Chapter 1

ANATOMY OF THE BRACHIAL PLEXUS

Hideo Kawai

The brachial plexus is formed from five spinal nerves: C5, C6, C7, C8 and T1. Each spinal nerve (plexus root) is the result of an intramedullary mixture of motor (ventral) and sensory (dorsal) roots (Fig. 1.1). At the spinal cord level, the ventral roots are numerous and apparent, but the dorsal roots are hidden in the collateral dorsal groove and are difficult to count. The length of nerve roots range from 10 mm to 168 mm, the shortest being the cervical roots and the longest the sacral, based on Sunderland (1978). The nerve root lengths in the spinal canal to compose the brachial plexus are given in Table 1.1. Soulié (1899) measured along the upper border of the root and Hovelacque (1927) along the lower border, while Sunderland (1976) along both borders. Short nerve roots suffer earlier and fail structurally before the long roots. Therefore, the short spinal nerve roots of the brachial plexus are particularly vulnerable to traction deformation. At the level of the perforation of the dura mater, the roots gather and organize in bundles, varying in number between two and six according to the level (Fig. 1.2). At the origin of the spinal nerves, the motor and sensory fibers are mixed as a result of the convergence of the ventral and dorsal roots. After the mixing of the ventral and dorsal roots, it is impossible to determine the topography of the motor and sensory fibers on the histological section.

The number of fascicles increases from the proximal to the distal portion of the plexus. The diameter of the fascicles progresses inversely, with large fascicles in the proximal part and small fascicles in the distal part (Table 1.2).

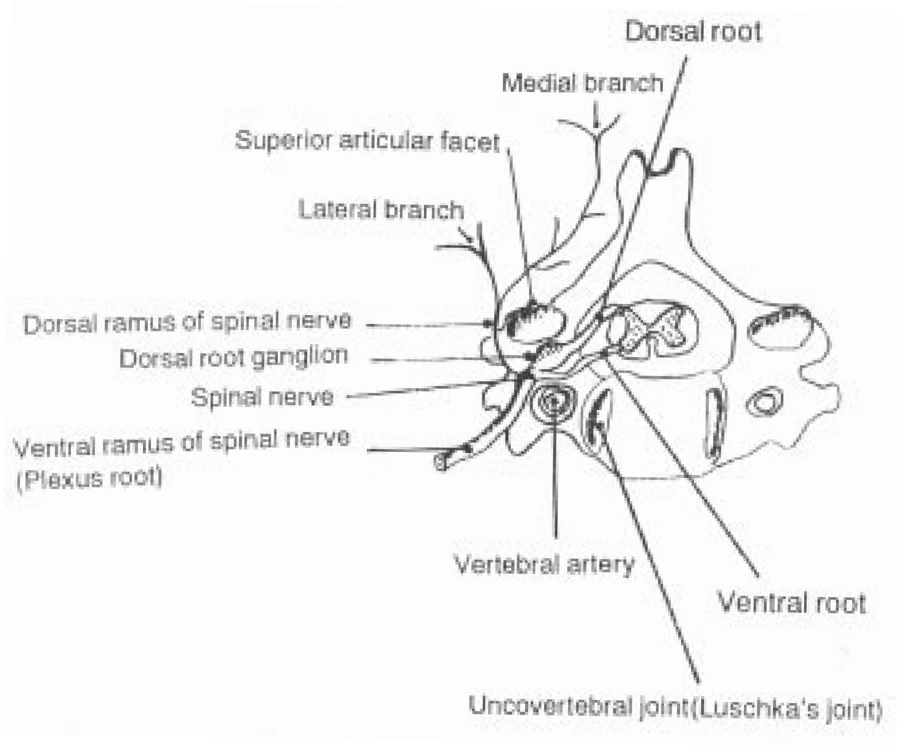

Fig. 1.1 The spinal nerve is formed from ventral and dorsal roots. (Reproduced with permission from Agur AMR: *Grant's Atlas of Anatomy*, 9th ed., p. 556, 1991).

Table 1.1 Nerve Root Length (mm)

Nerve Root	Testut and Latarjet (1949)	Soulié (1899)	Hovelacque (1927)	Sunderland (1976)	
				Upper Border	Lower Border
C5	26	20	10	15	11
C6		23	11	15	11
C7		25	11	15	11
C8		27	14	17	12
T1	33	29	16	25	17

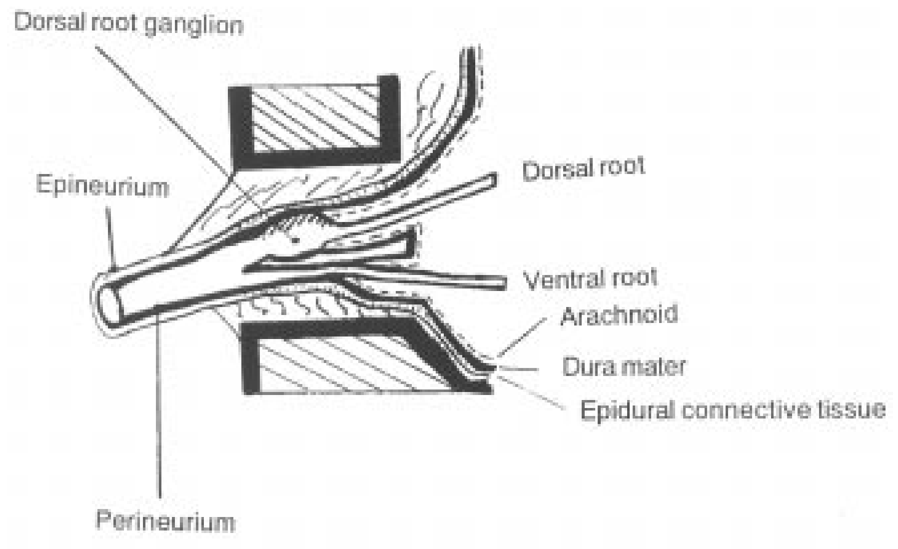

Fig. 1.2 The meningeal-neural relations in the intervertebral foramen. Dura becomes the perineurium, and epidural connective tissue on the external surface of the dura is continuous with the epineurium of the spinal nerve. (From Suderland SS: *Nerves and Nerve Injuries*. Edinburgh, Churchill Livingstone, p. 856, 1978).

