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The Funicular Pattern of Japanese Peripheral Nerves

by

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INTRODUCTION

Peripheral nerve injuries have been diagnosed and treated surgically for more than seventy years and experimental work during this time has provided answers to some of the problems about degeneration and regeneration of peripheral nerves[5]. Surgeons have used various methods to improve the results of operative treatment, either special materials for suture or materials to prevent invasion of the suture line by scar. Examples are the use of human hair[15], segment of artery[36], fibrin[39], plasma-clot[35], nerve glue[9], removable pull-out wire sutures[26], tantalu[29], millipore membrane[6], adhesive tapes[13] and the use of a special nerve holder[11]. None of these techniques have been followed by completely satisfactory results after nerve suture. The results of treatment of peripheral nerve injuries have been analyzed and published by various authors but in none does the information enable us to deduce exactly the cause of the less than satisfactory results[12)33)34)37)38)40)].

ÖNNE[25] stated in 1962 that, only a few patients would recover normal tactile sensation after a supposedly ideal suture. This report shows the limitation of normal maturation of the regenerating axon and makes one realize the limited efficacy of ordinary nerve suture.

ZACHAR and ROAF[41] commented on the numerous lesions in continuity of peripheral nerve trunks with isolated motor or sensory phenomena and that the incidence was different among the different nerve trunks but they gave no explanation for this finding.

In 1956 BARNES[3] related the differences of partial motor and sensory lesions in the different nerve trunks with a variation of the intrafunicular pattern but did not consider whether the level of the lesion in each nerve trunk had any significance (Figure 1). The statement of ZACHARY[40] is of interest: "the number of poor recoveries after treatment under good conditions is large enough to be important. This should preclude an attitude of complacency with present methods of treatment of peripheral nerve injuries and stimulate a search for better ones, both operative and conservative".

To achieve this object, it seemed necessary to consider the peripheral nerve injury more precisely and to delineate the funicular pattern of the peripheral nerve trunk in order to improve the accuracy of diagnosis and results of treatment. Improvements in nerve suture might follow accurate apposition of corresponding funiculi and this has been recommended by others.

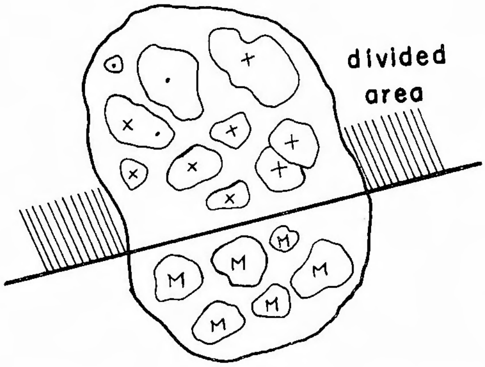

Fig. 1 a Partial division of the ulnar nerve at 20 mm.
Sensory funiculi are divided, giving an isolated rensory paralysis.
M Deep (muscular) division fibers
• Palmaris brevis fibers
× Cutaneous fibers from the 4th interspace
+ Cutaneous fibers from the ulnar side of the little finger
△ Dorsal cutaneous fibers of the hand

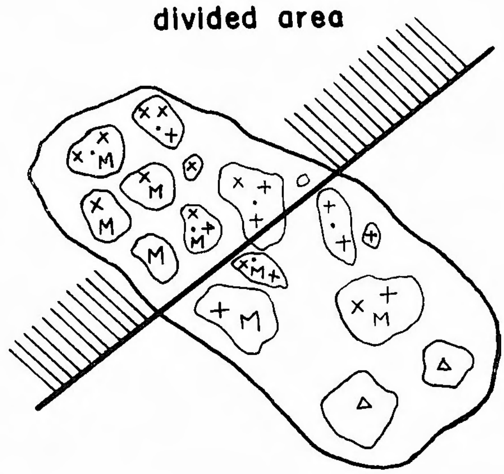

Fig. 1 b Partial division of the ulnar nerve at 96 mm.
Divided funiculi contain a mixture of motor and sensory fibers, so there is a mixed partial paralysis of the intrinsic muscles and sensation of the little and ringfinger.

This suggestion was made by LANGLEY and HASHIMOTO[20)21)] in 1917 and again by SUNDERLAND[31)] in 1952 but was not taken up clinically. Recently, BOYES[8)] stressed the importance of maintaining nerve alighment saying, "errors in rotation probably account for the poor results seen in ulnar nerve repair, since this nerve, repaired after its branching in the palm, can be repaired in either the motor or sensory division with good results" SMITH[27)28)] in 1963 used a dissecting microscope to differentiate the funicular pattern during repair. ITO et al[14)17)18)] on the basis of experimental work on dogs, also recommended funicular suture and not good clinical results. In 1967 BORA[7)] developed funicular suture in the cat.

If suture of the severed peripheral nerve is to be improved by correct apposition of the funicular pattern, then we must increase our knowledge of the topographic anatomy in the nerve trunks, particularly the funicular pattern, a knowledge which is woefully deficient at the present time. BARDEEN[4)] in 1906 concluded that it was usually difficult or impossible to trace nerve fibers from the lower extremities in man back to their origin from the plexus but that it was possible to draw up serial schematic cross sections of the nerve trunk. STOFFEL[30)] in 1913 described the functional topography in peripheral nerves and stated that the funiculi are continuous into the nerve branches and that they can be traced proximally in the nerve trunk. MARIE[23)] in 1915, KRAUS and INGHAM[19)] in 1920 came to the same conclusion as STOFFEL by using faradic stimulation of peripheral nerves exposed at operation. HEINEMAN[16)] in 1916, by means of a series of cross sections of the median, ulnar and sciatic nerves, stressed the numerous and irregular anastomses and divisions of bundles of these nerve trunks throughout their whole length. LANGLEY and HASHIMOTO[20] in 1917 dissected human sciatic nerve trunks and described the existence of an internal nerve plexus, "each peripheral nerve, whether it supplies muscles or skin, arises to a greater or lesser extent from the plexus but some peripheral norves, especially cutaneous nerves, run into the nerve trunk for more or less considerable distance and can be sutured separately, thus lessening crossing of efferent and afferent nerves and other distortion of nerve pattern". McKINLEY[24] also described the plexus formation of the sciatic nerve in 1121. DUSTIN[10] in 1918 following an extensive study of the median, ulnar and radial nerves, established conclusively the plexiform character of the intraneural fascicular pattern. He stated that, "the fascicular topography of the same nerve is continuously modified by the exchange of numerous anastomses between the various fasciculi, however, one may admit that in every quadrant of the nerve such and such motor, sensory fibers are grouped by preference". SUNDERLAND[32] in 1945 dissected specimens of the radial, median and ulnar nerves and studied the position of fiber content of the funiculus at different levels and the manner in which its fibers were redistributed. He concluded that, despite the changing plexiform character of the funicular pattern, fibers from the peripheral branches pursued a localized course in the nerve for a variable but often considerable distance above the site of branching. LEHMANN[22] considered that each nerve trunk changes its funicular pattern by frequent interchanging and interlacing of smaller funiculi and nerve fibers (Fig. 2). This interchange becomes more frequent as one ascends the nerve proximally.

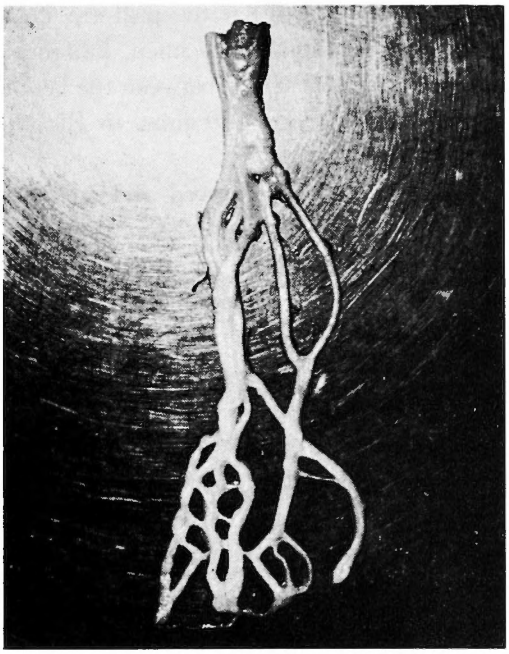

Fig. 2 Plexus formation in the medial popliteal nerve at middle third of the thigh

In 1965 ARAKAWA[1] and colleagues followed the course of nerve fibers in the nerve trunks of the spinal roots C_5 to T_1 in the rabbit and noted the tendency of nerve fibers from the same root to occupy certain positions in the major nerve trunks. Despite the extensive work of SUNDERLAND, it is not possible to determine sufficiently how much functional localization occurs at different levels and over what segment of nerve trunk such localization will persist in different individuals. We do not know whether there is any racial difference in the funicular pattern between SUNDERLAND's cases and our own.

