gentle scalpel dissection, as very little cutting was necessary. Connections between the branches and other bundles were maintained to form an axial pattern.
Fig. 4. A photomicrograph of the median nerve at the distal transverse carpal ligament level. The bundles and branches are clearly identifiable and are separated by loose epineurium. They can be easily dissected from each other without injury to the fascicles. [a, two fascicles comprising the thenar motor branch; b, the bundle of sensory fibers to the thumb and the radial side of the index finger; c, bundle of sensory fibers to second web space (index-middle fingers); d, already separate branch to the third web space (middle-ring fingers).]

within the nerve were noted and their size and number recorded. The superficial radial and posterior interosseous nerves were similarly dissected.

The number which is given in the tables for each branch’s microdissection distance is the most proximal level to which the branch could be readily and positively separated as a distinct anatomic unit within the main nerve trunk. This is the point where substantial connections with other bundles could be seen and where composition became speculative.

Results

Median nerve. The median nerves provided the most information since we examined them both histologically and by microscopic dissection (Figs. 2 and 3). We can compare these observations with each other as well as with those of Sunderland (Tables I and II). The distance from the medial epicondyle, where the highest histological sections were taken, to the radial styloid varied from 26 to 30 cm. The median nerves divided into their terminal motor and sensory branches on the average 4 cm distal to the radial styloid, and all of the distances described for these branches are referred to their origin. Branches which arose in the forearm are described in millimeters proximal to the radial styloid. The distances cited in the serial sections are based on the examination of a single nerve; the figures for the microdissections are representative of the five arms examined. All nerves in each arm were not dissected.

The motor branch to the thenar muscles. The motor branch to the thenar muscles rose as a single branch in all nerves and consisted of two fascicles. In the serial sections it joined the main trunk on its volar-radial side 40 mm distal to the radial styloid (Fig. 4). It could be identified and traced proximally in this position for about 70 mm (30 mm proximal to the radial styloid). Few interconnecting bundles were seen in this span. We saw the first connection at 35 mm after it joined the main trunk, a small branch to an adjacent sensory fascicle. We then followed the motor branch for an additional 35 mm before it became thoroughly mixed with the sensory bundles from the hand. Thus we could identify and follow the motor branch for a total of 70 mm by serial section, considerably less than the 112 mm measured by Sunderland, but still to a level well above the transverse carpal ligament.

Microdissection of the thenar motor branch was performed in four median nerves (Table II). It joined the main trunk 31 mm distal to the radial styloid, and the first visible connection appeared 28 mm proximal to this bony landmark. We could clearly trace the motor branch to 59 mm where we found large connecting branches to the adjacent sensory bundles. Since these interconnections were nearly as large as the motor branch itself, we could go no further with certainty. In
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Fig. 5. Serial sections of a 20 mm span of median nerve in the lower forearm viewed from proximal to distal and showing separation of the palmar cutaneous nerve (PCN) from the main trunk of the median nerve. In this patient the PCN consisted of two branches which arose 20 and 25 mm proximal to the radial styloid. A, The PCN is a separate bundle located on the left (radial) side of the main nerve. It is loosely held by thin epineurium. One large fascicle comprises the distal trunk (D) and two small fascicles form the proximal trunk (P). B, Both nerve branches are still present, but they are slightly further apart. C, The lower two fascicles (P) of the proximal branch have separated off and are no longer seen. D, The large fascicle (D) now has departed as a second branch of the PCN.

Thus we could follow each arm to a level well beyond the radial styloid, and the motor branch was present. It joined the superficialis. We saw two branches in the serial sections, the distal one at 102 mm and the proximal one at 208 mm. The distal branch entered on the radial dorsal aspect of the main trunk as a single large funiculus. Within 20 mm it had separated into four smaller funiculi. At this level one small funiculus continued with a sensory bundle, but the other three...
Deep motor branch

Ring finger, ulnar side
Little finger, radial side
Little finger, ulnar side

Dorsal cutaneous

Deep motor branch

Flexor dig., prof. elongated

Flexor carpi ulnaris

Dorsal cutaneous

Fig. 6. Component microdissection of the ulnar nerve. The dark lines diagrammatically illustrate the dissection distance for each branch. The ring and arrow depict the anatomic origin of the nerve branch. The dark line distal to the ring and arrow represents the extraneural dissection distance; the line proximal represents the intraneural dissection distance.