Table 1.2 Number of Fascicles and Percentage of Diameter Measuring between 250 and 1000 μm in 21 Brachial Plexus, based on Bonnel (1984)

	Average Number of Fascicles (Range)	Diameter between 250 and 1000 μm (%)
C5	2	49
C6	4	51
C7	7	67
C8	4	43
T1	2	42
Upper trunk	8(3–12)	64
Middle trunk	10(4–14)	67
Lower trunk	11(4–17)	61
Lateral cord	15(6–26)	80
Medial cord	13(5–-24)	64
Posterior cord	18(10–23)	81

Although the denticulate ligament stabilizes the spinal cord and reduces mechanical trauma to the ventral and dorsal roots, the major point of fixation is situated in the intervertebral foramen, where the dura mater adheres to the periosteum and contributes to the formation of the perineurium. The lateral portion of the transverse processes is a final anchorage. A few millimeters from its emergence at the intervertebral foramen, a dorsal ramus that innervates the spinal muscles is divided from the spinal nerve. There is a characteristic change in the direction of roots and spinal nerves where the intermediate portion tends to become horizontal in the transverse canal and then turns downward in the extravertebral portion. There are two slopes, one at the penetrating site of the dura mater, and the other external to the intertransverse canal. This Z-arrangement zone is vulnerable in traumatic lesions. The spinal nerves (plexus roots) have an oblique angle to a vertical axis in the frontal plane that decreases from 138° for C5, to 123° for C6, 114° for C7, 100° for C8, and finally 85° for T1 (Fig. 1.3). It appears that the upper roots should be contrasted with the lower roots by their relationships as well as by their means of fixation. The former are connected to the cervical spine by transversoradicular ligaments. This may explain why the avulsions are more frequent in the lower roots compared with the upper roots.

C5 and C6 unite to form the upper trunk, C7 continues to the middle trunk, and C8 and T1 make up the lower trunk (Fig. 1.4).

Each trunk divides to form the cords. The anterior divisions of the upper and middle trunks give rise to the lateral cord, the anterior division of the lower trunk gives rise to medial cord, while the postrior divisions of the upper, middle and lower trunks result in the posterior cord. The average length of the spinal nerves, from the exit of the intervertebral foramen to the point of origin of the trunk, varies: 43 mm for C5, 50 mm for C6, 58 mm for C7, 34 mm for C8, and 29 mm for T1. The length of the cords is also variable: the average length being 60 mm (range, 40–80 mm) for the lateral cord, and 50 mm (range, 34–78 mm) for the medial cord. A posterior cord is discrete in 25%, whereas in 71%, the posterior cord is not common

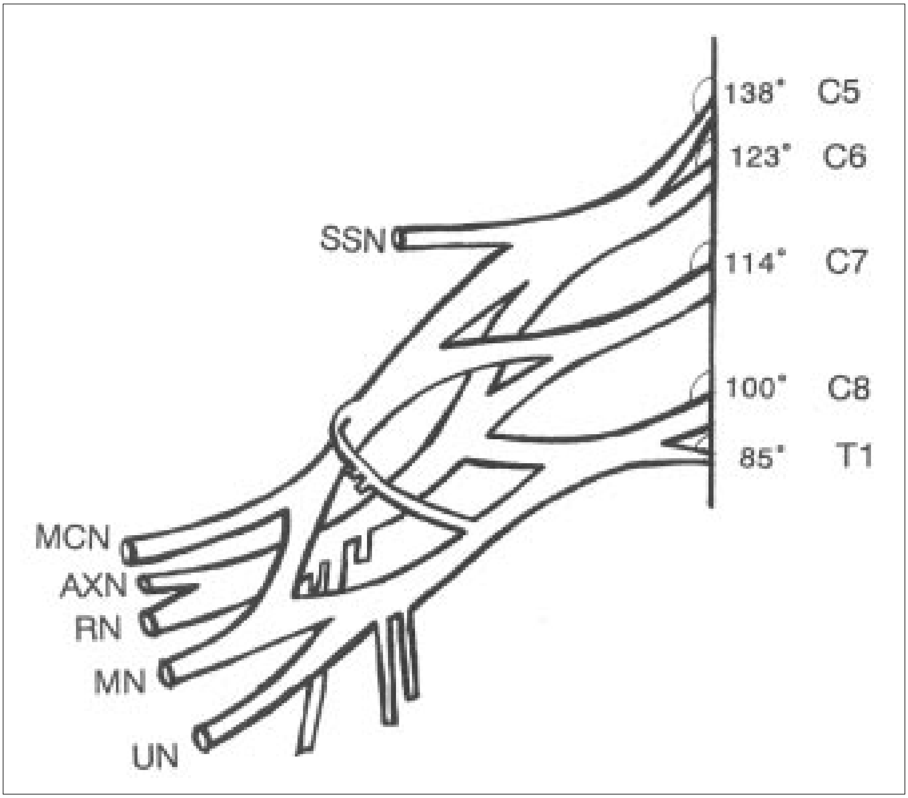

Fig. 1.3 The angle of the plexus root to a vertical axis in the frontal plane. SSN, suprascapular nerve; MCN, musculocutaneous nerve; AXN, axillary nerve; RN, radial nerve; MN, median nerve; UN, ulnar nerve.