It is the purpose of this present investigation to describe the funicular pattern of the peripheral nerve of the adult Japanese and to try to demonstrate the degree of functional localization of the bundle branch system if it should exist.

MATERIAL AND METHOD

Three cadaver upper extremities, two of them from the same subject, two of them right and one left, were examined and the nerves were dissected carefully throughout their course and every cutaneous and muscular branch was accurately identified. The plane which contains the coracoid process of the scapula, medial and lateral epicondyle of the humerus and the palmar surface was defined as the anterior surface of the nerve trunk and landmarks were established along the nerve trunks to make correct identification of the position and level in the cross sections of the nerves possible. The level of the division of each branch was measured, the radial nerve from the lateral epicondyle of the humerus and the median and ulnar nerves from the pisiform bone. Levels below these points were considered as minus and above them, plus.

The length of each specimen was measured considering the clinical application of the result to the upper limbs of different length. The distance between the pisiform bone and the lateral epicondyle of the humerus was 228 mms. in Right I specimen, 229 mms. in Left I specimen and 254 mms. in Right II specimen. The distance between the lateral condyle of the humerus and the coracoid process of the scapula was 250 mms. in Right I and Left I, and 280 mms. in Right II specimen.

The three radial, three median and three ulnar nerves were removed and stretched slightly on glass plate frames and fixed in 10% formaldehyde. After fixation, they were divided into small segments, embedded in paraffin, serially sectioned transversely at 20 intervals and stained with hematoxylin and cosin. The sections were examined under the microscope on their distal faces and fascicles of every terminal branch were traced proximally along the nerve and these examinations were recorded in a serial diagramatic fashion. Thus, an "Intraneural Topographic Atlas" (ITA) was drawn up on the basis of the findings of the Right II Specimen (Figs. 3, 4, 5).

A study of the proximal course of the funiculi which constitute particular branches of the major nerve was made. Four branches, the superficial branch of the radial nerve, the thenar muscle branch of the median nerve, the deep (Muscular) branch and the dorsal cutaneous branch of the ulnar nerve were chosen because of their importance at the time of the funicular suture. The object of this study was to assess the extent of interfunicular mixing of the nerve fibers as they were followed in proximal direction from the level of the branches. This assessment was done on the basis of approximate cross sectional area of the funiculi which was calculated by the caliber of the funiculi through the eyepiece micrometer. Funiculi which were entirely composed of the fibers from the particular branch were graded as zero mixing. Funiculi, where less than 50% of mixing with other branch fibers was present, were graded as + mixing. Funiculi, where 50 to 75% of mixing was present, were graded as ++ mixing. Funiculi, where more than 75% of mixing was present, were graded as +++ mixing. Figs. 7, 8, 9 and 10 show the extent of mixing at seven to nine arbitrary levels in the course of main nerve trunks. Four graded funiculi were represented as shown in Fig. 6.

Examination was made to compare the difference in the frequency of changes of the funicular pattern along each nerve trunk in the muscular and the cutaneous bundle branches in that segment where there is no intercommunication between the muscular and sensory fibers (Tables 14 and 15).

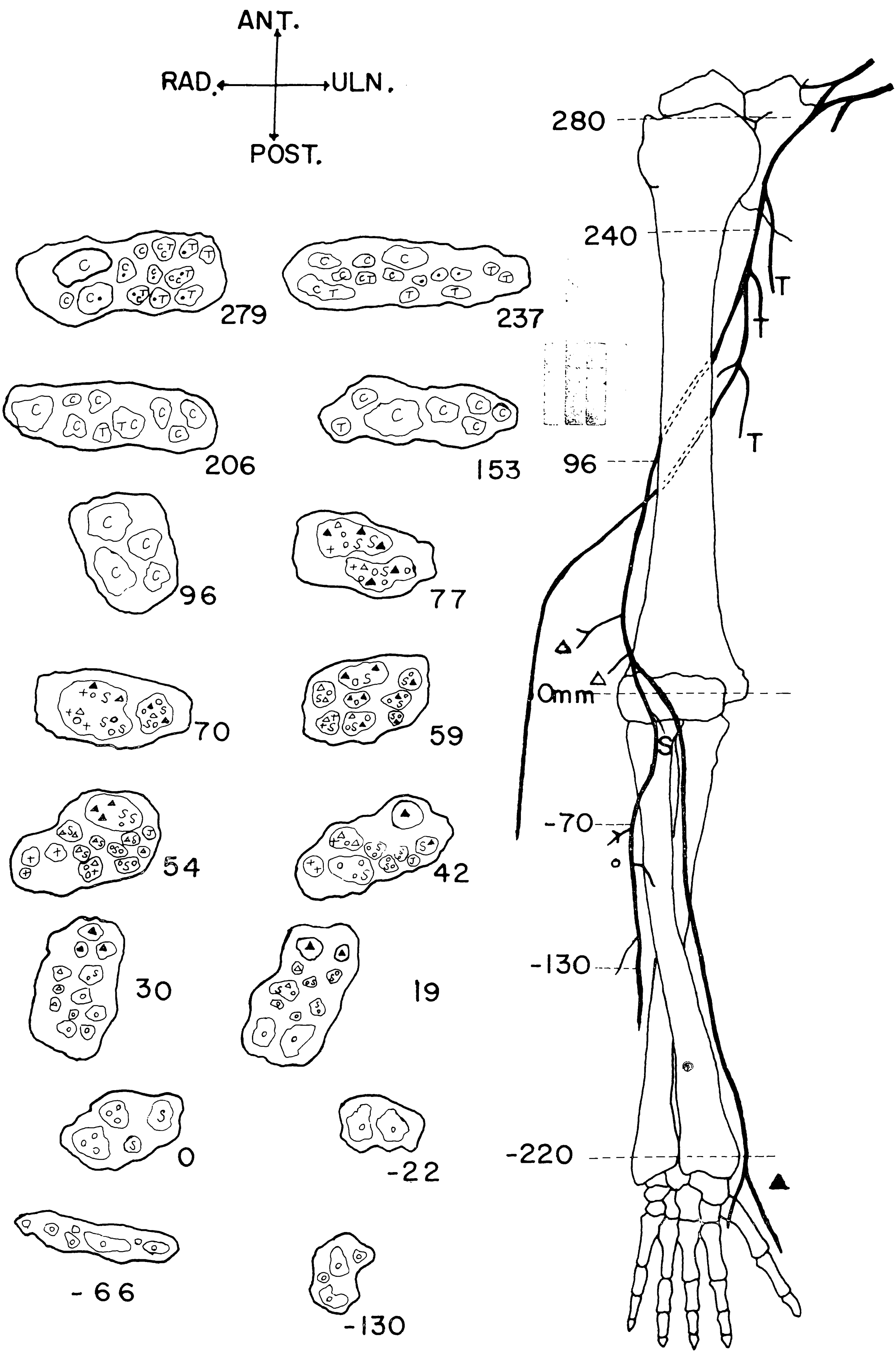

Fig. 3 The Intraneural Topographic Atlas (ITA) of the Radial Nerve. Right Radial Nerve Sections viewed from below
▲; Superficial radial fibers o; Posterior interosseus fibers S; Supinator fibers J; Fibers to the elbow joint
△; Extensores carpi radial fibers +; Brachioradialis fibers T; Triceps brachii fibers ●; Cutaneous antebrachii dorsalis fibers C; Combined terminal and extensors fibers