Table III. Ulnar nerve microdissection distances*

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<thead>
<tr>
<th>Branch</th>
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<td>81</td>
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<tr>
<td>Terminal sensory</td>
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<td>81</td>
</tr>
<tr>
<td>Individual sensory</td>
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<td>27</td>
</tr>
<tr>
<td>Hypothenar eminence</td>
<td>48</td>
<td>26</td>
</tr>
<tr>
<td>Ulnar little finger</td>
<td>48</td>
<td>26</td>
</tr>
<tr>
<td>4 th web space</td>
<td>171</td>
<td>209†</td>
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<tr>
<td>Dorsal cutaneous</td>
<td>7</td>
<td>97</td>
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<td>Flexor digitorum profundus</td>
<td>11</td>
<td>107</td>
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<tr>
<td>Flexor carpi ulnaris</td>
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<tr>
<td>Flexor carpi ulnaris</td>
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</tr>
<tr>
<td>Distal</td>
<td></td>
<td></td>
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<tr>
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<tr>
<td>Proximal</td>
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* Expressed in millimeters.
† Levels in the upper arm where branches could still be identified but dissection was arbitrarily stopped.

proceeded proximally for an additional 55 mm without further major change.

The proximal branch entered as a single large fascicle on the ulnar dorsal surface at 208 mm. It was easily traced for 22 mm without interconnection.

By microdissection of this nerve in a fresh autopsy specimen, we isolated four separate branches to the muscle, at 121 mm (radial side), 124 mm (posterior surface), 185 mm (ulnar side), and 196 mm (ulnar side). Although the first two branches were little more than filaments, they were clearly nerve branches. We traced them for 15 mm to substantiate this point, but they were too small to dissect further. The two more proximal branches were much larger and both originated from the same large bundle within the main trunk. The more proximal branch of the two came off 196 mm above the radial styloid, whereas the remainder of the bundle proceeded down to 174 mm, where it exited and traveled parallel to the proximal branch. The common trunk which contained all branches of the flexor digitorum superficialis could be separated for 58 mm without injury to any large interconnections.

Anterior interosseous nerve and flexor carpi radialis. The anterior interosseous nerve is the largest motor branch of the median nerve in the forearm (Fig. 2). In the histological sections it could be seen on the ulnar-dorsal surface, arising at the same level (208 mm) but separate from the proximal branch of the flexor digitorum superficialis. It contained 14 fascicles and traveled proximally in the same position on the outer perimeter of the remainder of the median nerve. We still could clearly identify the anterior interosseous nerve within the main nerve trunk at 267 mm, the level of the medial epicondyle, and we could see no interconnections with other portions of the median nerve during this 59 mm span.

By microdissection we located the anterior interosseous nerve arising on the dorsal surface at 239 mm. It could be easily separated to the level of the medial epicondyle (293 mm) and for an additional 93 mm beyond. Its only attachments to the median nerve were epineurial and these were easily divided. The branch to the flexor carpi radialis actually arose from the anterior
Fig. 7. Dissection of the ulnar nerve in the lower third of forearm and palm. The lower arrow points to deep motor branch. The upper arrow points to sensory component. The area to the right of the arrow is the common sensory bundle. The area to the left of the arrow has divided into sensory nerves to the ulnar side of the little finger and the little-ring finger web space.