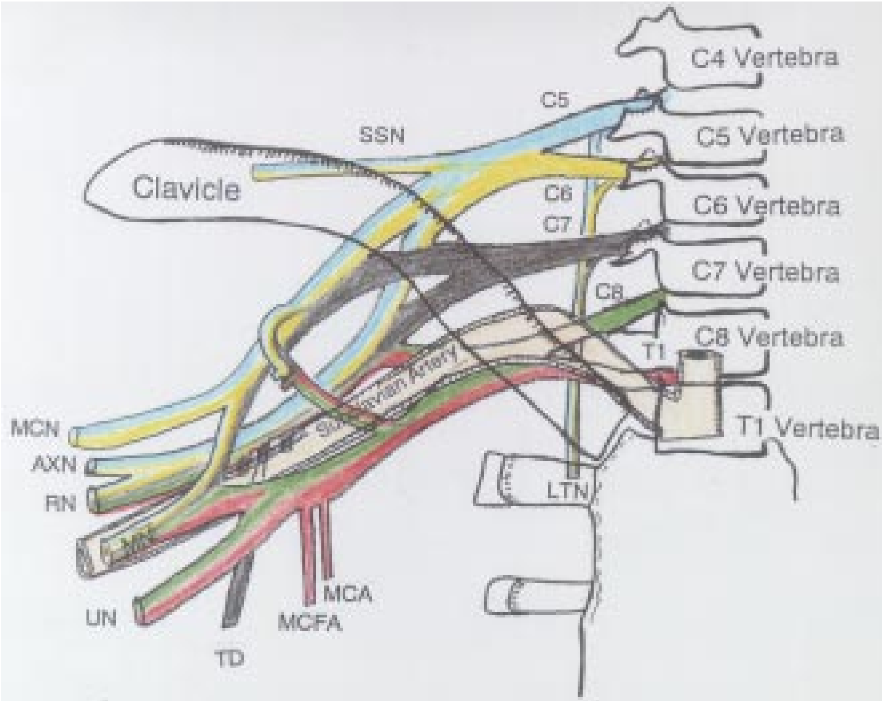

Fig. 1.4 The brachial plexus. SSN, suprascapular nerve; MCN, musculocutaneous nerve; AXN, axillary nerve; RN, radial nerve; MN, median nerve; UN, ulnar nerve; TD, thoracodorsal nerve; MCNF, medial cutaneous nerve of forearm; MCA, medial cutaneous nerve of arm; LTN, long thoracic nerve.

but diverge, such as the axillary and subscapular nerves, thoracodorsal nerve, long thoracic nerve, and radial nerve. In 4%, a posterior division continues on directly as the radial nerve.

The origin of the nerve to the serratus anterior muscle also varies. It arises directly from the nerve roots but does not pass between the scalenus anterior and scalenus medius muscles. Instead, it either traverses the scalenus medius muscle or goes between the scalenus medius and scalenus posterior muscles. The origin of occurrence is more frequently C5, C6 and C7, and less frequently C4. The suprascapular nerve is always large in diameter and is the first branch in the plexus. The origin is often C5 and occasionally C5 and C6. The subscapular nerves arise from C5 and C6. The nerve to the teres major muscle arises from C5 and C6, and occasionally C7. The musculocutaneous nerve is formed from C5 and C6 with minor participation of C7. The axillary nerve arises from C5, C6 and less frequently C7. The ulnar nerve arises from C7, C8 and T1. The brachial cutaneous nerve arises from T1. The radial nerve arises from C5, C6, C7, C8 and T1. The median nerve arises from C5, C6, C7, C8 and T1.

The difficulties are greater at the level of the trunks and cords since the higher number of fascicles does not allow topographical identification and their small diameter precludes bringing them into precise position. Because of dissection risks and connective errors, it is preferable to concentrate nerve fibers in a precise segment and to avoid sutures at the level of the trunks and divisions, if possible.

From the surgical point of view, Narakas (1985) classified the five levels of the brachial plexus as follows (Fig. 1.5).

The injuries of the plexus at Level 1 and Level 2 were found to be supraclavicular lesions; those at Level 3, retroclavicular lesions; those at Levels 1, 2, 4 and 5, associated lesions; those at Level 4, distal plexus lesions; and those at Level 5, lesions of nerves at their origins.

Bonnel described the dissection of 100 brachial plexuses in adult subjects, examining the angular variations of roots in the spinal canal and cervical portions. Myelinated nerve fibers of the brachial plexus and terminal branches were counted as in Table 1.3. Serial histological sections were also performed to determine the fascicular organization. Based on his study, the angle between the root and medullary axis of the spinal cord, or the angle of emergence, increases as one moves down the spine. The average angles of emergence of roots of the brachial plexus are 143° for C5, 141° for C6, 140° for C7, 150° for C8, and 160° for T1. Participation of the adjacent C4 and T2 varies. In 41% of the plexuses studied, this participation occurred in the cervical region by branching of C4 to C5. In 4% of cases, an inferior cervical branching was found to merge with T1 from a division of T2. The results of such studies vary from author to author. For

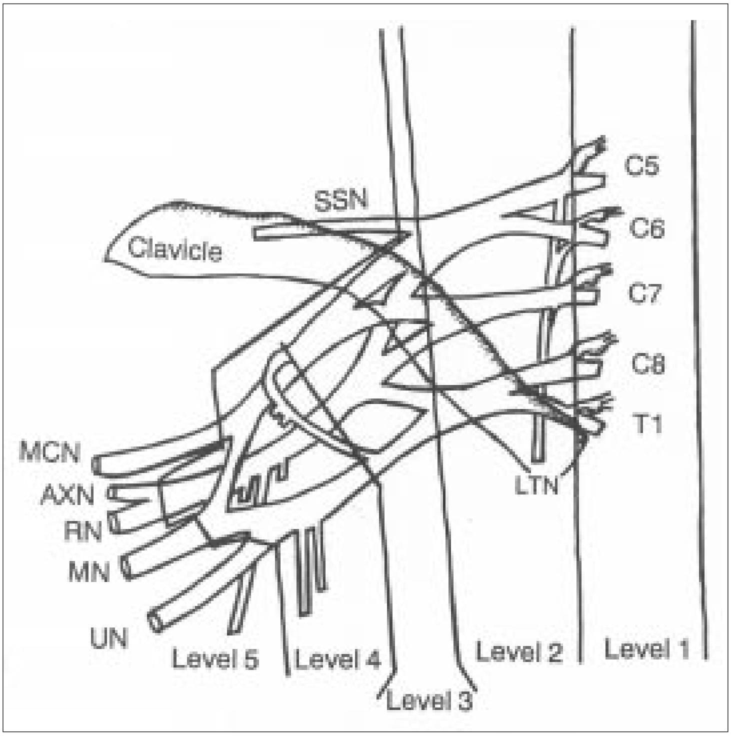

Fig. 1.5 From the surgical point of view, Narakas (1985) classified the brachial plexus into 5 Levels as follows.