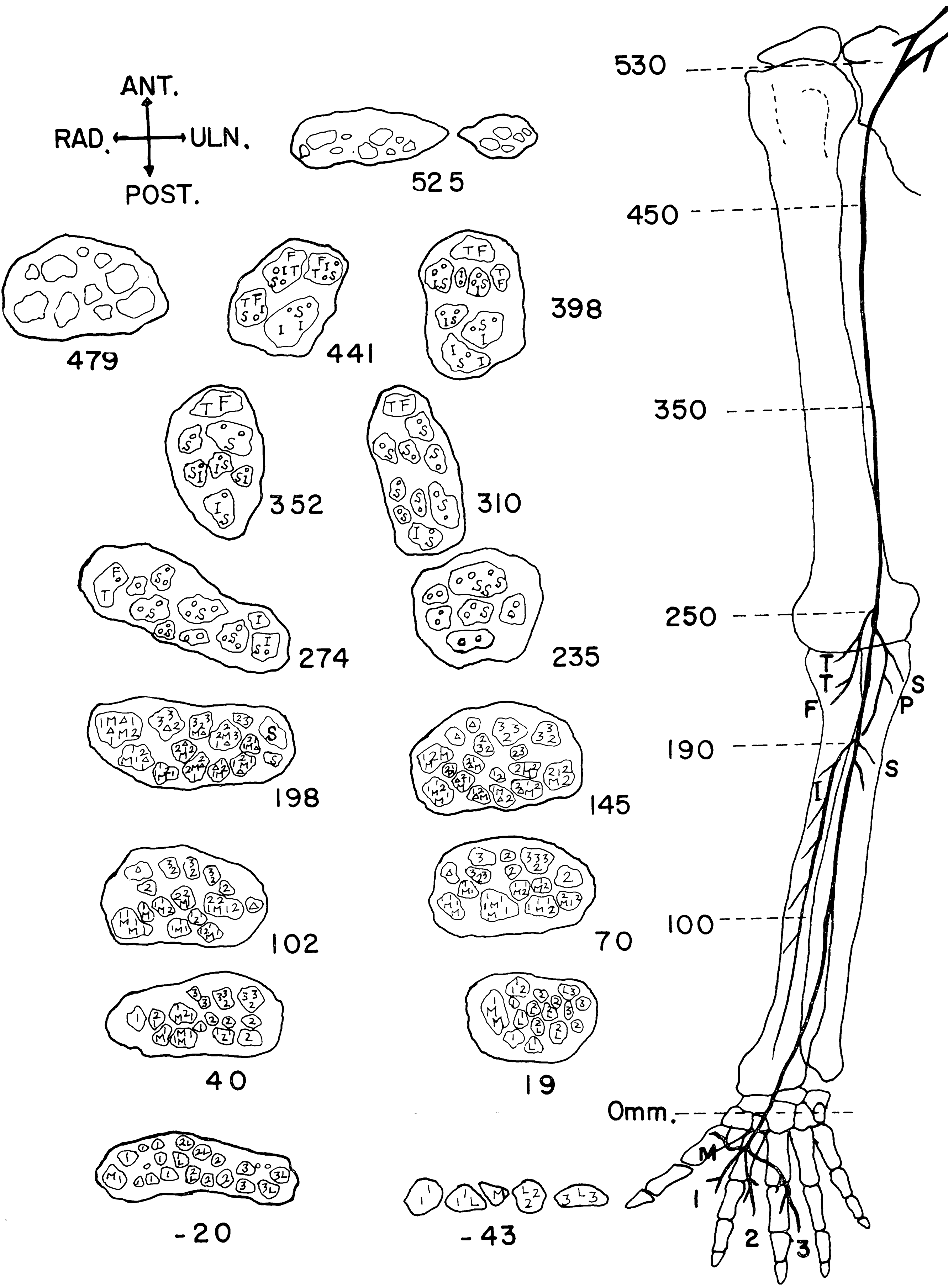

Fig. 4 The Intraneural Topographic Atlas (ITA) of the Median Nerve Right. Median Nerve Sections viewed from below
M; Thenar muscular fibers L; Lumbrical fibers 1; Cutaneous fibers from the thumb and 1st. Interspace 2; Cutaneous fibers from the 2nd. Interspace 3; Cutaneous fibers from the 3rd. Interspace P; Flexor digitorum profundus fibers C; Combined terminal muscular and cutaneous fibers above 212 mm. F; Flexor carpi radialis fibers T; Pronator teres fibers I; Anterior interosseus fibers △; Palamar cutaneous fibers S; Flexor digitorum sublimis fibers

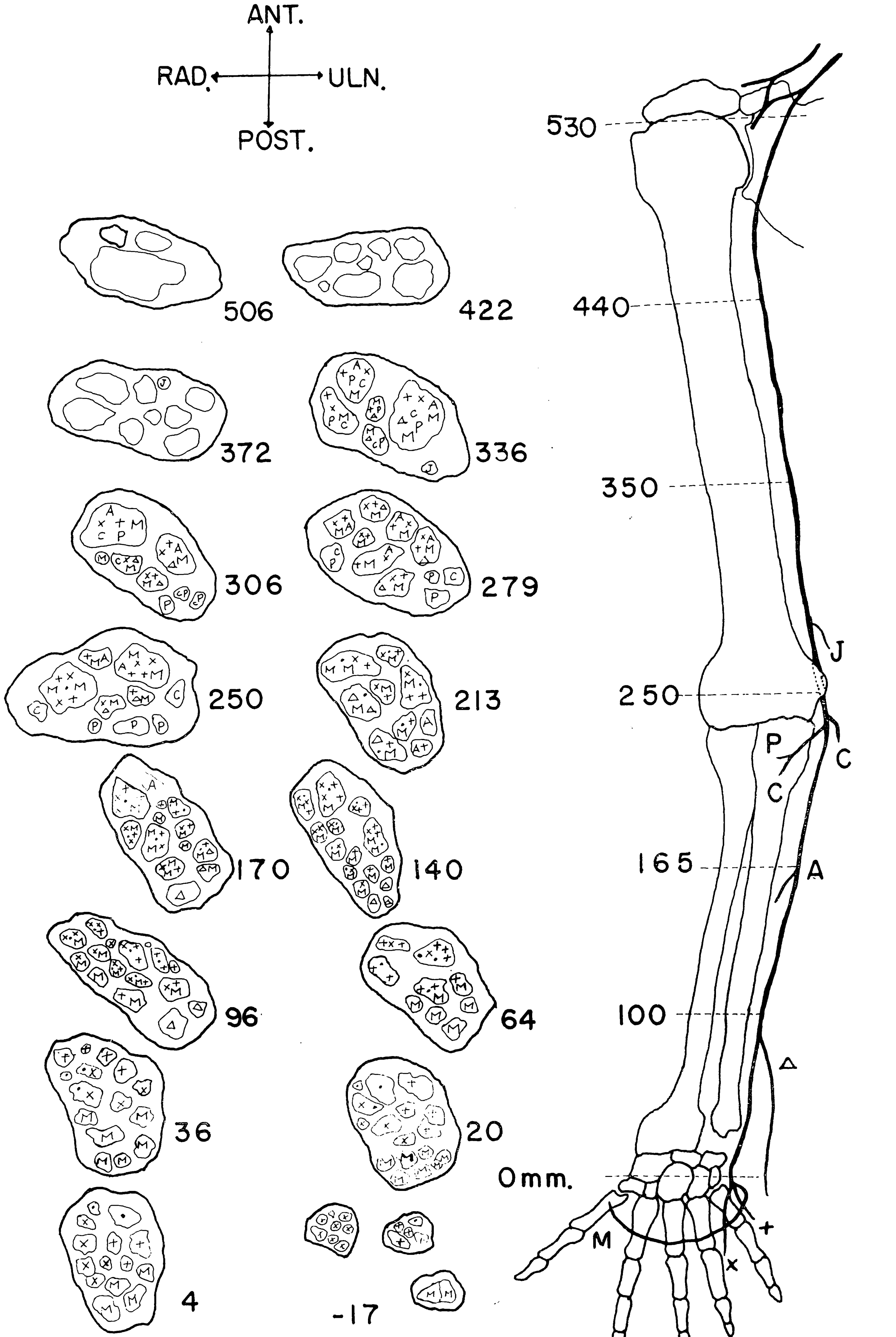

Fig. 5 The Intraneural Topographic Atlas (ITA) of the Ulnar Nerve. Right Ulnar Nerve Sections viewed from below
M; Deep (muscular) branch fibers ●; Palmaris brevis fibers X; Cutaneous fibers fromt he 4th Interspace +; Cutaneous fibers from the ulnar side of the little finger △; Dorsal cutaneous fibers of the hand A; Fibers to the ulnar artery
J; Fibers to the elbow joint C; Flexor carpi ulnaris fibers P; Flexor digitorum profundus fibers