Interosseous nerve. The interosseous nerve in the histological sections. It entered at 214 millimeters on the dorsal-ulnar aspect. The branch consisted of three medium-sized fascicles which joined as they proceeded proximally to become two and finally one, large fascicle. This single fascicle began 24 mm proximal to the branch point of the flexor carpi radialis from the anterior interosseous nerve. The branch to the flexor carpi radialis was traced to the medial epicondyle, a distance of 53 mm, without interconnection to other bundles.

Flexor digitorum profundus. The flexor digitorum profundus was located on histologic section at 230 mm as an independent branch from the radial side of the median nerve. An additional contribution to this muscle arose from the anterior interosseous nerve. Two fascicles, one large and one small, comprised the independent profundus branch at its point of departure from the main trunk of the median nerve (230 mm). They were traced proximally for 37 mm to the level of the medial epicondyle, where they joined to form a single large funiculus. No sections were made proximal to this point.

By microdissection the branch to the flexor digitorum profundus arose from the anterior interosseous nerve. Although it was dissected for only 10 mm proximal to its origin, the branch remained separate over this span.

Pronator teres nerve. The pronator teres nerve was the most proximal branch of the median nerve examined histologically. It arose as two separate branches at 226 and 240 mm from the radial-volar aspect. These branches contained two and three funiculi, respectively, and could be easily identified at the level of the medial epicondyle (267 mm). No detectable connections with other bundles were seen between the origin of these branches and the medial epicondyle, distances of 41 and 27 mm, respectively.

By microdissection five separate branches to the pronator teres arose from a single large trunk whose origin was well proximal to the medial epicondyle (303 mm). This trunk was 12 mm long and was easily dissected for 100 mm with no evidence of connecting branches to other portions of the median nerve.
Fig. 8. Dissection of the dorsal sensory branch of ulnar nerve in the forearm. This branch (arrow) could be isolated from the main trunk, beginning at its normal anatomic origin and going to a point well above the elbow without transsecting any interconnections. This distance is approximately 20 cm.

**Ulnar nerve.** We dissected four ulnar nerves into their component bundles with the aid of magnification (4.5 to 25 times) (Fig. 6), but we performed no histological examinations of this nerve (Table III). Beginning in the palm at the terminal branches, the motor and sensory components (deep motor branch and a common sensory trunk which became the sensory nerves to the ulnar side of the little finger and the fourth web space) could be separated for a total length of 81 mm (Fig. 7). In one nerve these two branches remained clearly separate to the midforearm level. No connections were noted before 21 mm; those seen were small filaments and did not make up a significant portion of the trunk. Within the sensory component the branches to the ulnar side of the little finger and the fourth web space were separable for 26 mm.

The level at which the dorsal cutaneous branch joined the main trunk of the ulnar nerve was variable. In one specimen it entered as far distal as 48 mm proximal to the radial styloid; another joined at the 91 mm level. It traveled proximally as a separate bundle for 209 mm, well above the epicondyle, without demonstrable connections to the main trunk (Fig. 8). *It was as though the dorsal cutaneous nerve and the ulnar nerve were two separate nerves traveling within a common epineural conduit while still retaining their autonomy. This arrangement was found in all of the ulnar nerves examined.*

Multiple motor branches to the two main forearm muscles, the flexor digitorum profundus and the flexor carpi ulnaris, were found in all instances. They sometimes arose separately from the main trunk of the ulnar nerve and sometimes as branches of a common trunk, but always in the region of the elbow. Representative levels of origin were 240 to 280 mm; representative dissection distances were 74 to 107 mm. These distances permitted separation of the flexor digitorum profundus and the flexor carpi ulnaris well into the upper arm.

**Radial nerve.** Technically, the radial nerve is not a forearm nerve, since it terminates at the level of the medial epicondyle. For this reason, we did not study it in detail (Fig. 9).

We dissected the posterior interosseous and superficial radial nerves above their origins and found that we could easily separate them from each other for 90 mm before encountering the first interconnection (Table IV). No attempt was made to separate individual motor branches of either the radial or posterior interosseous nerve.
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Internal autonomy.