Level 1. Avulsion of ventral and dorsal roots, i.e. separation of rootlets from the spinal cord. This can be partial, affecting the motor or sensory rootlets only, or involving some of each.

Level 2. (a) Lesions of the ventral ramus of the spinal nerves outside the intervertebral foramen are more common for the C5, C6 and C7 roots than for C8 or T1. In severe injuries, the C8 and T1 roots are mostly avulsed.
(b) Lesions of the trunks such as upper, middle or lower.

Level 3. Retroclavicular lesions which cause functional or anatomical interruption of the posterior cord, the lateral cord or both, but almost never of the medial cord.

Level 4. Lesions of the distal part of the cords.

Level 5. Lesions of the main nerves of the upper extremity close to their origins at the plexus, such as associated ruptures of the suprascapular, axillary and musculocutaneous nerves.

SSN, suprascapular nerve; MCN, musculocutaneous nerve; AXN, axillary nerve; RN, radial nerve; MN, median nerve; UN, ulnar nerve.

Table 1.3 Number of Myelinated Nerve Fibers in the Brachial Plexus

	Average (Range) by Bonnel (1984)
Brachila plexus (N = 21)	118 047 (85 566–166 214)
C5	16 472
C6	27 421
C7	23 781
C8	30 626
T1	19 747
Fibers serving the muscles of the scapular girdle	31 979
Musculocutaneous nerve	5023 (3465–9350)
Median nerve	15 915 (7457–27 190)
Ulnar nerve	14 161 (10 365–22 690)
Radial nerve	15 964 (10 029–32 210)
Axillary nerve	6547 (2073–12 711)

example, the participation of C4 was 28% for Jachimowicz, 62% for Kerr, and 35% for Senecail. T2 was included in the plexus from 73% for Adolphi and 16% for Ko Hirasawa.

Slingluff, Terzis and Edgerton offered consistent patterns in plexus organization to propose rules governing plexus microanatomy, despite its complexity and variability (Table 1.4). They defined a prefixed plexus as in Table 1.5. A postfixed plexus would be its converse.

Table 1.4 Laws of Plexus Organization Proposed by Slingluff, Terzis and Edgerton

1. Plexus anatomy and anomalies may be systematized on the basis of prefixation and postfixation.
2. Fascicular topography of the plexus is a summation of varied topographic arrangements of its elements.
3. Rules systematizing intraneural topography of the plexus are consistent with those governing the major nerves of the arm and forearm.
4. Fascicles supplying purely muscular or purely cutaneous branches are less common than mixed fascicles, but they may be found in certain regions near branch points or spinal nerves.
5. Connective tissue is more abundant than neural tissue throughout the plexus.

Table 1.5 Characteristics of a Prefixed Plexus Proposed by Slingluff, Terzis and Edgerton

Spinal nerves	C5 supplies over 15% of the plexus T1 supplies less than 13% of the plexus
Trunks	The upper trunk supplies over half of the posterior cord The lower trunk supplies less than 15% of the posterior cord The upper trunk supplies more than one third of the pectoral nerve supply The lower trunk supplies less than half of the median nerve The lower trunk supplies less than 25% of the radial nerve The upper trunk is larger than the lower trunk
Cords	The lateral cord does not receive a contribution from C8
Peripheral nerves	Less than 8% of the musculocutaneous nerve is supplied by C7 The ulnar nerve receives a contribution from C7

Slingluff, Terzis and Edgerton conclude that the microanatomy of the human brachial plexus, based on dissection of 21 brachial plexuses, including seven brachial plexuses serially-sectioned completely, is as follows.

Fascicle organization:

1. Fascicle sizes vary from 0.001 to 8 mm^2.
2. The number of fascicles at a given level may vary over a sixfold range from plexus to plexus, but most values are near the middle of the range.
3. Fascicle organization appears to vary less from right to left in the same individual than from individual to individual.
4. The number of fascicles at a given level is dependent both on the level and on the individual.
5. Monofascicularity is typical for the spinal nerves, the anterior and posterior divisions of the upper trunk, and the origins of the suprascapular and musculocutaneous nerves.
6. Bifascicularity is typical for the posterior division of the lower trunk.
7. F90 values, which is the minimum number of fascicles required to constitute at least 90% of the total neural tissue cross-sectional

areas of a given nerve or fascicle group, increase from a mean of 2.4 at the spinal nerve level to 7.4 at the trunk level and to 13.3 at the cord level (Fig. 1.6). The total number of fascicles increases from a mean of 8.0 to 24.6, and the range of fascicle sizes decreases, moving from proximal to distal.

8. A more generalized conclusion is that there is a local increase in fascicle numbers at all the joints of the upper extremity.