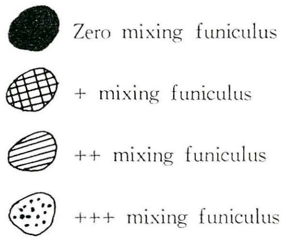

Fig. 6 The representation of 4 graded funiculi

Table 14 The frequency of change of funicular pattern in cutaneous and muscular branch fibers

Nerve	Length of independence	Group of fibers	Number of changes	Frequency of change/mm
Radial nerve	Right I 2～39mm	Cutaneous fibers Muscular fibers	1 19	0. 03 0. 51
	Right II 17～52mm	Cutaneous Muscular	5 82	0. 14 2. 34
	Left I 7～41mm	Cutaneous Muscular	3 20	0. 09 0. 59
Median nerve	Right I −30～5mm	Cutaneous Muscular	38 8	1. 50 0. 32
	Right II −13～15mm	Cutaneous Muscular	46 7	1. 64 0. 25
	Left I −31～15mm	Cutaneous Muscular	40 1	0. 87 0. 02
Ulnar nerve	Right I −2～48mm	Superficial Deep	54 25	1. 08 0. 50
	Right II −2～54mm	Superficial Deep	54 35	0. 98 0. 62
	Left I 19～42mm	Superficial Deep	15 3	0. 65 0. 13

Table 15 The frequency of change of funicular pattern in relation to site of median nerve trunk

Case	Right I	Right II	Left I
Low	1. 73 Changes/mm	1. 78	1. 50
Intermediate	0. 3	1. 07	1. 22
High	1. 22	0. 69	1. 00

Low : Below the branch to the flexor digitorum sublimis muscle
Intermediate : Between the branch to the flexor digitorum sublimis and ulnar nerve notch of humerus
High : Upper Arm

RESULTS

Radial Nerve

The level of this nerve trunk was measured from the lateral epicondyle of the humers. The levels of the division of the deep and superficial branches of the radial nerve are 2 mms. in the Right I specimen, 17 mms. in the Right II specimen and 7 mms. in the Left I specimen.

The radial nerve usually divides into its deep and superficial branches just above the lateral epicondyle of the humerus. The funiculi of the superficial branch are always located in the anterior parts of the radial nerve trunk near and at the site of division. The funiculi are usually only one or two in number and usually large in diameter. Often, another funiculus of smaller diameter in the anterior margin of the radial nerve could be found which is the branch to the brachioradialis muscle. The radial nerve trunk is oval in shape (the longer diameter is 2 to 2.5 times that of the shorter) at the division and it becomes more circular as it proceeds proximally. The longer diameter also changes direction from coronal to oblique (anterolateralposteromedial). The number of funiculi in each of the deep and superficial branches is five to ten in the distal radial nerve trunk but, become fewer proximally until a single funiculus is present at 64 mms. in the Right I, 68 mms. in the Right II and 71 mms. in the Left. I. The monofunicular bundle branch is 3 to 4 mms. in length and the number of funiculi is usually two or three at the junction of the middle and proximal third of the nerve.

In the middle third of the upper arm, the cross section is elliptical in shape, the longer diameter being in the coronal direction where the nerve is traversing the spiral groove. In the proximal third, the cross section changes to become more nearly circular and the number of funiculi increases to ten or twelve due to the emergence of the posterior cutaneous nerve of the forearm and the branch to the triceps.

THE COURSE AND FATE OF FIBERS IN EACH BRANCH OF THE RADIAL NERVE

1. The Fibers of the Superficial Branch (Fig. 7)

The levels of division are slightly different among the three specimens, but the bundle branches of the superficial ramus are always located in the anterior third of the elliptical nerve trunk in one to three funiculi. These funiculi are usually larger in diameter than those of the deep ramus. They can be differentiated because of their anterior location and low incidence of change of size or funicular pattern in that segment where there is no intermingling between motor and sensory funiculi. (2 to 39 mms. in Right I, 17 to 52 mms. in Right II, 7 to 41 mms. in Left I). In SUNDERLAND's case[32] this same tendency is noted over the segment between 0 and 48 mms. Above the 60 mms. the frequent intermingling of smaller funiculi makes it impossible to consider the localization of the deep and superficial rami fasciculi. Each nerve becomes monofunicular between 60 and 70 mms., indicating much more interlacing of nerve fibers in that funiculus.

2. The Fibers of the Deep Branch

In the Right II specimen, the terminal branches, i.e., the abductor pollicis longus branch, the extensor pollicis longus branch and the extensor indicis branch arise together at the level of -130 mms. The number of funiculi after juncture is two to five and they

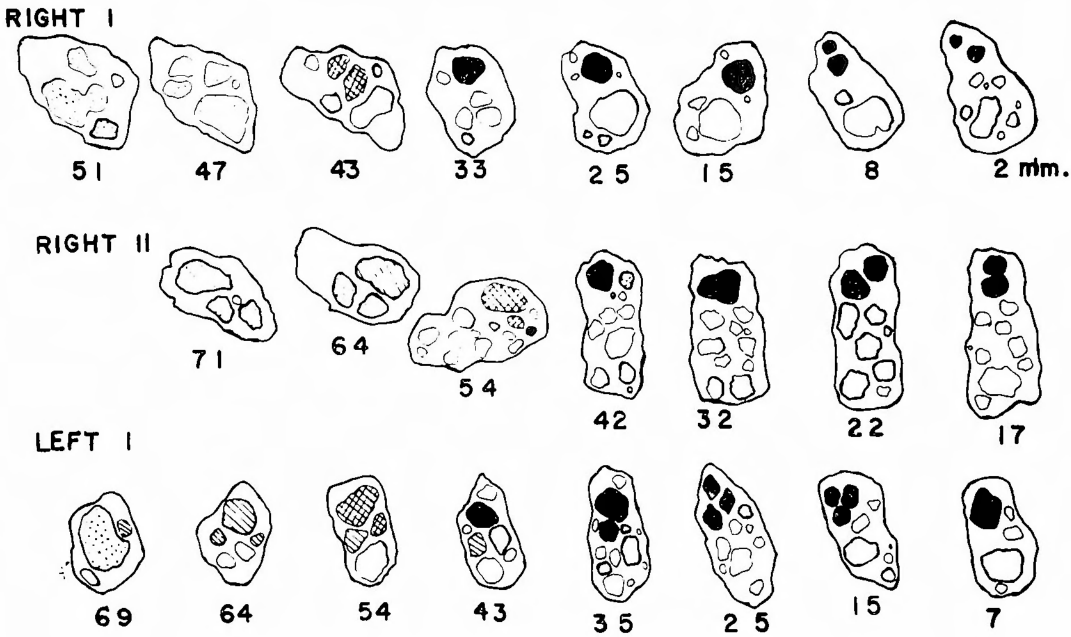

Fig. 7 The extent of mixing of the superficial ramus of the radial nerve

join into a monofuniculus at −80 mms. The end branch receives the extensor communis and extensor carpi ulnaris branches at 74 mms. These branches join into a monofuniculus at −53 mms. where the deep branch penetrates the belly of the supinator and here the cross section is flattened in shape. Above this level, the fibers of the five branches seem to be almost evenly distributed to each funiculus of the deep branch of the nerve. The levels of junction of the supinator muscle branch are slightly different among the three cases, but the quadrantal location of each appears to be similar (Table 1). There are usually two branches to the supinator muscle and they join together in the radial nerve trunk and are located between the superficial and deep ramus fibers for 20 to 30 mms., merging into the fibers of the deep branch. The fibers of the deep branch intermingle with the fibers of the superficial branch completely above the 70 mms. level.

Table 1 The supinator muscle branch

Case	Right I	Right II	Left I
Level of junction	−18mm	−10mm	−5mm
Quadrantal location at junction	Anteroulnar	Anteroulnar	Ulnar

3. The Fibers of the Nerve to the Extensor Carpi Radialis

In the three specimens, this particular nerve joins the deep branch just distal to its junction with the superficial branch (Table 2). The fibers of this nerve are usually located between the superficial and deep branch funiculi in the nerve trunks and soon join the fibers of the latter.