The ulnar nerves of the main forearm and the flexor masses. They sometimes span the ulnar common trunk, but the representative funiculus is not. These dissections of the digitorum profundus into the upper arm. The radial nerve is not a single trunk, but multiple, levels of the extremities and found that the interconnection of separate individual fibers in the posterior interosseous nerve. The Journal of Hand Surgery Vol. 5, No. 1 January 1980

Discussion

Studies conducted by numerous investigators over the past 70 years have demonstrated that the internal structure of peripheral nerves is characterized by numerous intercommunications, position changes, and the formation of funicular plexuses. Even in the early 1900s some investigators recognized the basic funicular character of the intraneural funicular pattern. The question of functional significance was rarely raised, however. Stimulation of exposed nerve by electrical currents suggested that the functional course of axons is straight, even if the funicular course is not, but the methods employed made these studies suspect. Now it has become important that we try to determine in what way and to what degree internal architecture matters in clinical practice.

Sunderland performed the exhausting task of serial histological section and examination of the major nerves of the extremities, cataloging both the arrangement of individual fascicles and the distances over which they could be identified. Furthermore, he performed microdissections of the branches and recorded the distances over which they could be isolated from the main trunk of the nerve without damaging or interfering with the fiber architecture. Although some authors took note and recognized the significance of this latter work, Sunderland's microdissections appear to have been largely unnoticed by most surgeons.

In his writings Sunderland emphasized that in the most proximal portion of nerves, the majority of the funiculi contain representative fibers of most if not all of the peripheral branches. His composite model of the musculocutaneous nerve illustrates this point (Fig. 1). At more distal levels, however, a regrouping of the fibers is gradually effected, whereby individual branches become identifiable as such and come to occupy different funiculi and bundles. He concluded that the purpose of the intraneural plexuses seems to be to assemble the requisite afferent and efferent fibers for each branch from the appropriate segmental sources. He further thought that often a plexus is the product of mesenchymal condensations which occur during development, regardless of the destination and function of the fibers. This is certainly possible, given the capricious nature and variation of developmental anatomy.

As we come to understand better the complex circuitry of the nervous system, we gain an appreciation for the large number of information interchanges required. The refining process begun at the spinal cord level must continue through the larger nerves and their branches until individual fibers can be appropriately positioned at their target organs. The sorting probably occurs irrespective of whether the fibers are motor or

Table IV. Radial nerve microdissection distances

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<td>Posterior interosseous (mm)</td>
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<td>90</td>
</tr>
<tr>
<td>Superficial radial (mm)</td>
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<td>90</td>
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Fig. 10. The current concept of the internal topography of a 3 cm section of the median nerve in the midportion of the forearm. Since this representation is of the more distal segments of the nerve, fascicular branching or mixing is infrequently seen, either in cross-section or longitudinal microdissection. This appearance differs from that seen in Fig. 1, which represents the musculocutaneous nerve at a more proximal location.

sensory. In fact, Terzis has referred to her unpublished work which suggests that even a nerve such as the deep motor branch of the ulnar nerve, heretofore thought to be a "pure motor nerve," may contain as much as 50% sensory fibers. Despite these obligatory changes in fiber location, it now appears that the forearm and hand are characterized by connections within, not between, bundles, and that bundles are separable surgically.

Perhaps the most important aspects of Sunderland's work are these: "Despite the changing plexiform character of the funicular pattern, fibers from the peripheral branches pursue a localized course in the nerve for variable, though often considerable distances." The redistribution of bundles implied in the plexus principle "is local and not general." Fibers "scatter gradually" and, even with intermingling, "remain in the same quadrant over long distances."

Moreover, he points out that, "there is no proof that the intercommunications effect a complete reorientation or redistribution of fibers or that the intercommunication erased localization." In fact, he even cautions that "conclusions based on such investigations have given very misleading results." Despite Sunderland's clear recognition of the plexiform nature of intraneural topography, these statements do not imply a constant (and hopeless) intermixing of the components of a peripheral nerve. Rather, they suggest an orderliness and purpose which might be used to advantage in treating mechanical ailments and injuries if it is recognized and understood.