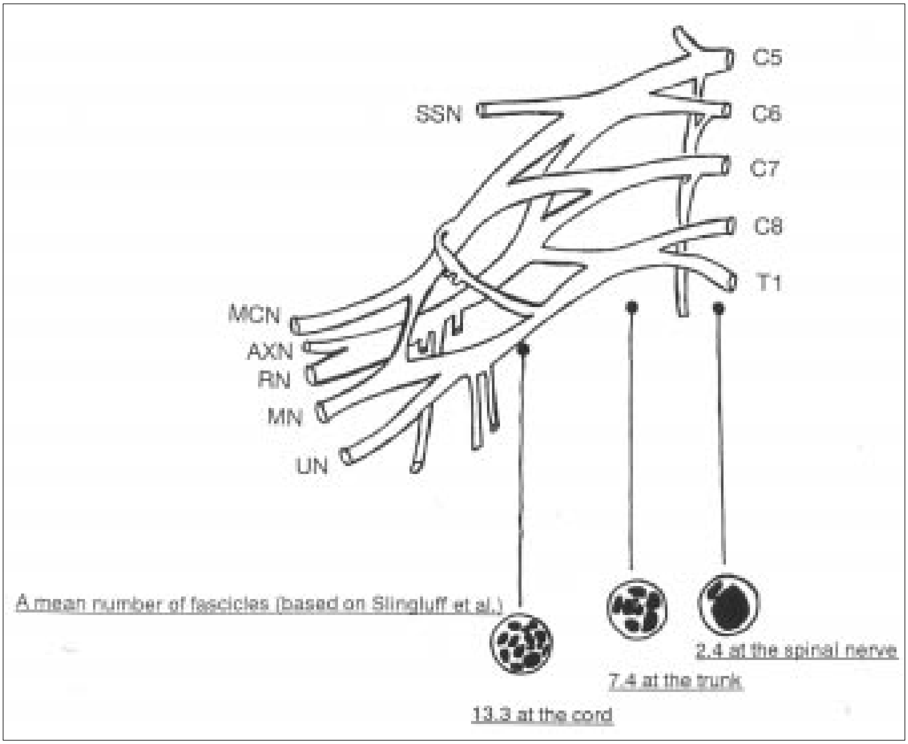

Fig. 1.6 The number of fascicles increases from a mean of 2.4 at the spinal nerve level to 7.4 at the trunk level and to 13.3 at the cord level. SSN, suprascapular nerve; MCN, musculocutaneous nerve; AXN, axillary nerve; RN, radial nerve; MN, median nerve; UN, ulnar nerve.
(From Slingluff CL Jr *et al.*: The quantitative microanatomy of the brachial plexus in man: reconstructive relevance. In Terzis JA (ed.): *Microreconstruction of Nerve Injuries*. Philadelphia, WB Saunders, pp. 285–324, 1987.)

Fascicle topography:

1. The average distance a fascicle travels without merging or branching is 5 mm. Rarely, a fascicle will travel over 1 cm without interaction.
2. The elements of the brachial plexus have a plexiform intraneural topography.
3. Fortuitous branching occurs.

Branches:

1. Fascicle groups can be traced proximally an average of 1.1 cm from the point of exit to the point of segregation from the rest of the plexus element; 1.5 cm to the level of purity; and 2.5 cm to the level of localization.
2. Fascicle groups of branches generally assumed the same cross-sectional localization in different plexus specimens.

Quantitation of neural tissue:

1. C6, C7 and C8 consistently contribute to 24% of the plexus neural tissue each, whereas C5 and T1 vary remarkably in an inverse fashion to supply the remaining 28% of the plexus neural tissue.
2. The motor supply to the shoulder girdle receives 28.2% of the plexus neural tissue and the cutaneous supply, 1.6%; therefore, the shoulder receives 30% of the plexus neural tissue.
3. 22% of the plexus neural tissue supplies the median nerve.
4. 21% supplies the radial nerve.
5. 14% supplies the ulnar nerve.
6. 8% supplies the musculocutaneous nerve.
7. 4% supplies the medial cutaneous nerves.

Distribution of neural tissue:

1. There are several "gray zones", i.e. plexus regions where little or no localization of fascicle groups can be made because of mixing. Although gradual both proximal and distal to these regions, it appears extensive in these gray zones because of a

summation of this gradual mixing over distance. These zones are: (a) the upper trunk at the formation of the divisions and the origin of the suprascapular nerve; (b) the lower trunk as it forms the medial cord; and (c) the posterior cord between the posterior divisions and the axillary nerve origin. The monofascicular character of all the elements entering the upper trunk (C5, C6, anterior division, posterior division, and suprascapular nerve) often renders impossible the task of differentiating subset fascicle groups.

2. The upper trunk supplies approximately 50% of the posterior cord; T1 supplies less than 10% in all individuals and less than 5% in most persons.
3. C8 may supply as much as 38% of the lateral cord in postfixed plexuses.
4. C7 may supply at least 10 to 15% of the musculocutaneous nerve, although it usually supplies less than 10% and mostly tends to supply the coracobrachialis nerve.
5. C6 is the primary contributor to the long thoracic nerve in most individuals.
6. C5 and C6 together supply only about 15% of the median nerve on average. C7 supplies about 35%, and C8 and T1 supply about 25% each.
7. T1 supplies most of the medial cutaneous nerves as well as the intercostobrachial nerve, but C8 often contributes to these nerves.
8. Nerve supply to the subscapularis muscle is from C5, C6 and C7, with the upper trunk usually supplying 100% of the first subscapular branch.
9. The thoracodorsal nerve may in some cases have no upper trunk supply, but its spinal nerve origins are variable and confused by substantial mixing.
10. At least 40% of the ulnar nerve was supplied by C8 in most cases, the average proportion of ulnar neural tissue supplied by C8 being between 31.7 and 81.7%.

Percentage of neural tissue:

1. 32% of the plexus consists of neural tissue, the remainder being connective tissue.

Anomalies of the plexus:

1. Anomalous C8 contributions to the lateral cord correlated well with the size of C5.
2. Anastomoses between the musculocutaneous and median nerves were observed in 24% of cases, and such anastomoses were one-third the size of the musculocutaneous nerve.
3. Anastomoses between the anterior and posterior elements of the plexus are unusual and small, but may exist.

Based on Narakas's schema, there are two distinct groups of funiculi: the ones for the posterior cord and the others for the lateral and medial cord with some fascicles in-between for proximal individual nerves such as the suprascapular or those for the pectoral muscles (Fig. 1.7). In the C5 nerve, the funiculus of the suprascapular nerve was located anterocranially; funiculi containing the musculocutaneous nerve, anterocaudally; and those containing the axillary nerve, posterocaudally (Yokoyama). The intraneural topography of the fascicles from the trunk and cord to the peripheral nerves was found to have guess work in part as follows (Alnot, Narakas and Yokoyama).

Upper trunk: suprascapular nerve was located cranially; musculocutaneous nerve and median nerve, anterocaudally; and axillary nerve and radial nerve, posteriorly.

Middle trunk: radial nerve was located posterocranially and median nerve anterocaudally.

Lower trunk: median nerve was located anteriorly; radial nerve, posterocranially; and ulnar nerve, caudally.

Lateral cord: musculocutaneous nerve was located cranially and median nerve caudally.

Posterior cord: axillary nerve was located cranially; and subscapular nerve, thoracodorsal nerve and radial nerve, caudally.