Table 2 The extensor carpi radialis muscle branch

Case	Right I	Right II	Left I
Level of junction	－15mm	－15mm	2mm
Quadrantal cocation at junction	Anteroradial	Posteroradial	Anteroradial

4. The Fibers of the Nerve to Brachioradialis Muscle

In each of the three specimens, this nerve joins the nerve trunk just proximal to its junction with the superficial branch (Table 3) and almost immediately intermingles with the fibers of the deep branch and the fibers of the nerve to extensor carpi radialis.

Table 3 The brachioradial muscle branch

Case	Right I	Right II	Left I
Level of junction	11mm, 20mm	38mm	23mm
Quadrantal location at junction	Radial	Posteroradial	Ulnar

5. The Articular Fibers

In each specimen, this nerve joins to the main nerve trunk and soon intermingles with the fibers of the deep branch (Table 4).

Table 4 The articular branch

Case	Right I	Right II	Left I
Level of junction	10mm	36mm	12mm
Quadrantal location at junction	Ulnar	Ulnar	Ulnar

6. The Fibers of the Posterior Cutanecous Nerve of the Forearm

This nerve merges into the medial margin of the elliptical nerve trunk at levels of 103 mms. in Right II and 139 mms. in Left I. In the first cadaver specimen, the posterior cutaneous nerve of the forearm and the branch to the triceps muscle of the right and the left side do not join, but in the Right II specimen, they join before merging into the radial nerve trunk. The fibers of the cutanoues nerve keep an independent location on the medial side of the nerve trunk for 40 to 50 mms. and then intermingle completely with the combined terminal and extensor fibers.

7. The Fibers of the Nerve to the Triceps Muscle

This branch joins the nerve trunk at different levels, i.e., 135 mms. in Right I, 135 mms. and 200 mms. in Right II and 193 and 196 mms. in Left I. The intermingling with combined terminal and extensor fibers does not become complete in the proximal portion of the nerve examined.

Median Merve

The levels (of section) of this nerve trunk were measured from the pisiform bone (Table 5). The terminal branches of the median nerve join in the proximal palm. The shape of the median nerve in this region is oval with the longer diameter four times that of the shorter and it keeps a horizontal oval shape throughout its course in the forearm. It receives the branch to the flexor digitorum sublimis muscle and the anterior interosseus nerve of the forearm on its posteromedial margin close to the elbow where it changes to an oblique oval with the longer diameter in the anterolateral and posteromedial directions.

Table 5 The levels of the median nerve trunk

Case	Right I	Right II	Left I
Junction of thenar muscle branch	-13mm	-36mm	-30mm
Median epicondyle of the humerus	201mm	250mm	207mm

It is almost circular in shape at the elbow and affter receiving the branches to the flexor digitorum profundus, flexor carpi radialis and pronator teres muscle, becomes oval again in the distal half of the arm. In the proximal third of the arm the longer diameter of the oval changes to the coronal direction and the nerve divides into medial and lateral cords at the level of the coracoid process. The number of funiculi in the median nerve trunk in the distal forearm is large, ranging from 20 to 40 with much interlacing offunicular pattern, but with a reduction in funiculi to between 5 and 10 as one follows the nerve proximally.

THE COURSE AND FATE OF THE FIBERS OF EACH BRANCH OF THE MEDIAN NERVE

1. The Fibers of the Terminal Digital Branches

The radial cutaneous fibers of the thumb, first interdigital space fibers, second interdigital space fibers and the third interdigital space fibers are arranged side by side in that order from the lateral side of the nerve. The nerves to the lumbricale join the interdigital space branches at 15 to 30 mms. distal to their junction with the main nerve. The four terminal cutaneous rami join together just before entering the main nerve. The fibers of the nerves to the lumbricale muscles intermingle with the cutaneous interdigital space fibers in the main median nerve trunk, but they do not mix with the thenar muscle branches until 30 mms. above the junction. Over a length of about 40 mms. above the junction, where the fibers of the branch to the thenarmuscle are beginning to move to the posterolateral quadrant, the shape of the nerve trunk becomes oval with the fibers of the third interdigital space being anteromedial, of the second space posteromedial, of the first space and thumb anterolateral in location. Thereafter, the third interdigital space fibers and the second interdigital space fibers begin to intermingle as do the first interdigital space fibers and the cutaneous fibers of the radial side of the thumb and the thenar muscle fibers. The former usually take up a location on the medial or anteromedial quadrant of the nerve and the latter on the lateral or posterolateral quadrant. They maintain such location in the proximal third of the forearm up to 140 mms. in Right I specimen and to 171 mms. in Left I specimen.

2. The Fibers of the Nerve to the Thenar Muscle (Fig. 8)

This nerve joins the terminal digital branches anteriorly between the first and second interdigital space fibers. The branch has six to nine funiculi before it merges into the nerve where they are rearranged into one large funiculus and a few smaller funiculi at the junction. In the median nerve trunk, the large funiculus is anterior in location for

20 mms. and moves to a lateral or posterolateral and later posterior portion. The funiculi usually begin to intermingle with the terminal branch fibers of the thumb and index finger a 30 mms. or so above the junction. The length of the segment over which the fibers of the branch of the thenar muscles exist in zero and + mixing funiculi (Fig. 6) is 48 mms. in Right I, 60 mms. in Right II, and 57 mms. in Left I. It is possible that the fibers of the thenar muscle branch take an independent course for 50 mms. or so above the junction. Their quadrantal location over this distance changes as the fibers shift. After joining with the fibers of the terminal digital branches, the funiculus which contains the thenar muscle fibers remains located on the posterolateral or posterior part of the nerve trunk in the distal and middle thirds of the forearm. In the proximal third of the forearm, the branches from the flexor muscles join the nerve trunk and the terminal branches of the median nerve intermingle completely. In the Right II specimen, 212 mms. is the level where each funiculus of the median nerve trunk appears to have similar constituent fibers.

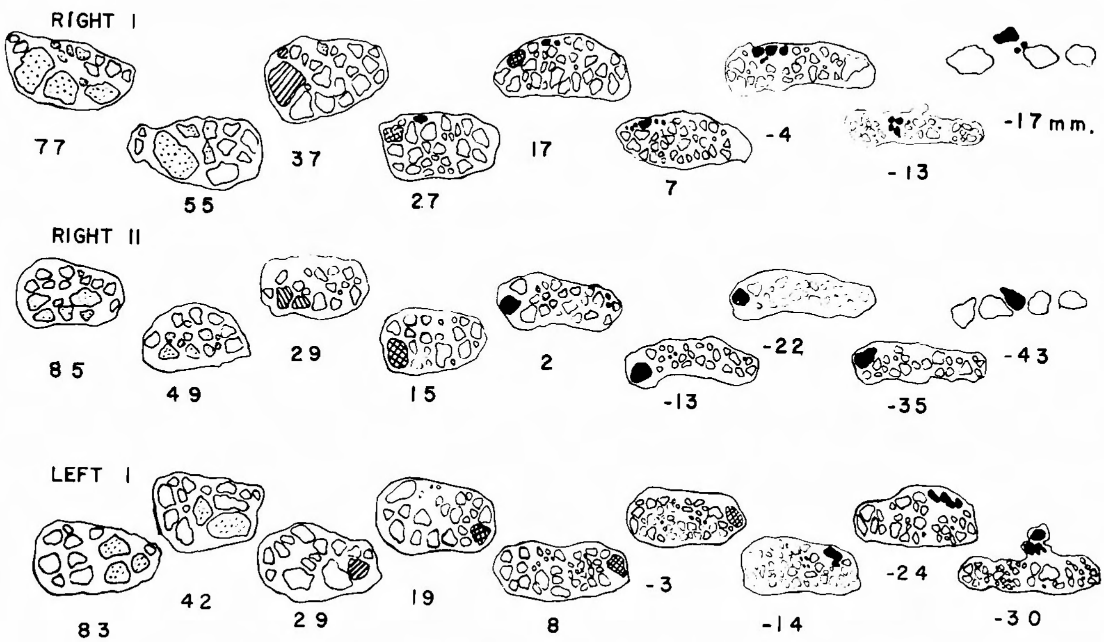

Fig. 8 The Extent of mixing of the thenar muscle fibers of the median nerve

3. The Fibers of the Nerve to the Flexor Digitorm Sublimis Muscle

This muscle has many branches and they merge into the medial portion of the nerve trunk at different levels (Table 6). The distal branch fibers, on merging into the trunk, often intermingle with the funiculi coming mainly from the second and third interdigital

Table 6 The flexor digitorum sublimis muscle branch

Case	Right I	Right II	Left I
Levels of merging	105mm	180mm	105mm
Into the nerve	210mm	180mm	
Trunk	245mm	192mm	202mm

space fibers. The proximal branch fibers usually join with the fibers of the muscle branch to pronator teres and then later on, intermingle with the combined terminal branch fibers in the upper arm.