It is noteworthy that subsequent investigations by others have confirmed these points, and we are unaware of any contradictory studies. Analysis of our data based on serial sections of the median nerve further documents Sunderland's interpretation of his microscopic results. In the 33 years which have elapsed since Sunderland's publication, many surgeons have grasped the fact that funicular plexuses and interconnections exist but they have failed to appreciate his demonstration that functional units (and often discrete branches) remain localized in the same quadrants of nerve trunks for considerable distances and are accessible to surgical manipulation and repair.

Comparison of the absolute distances in our study and those of Sunderland show many discrepancies and these distances deserve comment (Tables II, III, and IV). Dissection distances are not important in and of themselves, for they vary from nerve to nerve and person to person. Moreover, landmarks such as bony prominences cannot be strictly defined, and actual measuring techniques are imprecise. Finally, in fresh specimens the epineurium is loose and one can vary the origin of a branch by a few millimeters simply by tugging on it. For all these reasons, the absolute distances that branches travel are probably unimportant, except insofar as they relate to each other. The point to be made is that, while some internal sectors of a nerve may be changing, other portions may proceed for considerable distances with no major change in position or composition and thus may be isolated surgically. If one is to perform intraneural dissections, an understanding of the branch patterns and bundle arrangements is of the utmost importance.

It is impossible, of course, to study the courses of individual axon fibers by the techniques employed in this study. Sunderland assumed that constituent fibers intermingled whenever there was fusion of funiculi and
Internal topography of peripheral nerves

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Fig. 11. A, A partially dissected median nerve, seen through the operating microscope. The undissected portion is at the bottom of the photograph. The upper portion shows several parallel bundles and fasciculi which were separated by incising their epineurium. Only an occasional connection is seen. B, A high power view of the mixed area. There are several large parallel fasciculi with no interconnection. A medium-sized connection is seen in the center of the field and a smaller one is located at the lower right.
that subsequent separations left representatives of all the daughter fibers in each newly formed fascicle. He further classified plexuses as (1) those where all the fascicles are derived from one branch and where changes are confined to bundles of like origin. (2) Those where the fascicles of a bundle or branch blended with fascicles of a nearby but separate bundle, i.e., one of a different origin. This implies a blending of unlike fibers. (3) Those occurring at the most proximal levels of a nerve, where bundles which already contain fibers of diverse sources divide and recombine repeatedly. These three types of union probably occur in a distal-to-proximal direction and result in progressively greater fiber mixing as nerves become nearer to their central origin. Since our study was limited to the forearm and hand, many of the changes we noted in funicular pattern were similar to Sunderland’s first type: as two adjacent funiculi moved closer to each other, the intraneural epineurium between them thinned and then disappeared; the position and appearance of the bundles changed, but there may have been no actual mixing of fibers (Fig. 10). If this supposition is true, then bundles which behave in this fashion can probably be separated surgically until a level is reached where fibers actually pass from one bundle to another. Such fiber mixing rarely occurs when branches and bundles first fuse, but only at more proximal levels in the nerve.

In our microdissections of the median, ulnar, and radial nerves, we found that major branches could be separated from the main trunk for considerable distances by incising the epineural sheath and teasing the intraneural epineurium apart (Table II, III, and IV). These data are comparable to similar observations by Sunderland and Seddon. Further corroboration can be found in those clinical studies which describe the separation of the motor branches for transposition of the ulnar nerve at the elbow and separation of the motor and sensory branches of the ulnar nerve at its termination to permit rerouting and individual repair of the branches in the palm. In addition, neurolyses of the median nerve at the carpal tunnel are performed successfully without functional loss. More recently, Millesi has reported separating the palmar branches of the median nerve “to the middle or proximal half of the forearm” in preparation for specific funicular grafts to these branches. These observations all lend credibility to the conclusion that it is possible to perform such separations in the clinical setting as well as in the laboratory. They suggest that many of the interconnections found below the elbow in the median and ulnar nerves may be of less surgical importance than has been thought heretofore.