Medial cord: median nerve was located cranially and ulnar nerve caudally.

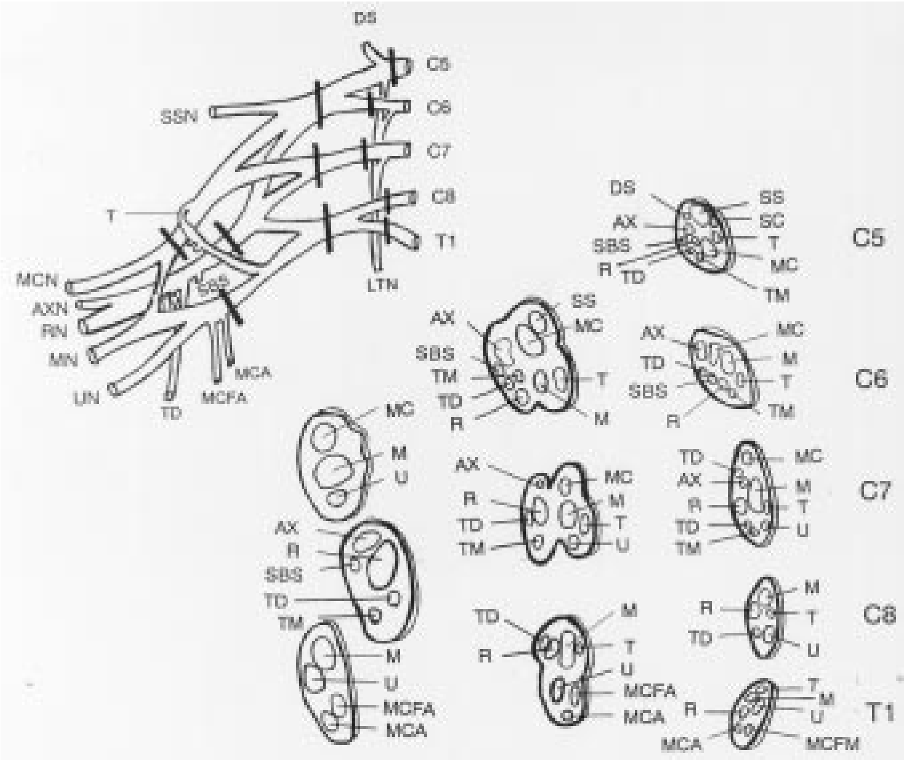

Fig. 1.7 The gross funicular distribution in a normal brachial plexus based on Narakas (Reproduced with permission from Narakas A: Surgical treatment of traction injuries of the brachial plexus. *Clin Orthop* **133**: 81, 1978). This map is based on several microscopic dissections on fresh human cadavers to identify the anterior and posterior groups as a guess-work in part. The funiculi are labeled as follows: AX, axillary nerve; DS, dorsal scapular nerve; LTN, long thoracic nerve; M, median nerve; MC, musculocutaneous nerve; MCA, medial cutaneous nerve of arm; MCFA, medial cutaneous nerve of forearm; R, radial nerve; SBS, subscapularis nerve; SC, subclavius nerve; SS, suprascapular nerve; T, thoracic nerve; TD, thoracodorsal nerve; TM, teres major nerve; U, ulnar nerve.

THE MUSCULOCUTANEOUS NERVE

Murase and Kawai examined 25 musculocutaneous nerves from 14 embalmed cadavers and dissected them to the level of the fascicles under an operating microscope (Fig. 1.8). The funicular patterns were studied at each level. The levels of branching and neuromuscular junctions were measured from the coracoid process level (Fig. 1.9).

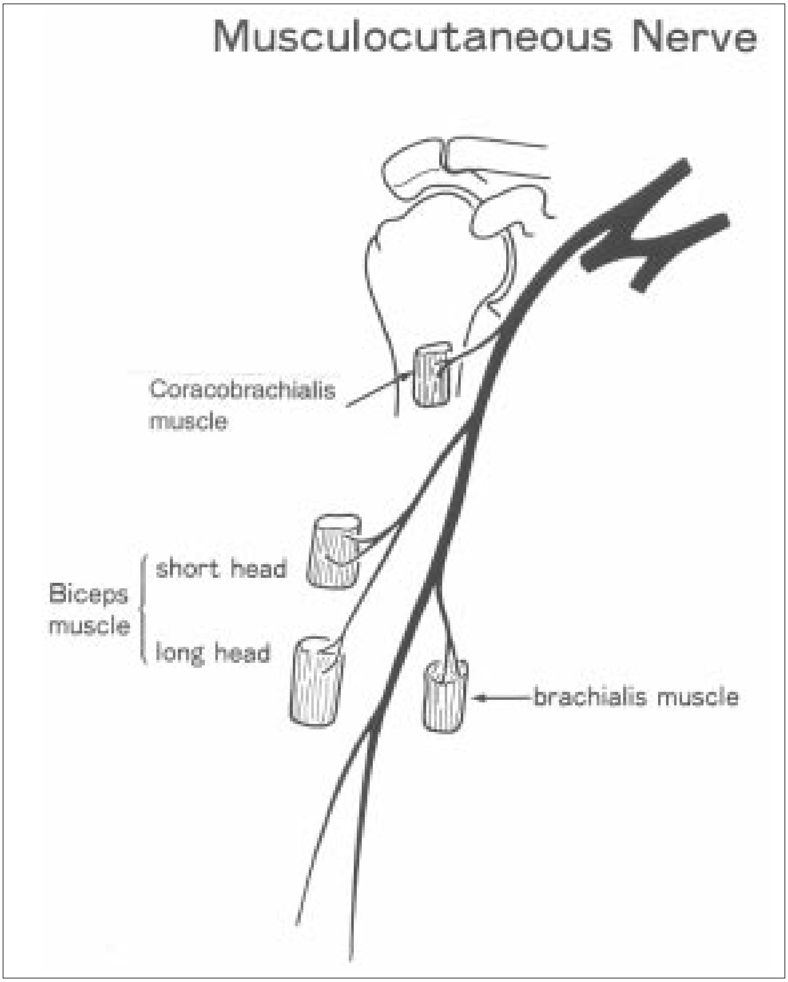

Fig. 1.8 Illustration of the musculocutaneous nerve.