4. The Fibers of the Nerve to the Pronator Teres Muscle

The level and quadrantal location of the fibers of this nerve are slightly different among the three specimens (Table 7). In the Right II specimen, this branch joins the nerve to the flexor carpi radialis before joining the nerve trunk. This combined branch then joins with the flexor digitorum sublimis branch and or the flexor carpi radialis branch to take up a location in the anterolateral portion for some distance without intermingling with the combined terminal branch fibers.

Table 7 The pronator teres muscle branch

Case	Right I	Right II	Left I
Level of junction	204mm	254mm	190mm
Quadrantal location at junction	Anteroulnar	Anteroulnar	Anteroradial
Length of independence	152mm	158mm	168mm

5. The Fibers of the Nerve to the Flexor Carpi Radialis Muscle

The level at which these fibers merge into the main trunk are different among the three cases (Table 8). In the Right I specimen, the fibers soon join with those of the nerve to the flexor digitorum profundus.

Table 8 The flexor carpi radialis muscle branch

Case	Right I	Right II	Left I
Level of junction	210mm	254mm	200mm
Quadrantal location at junction	Post	Anteroradial	Anteroulnar

6. The Fibers of the Nerve to the Flexor Digitorum Profunds Muscle

In the Right I and Left I specimens, there are distal and proximal branches and the former merge into the anterior interosseus nerve of the forearm (Table 9). The levels of branching and quadrantal locations are quite different among them.

Table 9 The flexor digitorum profundus muscle branch

Case	Right I	Right II	Left I
Level of junction of distal branch	180mm	128mm	153mm
Level of junction of proximal branch	210mm		198mm
Quadrantal location at junction	Posterior	Ulnar	Posteroradial

7. The Fibers of the Anterior Interosseus Nerve of the Forearm

This nerve consists of the branches from the pronator quadrantus, flexor pollicis longus and the deep and superficial long finger flexors. The numbers and levels of merging of the above branches are different among three (Table 10).

Table 10 The anterior antebrachii interosseus nerve

Case	Right I	Right II	Left I
Flexor pollicis longus	176mm	75mm 105mm	153mm
Flexor digitorum profundus	180mm	128mm 145mm	153mm
Flexor digitorum sublimis		170mm 180mm	192mm

It should be note that the Right II specimen has two distal branches but no proximal branch, whereas Right I has a proximal branch just above the elbow. The anterior interosseus nerve joins to the median nerve trunk on the posteromedial quadrant at different levels (190 mms in Right I, 241 mms. in Right II and 214 mms. in Left I) and then, in the distal third of the upper arm, begins to intermingle partly with the combined fibers. After this intermingling, the anterior interosseus fibers take up their location in the posterior half of the nerve trunk up to the proximal third of the arm when they are distributed to all of the funiculi of the nerve trunk.

The Ulnar Nerve

The levels of this nerve trunk are measured from the tip of the pisiform bone which can be felt at the base of the hypothenar eminence (Table 11). The terminal deep and superficial branches join together at the level of the pisiform bone, although this junction is more proximal in the Left I specimen despite the coursing of the branches side by side from the region of the pisiform bone. The section of the nerve trunk is oval with its greatest diameter in the anteroposterior direction at that level and changes to an oblique ellipse with the longer diameter running from the anterolateral to the posteromedial aspect of the nerve in the middle of the forearm where the dorsal cutaneous branch to the hand joins the main nerve trunk. More proximally in the upper third of the forearm, the trunk becomes more circular without obliquity of its long diameter by the time it reaches the epicondular groove. In the upper arm it is usually obliquely oval and changes to a horizontal oval in its proximal third.

Table 11 The Level of the ulnar nerve trunk

Case	Right I	Right II	Left I
Junction of deep and superficial branch	−2mm	−2mm	19mm
Level of junction of dorsal cutaneous branch of hand	85mm	80mm	73mm
Ulnar of nerve notch in humerus	228mm	254mm	229mm

1. The Superficial Branch of the Ulnar Nerve

This branch consists of the fibers from the fourth interdigital space, the ulnar side of the little finger and the palmaris brevis muscle. The palmaris brevis muscle branch fibers run with the fibers from the ulnar side of the little finger initially but intermingle with the fourth interspace fibers a a level of 12 mms. and later also with the fibers from the little finger.

At the wrist, the fourth interspace fibers are located anterolaterally and the little finger fibers anteromedially. Both branches contain five to seven small funiculi and follow their individual course for some distance (17 mms. in Right I, 14 mms. in Right II and 33 mms. in Left I) before joining abruptly into a single funiculus.

2. The Deep Branch of the Ulnar Nerve (Fig. 9)

This branch consists of the fibers from the abductor pollicis, dorsal and palmar interossei, lumbricales, adductor digiti quinti, opponens and flexor muscles. The first three of them make up a large diameter funiculus near the pisiform bone and the latter three, a smaller funiculus. Both funiculi are joined togethe near the junction with the superficial branch and the deep branch fibers take up a position on the posteromedial aspect for a distance of 5 to 10 mms., then moving posteriorly and remaining in this location for a further length of the nerve (Right I from −2 to 48 mms., Right II from −2 to 54 mms., Left I from 19 to 42mms.) without any intercommunication with the fibers of the superficial branch.

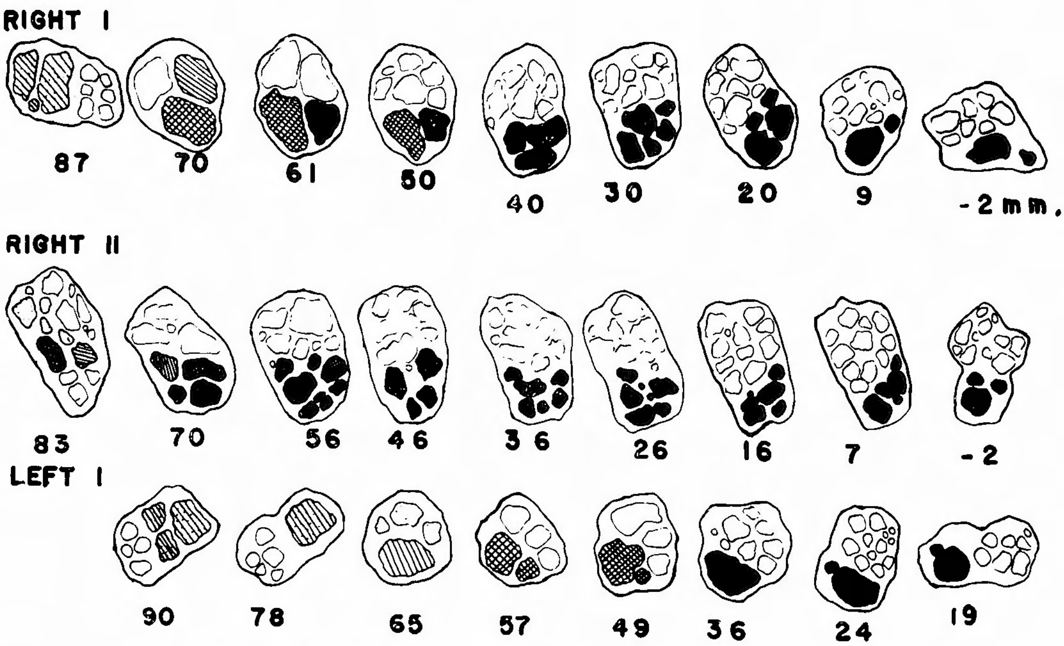

Fig. 9 The extent of mixing of the deep ramus fibers of the ulnar nerve

The fibers of the deep branch keep this posterior location in the Group A or Group B funiculi even further proximally (up to 64 mms. in Right I, to 70 mms. in Right II. and to 62 mms. in Left I). After joining with the dorsal cutaneous fibers of the hand, the deep branch fibers are located between the dorsal cunaneous fibers and the superficial branch fibers but soon begin to intermingle with each other.