In our microdissections of the fresh autopsy material, we were able to identify large interconnecting branches with ease (Fig. 11). There were relatively few such connections in the distal portion of the forearm. Although it is possible that smaller branches were present and could not be seen through the microscope, it is more likely that microdissection is an effective way of separating bundles and funiculi with very little damage to whatever connections exist. It is even possible that the plane of clinical dissection was between funiculi which might have appeared to be associated in a single bundle by histological examination. Since limited dissections were performed above the medial epicondyle of the humerus, we cannot say whether such separations would also have been possible in the more proximal portions of the nerve where considerable intermingling of fibers is thought to occur. Sunderland’s dissections at this level suggest that such separation would have been less likely.

An understanding of the character of the non-neural connective tissue layers of peripheral nerves suggests a possible explanation for the ease of dissection of individual bundles (Fig. 12). The epineurium invests the entire nerve trunk as well as groups or single funiculi. The intraneural epineurium is loose and areolar, it tears easily, and it possesses relatively little strength, but it is the stuff which separates the bundles. Perineurium, on the other hand, surrounds each funiculus, has a tight lamellar composition, and is quite strong. It is the material one sews when making an interfascicular stitch, and it is the natural plane of dissection upon which one separates fascicles. In performing interfascicular dissection, the tissue which gives way most easily is epineural connective tissue. Thus one would expect that in the relatively distal segments of peripheral nerve, the bundles, might be separated into their component funiculi with little or no loss of function because there are relatively few interconnecting fibers. Our findings suggest that this is indeed the case.

It is unclear why a funiculus would travel first with one bundle and then with another. Sunderland’s explanation that it is part of the sorting process which begins with spinal segments and evolves to branches is most acceptable. Furthermore, his idea of fortuitous condensation of mesoderm also may be true. The impression we have formed is that fiber and funicular behavior, at least in the more distal portions of nerves, is rather purposeful and that it is the random wandering of epineurium which is responsible for much of the change observed. Although this may seem a subtle distinction, its importance must be emphasized. It is quite a different matter to suggest that the epineurium shifts and not
The fascicular, but this seems to be the case over the distances encountered in our lower forearm dissections.

What is certain and what must be stressed is that the connection between the cell body in the dorsal or ventral ganglia and the end organ, whether sensory or motor, is continuous. Over the distances commonly encountered in peripheral nerve repair, lysis, or graft, it appears that the fibers, collected in small funiculi, travel in identifiable bundles and can be separated surgically with little or no damage to the component parts. Since most injuries occur in the more distal portion of a nerve, the funicular arrangement and relationship at this level is critical and appears to favor the surgeon.

We have speculated before that the nervous system...
is blessed with many times the number of sensory fibers necessary to perform basic functions, provided their central connections are appropriate and undistorted. Thus a reduction in functioning axons of some measurable percentage, if it could be accomplished in an orderly fashion, still might permit relatively normal sensation which is simply less discriminating. This may well happen when one performs a neurolysis or separates branches of a nerve. It almost surely occurs in a repair or graft where regenerating axons are fewer in number and may reach similar but different end organs. Useful function returns, but the strength or ability to discern is reduced. This phenomenon occurs naturally in peripheral neuropathies and affects both motor components, where it is easily measured, and sensory components, where it is not.

Clinical applications

Carpal tunnel and other entrapment syndromes. Curtis and Eversman suggested, and others have corroborated, that internal neurolysis, when indicated, can be safely carried out in patients with carpal tunnel syndrome and that functional recovery will be more complete than in those patients in whom only division of the transverse carpal ligament is performed. We now know that axons can be compressed by an epineural sheath which is scarred or thickened, as well as by a tight carpal tunnel, and that only incision of this epineurium will relieve symptoms of intraneural compression. Our studies suggest that in such cases, whether at the elbow or wrist, the bundles or individual funiculi can be safely separated and that little or no functional loss is likely to occur.