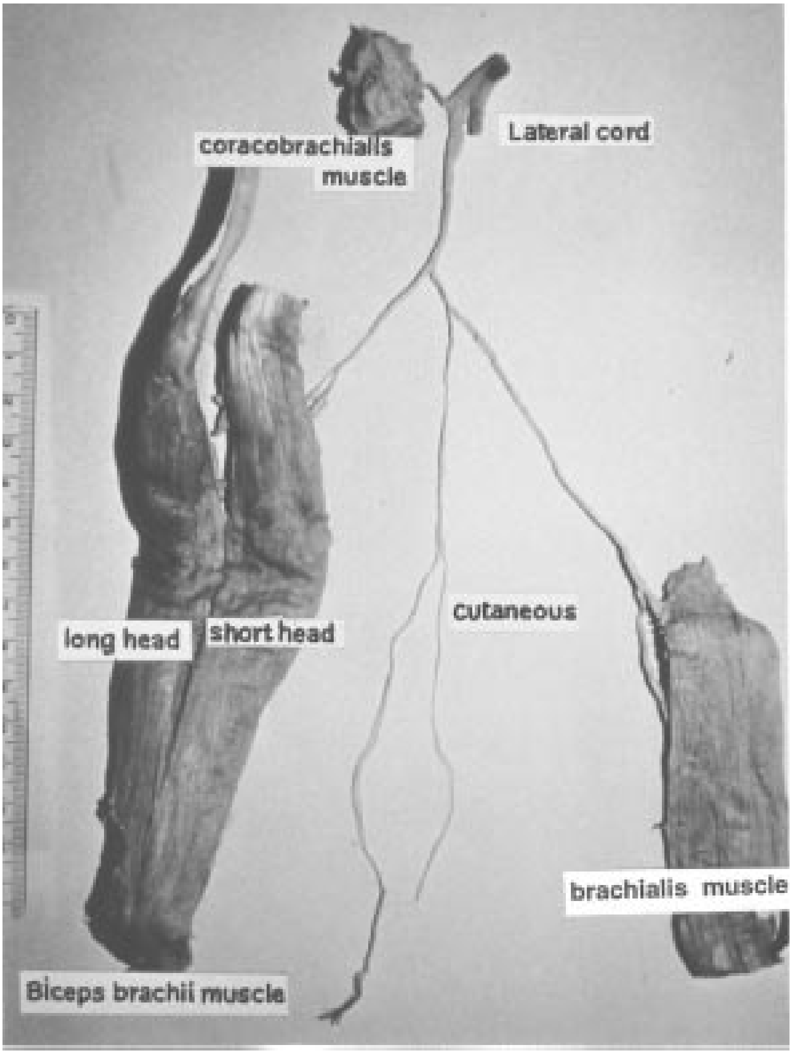

Fig. 1.9 The musculocutaneous nerve and its innervated muscles taken from an embalmed cadaver.

The musculocutaneous nerve leaves the lateral cord at a level 0.3 cm distal to the coracoid process level, and sends the branch to the coracobrachialis muscle at a level 0.5 cm distally, then runs between the long and short heads of the biceps, branching to the biceps at a level 7 cm distally from the coracoid process, and finally branches to the brachialis at a level of 11.2 cm. The motor point of the biceps from the coracoid process level was 11.7 cm for the short head, and 13.7 cm for the long head of the biceps (Fig. 1.10). At a level of

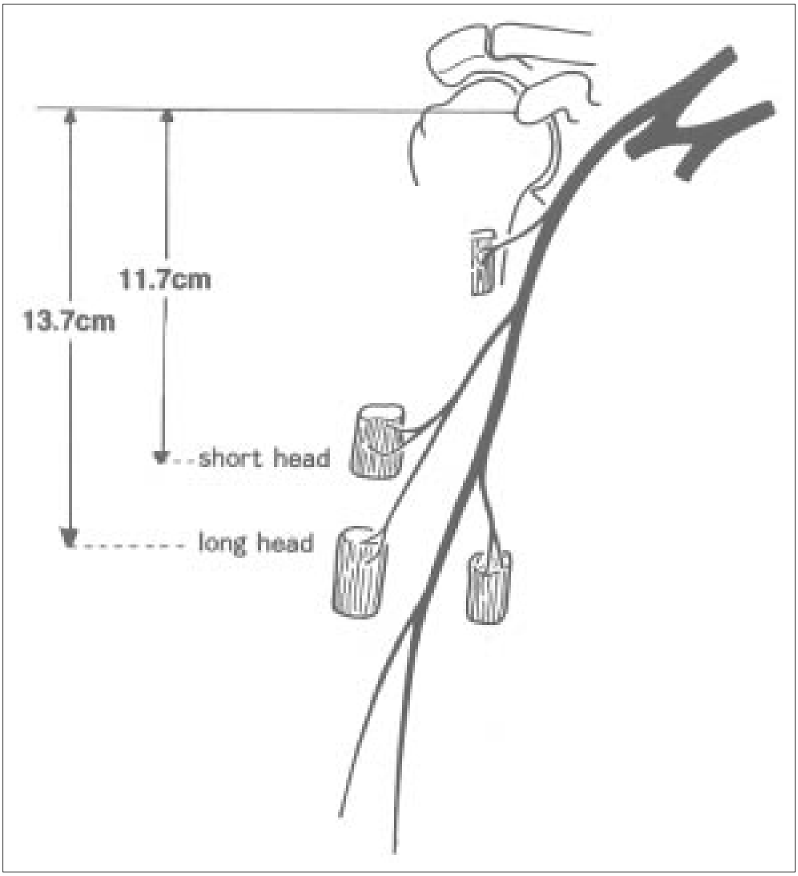

Fig. 1.10 The motor point of the biceps brachii muscle (short head and long head) of the musculocutaneous nerve measured from the coracoid process.