In the proximal third of the forearm, the deep and superficial branch fibers have so intermingled that it is difficult to trace them proximally.

3. The Fibers of the Dorsal Cutaneous Nerve of the Hand (Fig. 10)

The levels of joining and the number of funiculi of these fibers are slightly different among the different specimens but they merge into the posteromedial margin of the nerve trunk and follow an independent course for quite a distance (105 mms. in Right I, 84 mms. in Right II and 103 mms. in Left I).

They remain in a posteromedial location in + mixing funiculi further proximally for 30 to 50 mms., but the joining of new branch fibers from the ulnar artery, flexor carpi ulnaris muscle and the flexor digitorumprofundus muscle with them, makes it impossible to identify the cutaneous nerve fibers.

These fibers are surrounded by a fairly thick perineurium over the length for which they are independent and this helps to differentiate them from the terminal branch fibers.

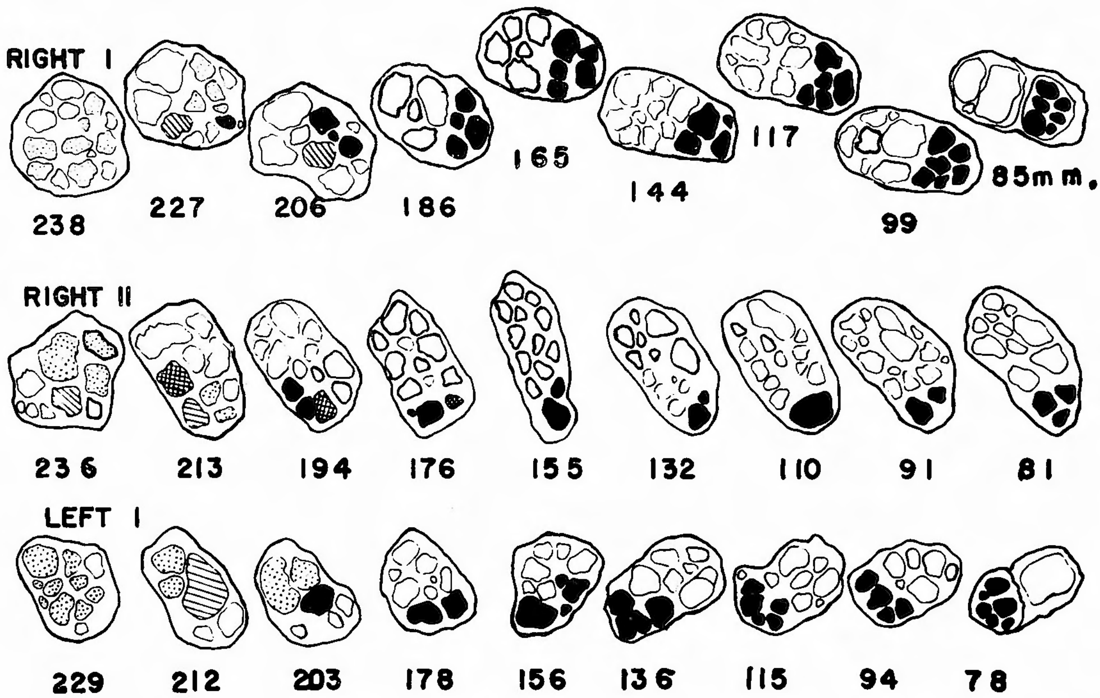

Fig. 10 The extent of mixing of the dorsal cutaneous fibers of the hand of the ulnar nerve

4. Fibers of the Nerve to the Ulnar Artery

These branches merge into the anteromedial margin of the nerve trunk at 165 mms. in Right II and 115 mms. in Left I. They do not course independently, although located mainly in the anterior half of the nerve trunk.

5. The Nerves to the Flexor Digitorum Profundus and Flexor Carpi Ulnaris

Theso flexor muscle nerves join to the main nerve trunk at the same levels, but at different locations (Table 12). On occasions, they may join together (Right II case) before merging into the main nerve trunk. They begin to intercommunicate at 40 mms. or so after they merge and take up a position in the posterior half of the nerve trunk mixing with other fibers at random. The only characteristic of these fibers is the frequent changing of position in realtion to the nerve trunk before the intercommunication.

6. Fibers of Articular Branches to the Elbow

The level at which these fibers join the main trunk and their quadrantal location,

Table 12 The flexor digitorum profundus and flexor carpi ulnaris branch

Case	Right I	Right II	Left I
Level of junction of Flex. Dig. Prof.	195mm	232mm	188mm
Quadrantal location at junction	Posteroulnar	Posteroradial	Posteroradial
Level of junction of Flex. Carp. Uln.	195mm	236mm	188mm
Quadrantal Location at junction	Anterior	Posteroulnar	Anteroulnar

Table 13 The branch to blbow joint

Case	Right I	Right II	Left I
Level of junction	217mm	228mm	300mm
Quadrantal location at junction	Posteroradial	Posteroulnar	Ulnar

have no special features (Table 13). These fibers cannot be traced very far proximally due to their small number and early intermingling with other fibers.

DISCUSSION

In this paper, for the purpose of clinical use, intraneural topography of the peripheral nerves of the upper extremity was examined in three Japanese specimens. The results obtained should be considered from the clinical viewpoint.

1. Radial Nerve

In the radial nerve injury, it should be kent in mind that, from the viewpoint of intraneural topography, the funiculi of the superficial branch are located in the anterior third of the elliptical radial nerve trunk for 4 to 5cms. above the division. On the basis of this fact, for improvement on the result of the surgical suture between the proximal radial nerve trunk and the deep branch, it may be reasonable to exclude the superficial branch fibers of less clinical importance from the proximal main trunk[31)].

We can also expect to find the bundle branches of the posterior cutaneous nerve of the forearm and the branch to the triceps muscle in the medial or lateral margin of the elliptical nerve trunk in the proximal third of the upper arm.

The incidence of radial nerve injury is high in the distal half of the upper arm and the results of operative suture at this level are much better than at other levels (Zachary, 40). This may be due to:

(i) The number of funiculi is small and the diameter of the funiculi is big in this segment, so that the interfascicular tissue is small and it will lessen the chance of migration of growing axon into the interfascicular tissue.

(ii) The distance to the muscular end plate is short.

2. Median Nerve

In comparing the recovery of the thenar muscle function after median nerve suture in ZACHARY's cases where both low and intermediate sutures have been performed, there is only 5% superiority in the low suture. It is supposed that the large number of funiculi in this segment will increase chances of migration of the growing axons into the interfascicular tissue. On the other hand, this seems to be a minimal difference considering the greater difference of 10% between intermediate and high site sutures. The poor results of epineural nerve suture might be due to an imprecise apposition of thenar muscle branch funiculi for lack of knowledge of the intraneural topogrphy. There must be a chance for improvement in the results of low site suture of the median nerve if funicular suture is carried out with an exact technique on the basis of characteristic intraneural topography.

The thenar muscle branch fibers funiculus can be identifid in the distal part of the nerve trunk because of the large diameter and its location. Sometimes, they may not make up a large funiculus. It should be recalled that the thenar muscle branch fibers take a posterolateral or posterior location in the nerve trunk in the distal and middle third of the forearm. Aschan and MOBERG[2] determined an extent of lesion according to SUNDERLAND's description and also by ninhydrin test in cases of partial lesion of the median and ulnar nerve.

As for the terminal cutaneous and muscular fibers, each funiculus appears to have the same constituent fibers just below the elbow. After joining of the proximal flexor fibers, these fibers are distributed evenly throughout the nerve in the proximal third of the upper arm (345 mms. in Right I, 445 mms. in Right II, and 356 mms. in Left I).

3. Ulnar Nerve

The ulnar nerve has the most complicated and characteristic funicular pattern especially in the forearm. Poor results of surgical repair of this nerve is mainly due to this anatomical structure which makes it impossible to obtain correct apposition of the corresponding funicular cut ends.