Primary or secondary repair of transsected nerves. In cases where a nerve is sharply transected or where the zone of injury is limited, gaps of up to 5 cm may be encountered, and primary or secondary repair, including excision of neuroma and glioma, can be performed. It is not our purpose here to discuss the role of tension in the outcome of such cases, and whether such gaps should be managed by direct suture or by interpositional graft. We only wish to emphasize that it is possible to recognize anatomically similar bundles in the proximal and distal stumps at these distances and to connect them correctly by whichever means one wishes. In the forearm and wrist, distances of a few centimeters have the anatomic potential for recovery of motor and sensory function, other factors notwithstanding.

Interpositional grafts. As the gap between nerve ends increases, there occurs a point where an interpositional graft becomes necessary. The technique of inter-
In a cooperative patient, one might use the sections of graft as necessary. If appropriate quadrants branches and no major quadrant changes. Here corresponding quadrants can be connected directly or with sections of graft as necessary. If appropriate quadrants are joined, the likelihood of a correct match-up is good.

In the distal third of the forearm, there are very few sections of the forearm nerve trunk through the forearm and well proximal to the medial epicondyle. In reality it is a separate nerve traveling in the same epineurial sheath with the ulnar nerve. The situation is similar to the arrangement of the tibial and common peroneal nerves. It offers some intriguing opportunities. In an acute ulnar nerve injury at the midforearm level proximal to the separation of the dorsal cutaneous nerve, this branch can be dissected out and repaired separately, thereby increasing the likelihood of accurate alignment of the remaining motor and sensory components. If an injury at this same level requires a nerve graft, yet another possibility exists. In some instances, the dorsal cutaneous nerve may be considered expendable. Should this be the case, it might be possible to dissect it for some distance and to use it as a graft. This maneuver could provide as much as 25 cm of graft and have three major advantages: (1) a graft from the same operative site, (2) a reduction in the cross-sectional size of ulnar nerve requiring a graft, and (3), again, a corresponding increase in the accuracy of alignment.

Little can be said about the radial nerve, since so little of this study pertains to it. It is not primarily a forearm nerve, but it is clear that its major sensory branch and the posterior interosseous nerve can be separated for several centimeters above the medial epicondyle without difficulty and that the principles previously outlined for the median and ulnar nerves also apply to the radial nerve. Again, the intriguing possibility exists for using the radial sensory component for a donor graft in irreparable injuries above the elbow-by dissecting it out and using it to bridge the motor deficit in the posterior interosseous nerve. Although there is a possibility of painful neuroma formation in the superficial radial nerve when it is injured more distally, the rarity of this problem in the upper arm makes its use as a donor nerve at least a possibility. This suggestion is speculative and we have not used this nerve as a graft.

Finally, a word of caution: The study of Rydevik, Lundborg, and Nordborg suggests that intraneural dissection in animals may induce fibrosis within the nerve and aggravate rather than relieve intraneural constriction which has resulted from epineural scarring. Incision of the epineurium and interfascicular dissection is a procedure which should be reserved for the specific situations where it is likely that epineurium is constricting the fasciculi and producing symptoms which cannot be relieved by external decompression alone. Our data suggest that this procedure, if performed carefully, can be accomplished without significant injury to the perineurium and without further loss of function. Similarly, if intraneural dissection is indicated to facilitate
repair, rerouting, or grafting of peripheral nerves, it can be performed, but one must always weigh the potential gain against the risk of further damage.

A project of this magnitude has many contributors and we gratefully acknowledge their contributions: Mr. Thomas White, an aspirant medical student, prepared all the microscopic sections. Mr. James Goodman created the original art work, and Mr. William DeVeer produced the photographs. Ms. Cheryl Lyon expertly prepared the manuscript, and Ms. Mary Lou Percy provided the scanning electron micrograph. Dr. Douglas Gorman assisted with the microdissections.

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