The characteristic location of the deep branch fibers and the fibers of the dorsal cutaneous nerve of the hand in the forearm should be kept in mind at the time of funicular suture. A precise apposition of the corresponding funicular cut ends containing the deep fibers in the distal third of the forearm may result in good recovery of intrinsic muscle function and moreover, funicular exclusion of the dorsal cutaneous fibers will be effective to obtain recovery of motor function. Furthermore, identification of the thick sheath of the dorsal cutaneous fibers funiculus will help to maintain the exact rotation of the nerve.

In case of partial sensory loss in the ulnar nerve distribution, the separate location of the fourth interspace fibers and fibers from the ulnar side of the little finger where these join near the wrist, may help to delineate the precise site of the lesion. In the upper arm however, there is no characteristic location of each of these fibers as seen in the forearm. This intercommunication of the branch fibers is completely established in the distal third of the upper arm (260 mms. in Right I and Left I and 337 mms. in Right II) and the author could not trace them further proximally. They make up into a large monofuniculus in the Right I and Left I for a certain length, but in the Right I regain a number of funiculi, five to ten in number, for the full length of the nerve.

4. Change in Funicular Pattern

The frequency of the change in the funicular pattern was compared in relation to the different nerves, different individuals, different sides, cutaneous and muscular rami and the levels in the nerve trunk. It showed that:

(a) The difference due to individuals, sides and different nerves is not significant (Table 14).

(b) The frequency of change in funicular pattern has not definite reiationship to the functional classification of the branch fibers (abmitting that the terminal cutaneous fibers of the median nerve contain the lumbricale muscle fibers and the superficial branch of the ulnar nerve contain the palmaris brevis muscle fibers (Table 14).

(c) The frequency of change decreases proximally in the median nerve trunk which is contrary to the report of Lehmann (Table 15).

(d) The frequency seems to be related to the numbe of funiculi rather than the numbe of nerve fibers.

5. What Features Influence the Quadrantal Location of the Nerve Fibers?

In the median nerve, the branches to flexor carpi radialis and pronator teres lie side by side in the arm and the segmental innervation of both is noted to be C_6. The thenar muscle branch fibers ($C_{6,7}$) intermingle with the thumb (C_6) and interdigital space fibers (C_7) in the proximal and middle third of the forearm.

In the ulnar nerve, the flexor carpi ulnaris branch (C_8, T_1) and the flexor digitorum profundus branch (C_8, T_1) join together before the combined branch joins to the nerve trunk. The branch to palmaris brevis (C_8, T_1) first joins with the fourth interdigital space fibers (C_8) even though these lie on the medial side of the branch to the little finger (T_1).

These findings suggest that segmental innervation may have some influenc on the arrangement of nerve fibers in the nerve trunk and this thinking corresponds to the report of ARAKAWA.

6. The Change in the Position of the Funiculi in the Nerve Trunk

The role of intricate internal nerve plexuses was discussed by KRAUS and INGHAM[20] and they grouped them into three types:

(i) A plexus formed by anastomses between the nerve fibers of the anterior and posterior root origin.

(ii) A plexus formed by intermingling of the nerve fibers from different segmental origins.

(iii) A plexus to rearrange the sensory fibers of different modalities to conform to the regular arrangement of ascending tracts to the spinal cord.

When following the change in funicular pattern, the change in the position of the funiculi on the surface of the nerve trunk was found to be greater than change in the funiculi in the center in those segments close to the origin of branches.

The reason for such changes in position were conjectured by their behaviour as follows:

(i) To reach a certain quadrantal location, e.g., the thenar muscle branch fibers of the median nerve move from the anterior surface to the lateral surface, then posterolateral and then posterior where they remain for a considerable legth.

(ii) To intercommunicate with the fibers of other funiculi, e.g., in the Right II case, the pronator teres branch fibers merge into the anterolateral surface of the nerve trunk, and then move medially to intermingle with the fibers in the flexor carpi radialis, later returning to the anterolateral aspect of the nerve.

(iii) Changes in pesition, though the reason for which is sometimes unclear, is usually considered as a preparatory movement in the formation of plexuses, e.g., the flexor muscle fibers which join to the ulnar nerve at the elbow show considerable change in position without any intercommunication, but they intermingle with the fibers of the mixed terminal branches after a while.

7. Considering that there are a number of variations in the branching, shape and innervation of the muscles by the peripheral nerves from person to person, it is difficult to establish a completely universal funicular pattern. It is hoped that this investigation will contribute to more precise estimation of peripheral nerve injuries and improvements in the results of nerve suture.

SUMMARY

1. The funicular pattern of peripheral nerves in the upper extremity of three adult Japanese limbs, has been described and an intraneural topographic atlas was drawn.

2. The possibility of fixed quadrantal locations of the individual branch fibers has been discussed and characteristic locations were identified as follows :

(a) The fibers of the superficial branch of the radial nerve are situated anteriorly for a distance of 40 mms. or so above the junction with the deep branch.

(b) The thenar muscle branch fibers of the median nerve are situated posterolaterally in the middle and distal third of the forearm.

(c) The cutaneous terminal branch of the median nerve is situated separately in the distal and middle third of the forearm.

(d) The fibers of the deep branch of the ulnar nerve remain in a posterior location in the distal third of the forarm.

(e) The dorsal cutaneous branch to the hand of the ulnar nerve can be clearly differentiated in the posteromedial quadrant in the middle third of the forearm.

3. The distance over which such characteristic locations exist makes funicular suture feasible. Where there are many funiculi such as in the median and ulnar nervein the proximal forearm, funicular suture may be carried out by reference to the terminal muscular branch funiculi if these can be identified and a standard perineural suture performed with the rest of the nerve.

4. The frequency of the change in the funicular pattern was analyzed and it was noted that the frequency was usually greater distally than proximally.

5. The possible role of the segmental innervation on the arrangement of nerve fibers was discussed.

6. The shifting of the funicular patterns in the cross sections has been discussed and reasons for this postulated.

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和文抄録

日本人末梢神経の Funicular Pattern

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末梢神経損傷の診断と治療にあたつて尚解明向上されるべき点は多々考えられるが,末梢神経横断面に於ける構造と機能の局在性についてはこれまで Sunderland の研究以外には特記すべきものは見当らない.伊藤らは手術用顕微鏡下に神経束を縫合する Funicular Suture の実験的研究を行ないその優秀性をたしかめた.Funicular Suture を臨床的に行なう際 Funicular Pattern の決定は非常に重要であるが,Sunderland の Atlas によつても各神経線維の機能的局在性の程度及びその範囲は明瞭を欠き臨床的には応用し難く,かかる目的を充足する Atlas の出現が望ましい.

ここに著者は日本人屍体3上肢の橈骨,正中,尺骨神経を細小枝に至る迄精細に解剖し神経断面の位置付けを注意して行なつた後採取した神経幹の連続切片を作り,H・E染色標本を中枢側より検鏡することにより Intraneural Topographic Atlas (ITA) を作製した.これによるとその複雑な Plexus 影成のため単一 Funiculus の機能的特性を決定することは必ずしも容易ではないが,詳細に観察すると Plexus 影成は神経断面の全巾にわたつているものは少なく,多くの場合同一成分又は近似成分の Funiculus が断面の限局された小部分において交錯するものであつた.この傾向は神経枝分岐部附近に於て著しくみられた.更に Funicular Suture 及び Funicular Exclusion に際してその神経幹内局在性が重要と思われる橈骨神経浅枝,正中神経拇指球筋枝,尺骨神経深枝及び手背皮枝神経線維の神経束内混在度を追求した.これらの結果下記の諸神経枝神経線維の末梢神経幹内における局在性について確かめることが出来た.

1. 橈骨神経浅枝神経線維は浅深枝分岐部より高位約40mmの範囲では橈骨神経幹断面の前部に位置していた.

2. 正中神経拇指球枝神経線維は前腕中1/3及び遠位1/3の範囲では正中神経幹断面の後外部に位置していた.

3. 拇指,示指,中指への知覚枝である正中神経終末枝神経線維は前腕中1/3及び遠位1/3の範囲では各分枝が神経幹内の異なつた位置をとつていた.

4. 尺骨神経深枝神経線維は前腕遠位1/3の範囲では神経幹断面の後部に位置していた.

5. 尺骨神経手背皮枝神経線経は前腕中1/3の範囲では神経幹断面の後内側部にはつきり分離した位置をとつていた.