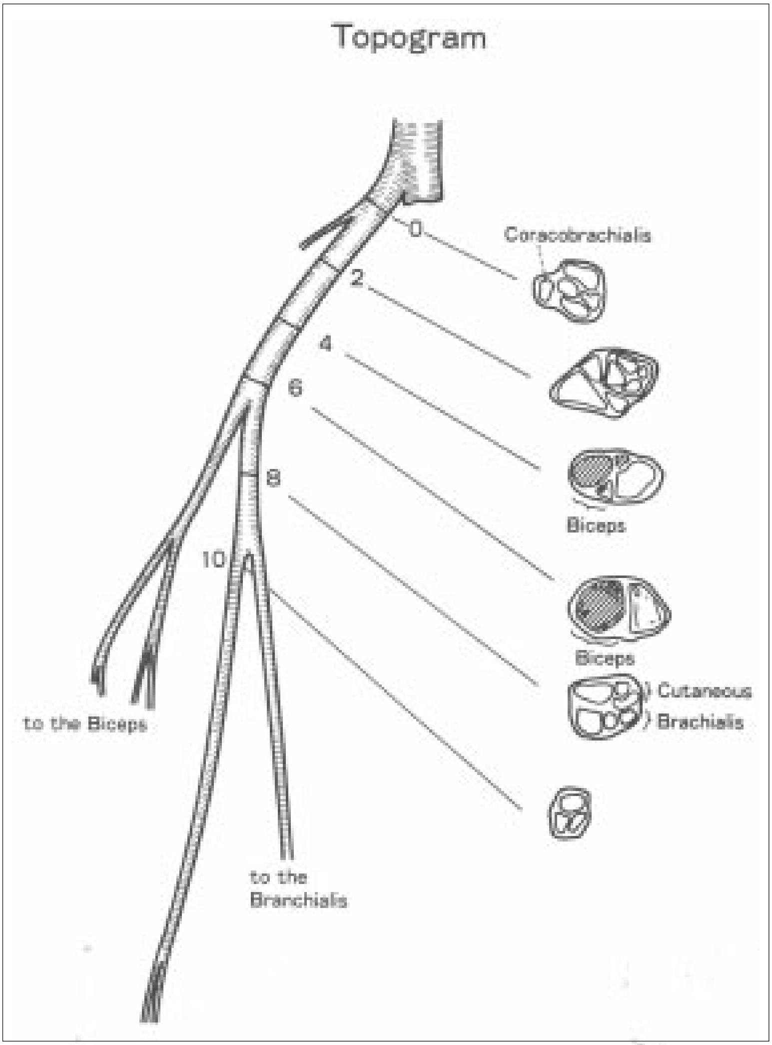

Fig. 1.11 Topogram of the musculocutaneous nerve.

4.8 cm from the coracoid, the funicles to the brachialis and a cutaneous nerve were located medially, while the funicles to the biceps were located laterally in 12 (80%) out of 15 cases. However, topographical identification is next to impossible in the more proximal segment (Fig. 1.11). In the case of the intercostal nerve transfer to the musculocutaneous nerve, the first muscle contraction of the biceps brachii muscle develops around 5 or 6 months after operation (Fig. 1.12). This is evidence that the length from the cross-nerve suture point to the motor point of the biceps is about 12 cm where the nerve regenerates 1 mm / day, or that the nerve regeneration takes 4 months to reach the motor point of the biceps. Moreover, a further 1 or 2 months are needed for clinical muscle contraction to be achieved.

The musculocutaneous nerve is in part connected to the median nerve in 5 (20%) out of 25 limbs. Slingluff *et al.* also found that the musculocutaneous nerve sent a branch to the median nerve in a proximodistal direction. In no case was there tranfer from the median to the musculocutaneous nerve for the three specimens.

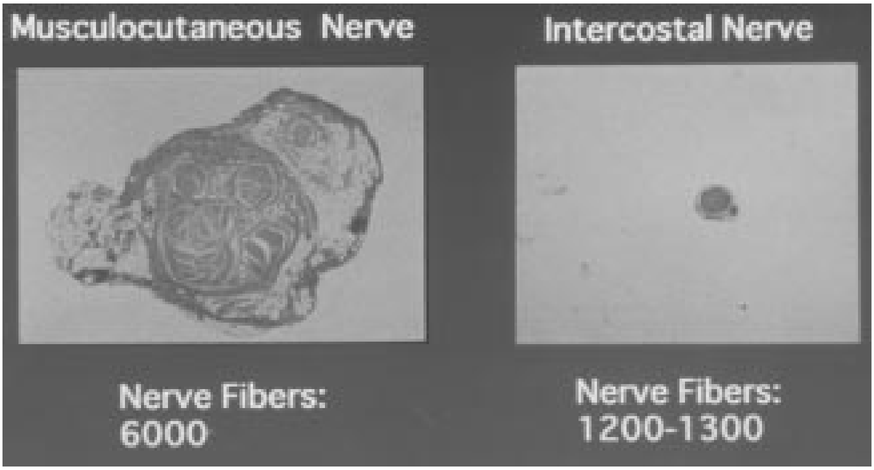

Fig. 1.12 The cut surface of the musculocutaneous nerve and intercostal nerve. The musculocutaneous nerve has 6000 myelinated nerve fibers, whereas the intercostal nerve has one-fifth of the musculocutaneous nerve fibers.

SYMPATHETIC CONTRIBUTION TO THE ROOTS OF THE BRACHIAL PLEXUS

All the roots of the plexus carried post-ganglionic sympathetic fibers to the periphery. Sunderland and Bedbrook (1949) investigated the sympathetic contribution to each nerve root, based on the cross-sectional areas of the sympathetic rami. The relative percentage contribution of sympathetic fibers to each individual root of the plexus varied. The C5 and C6 nerves received single or multiple gray rami from the middle cervical ganglion, or the superior cervical and stellate ganglion, and/or the intervening sympathetic trunk. Indirectly those nerves received from the stellate ganglion by way of the plexus which accompanied the vertebral artery cranially. This stellate ganglion is considered appropriate for the combined ganglia, inferior cervical and first thoracic sympathetic ganglia. C5 had the fewer post-ganglionic fibers (1 to 9%), C6 (8 to 27%) and C7 (15 to 25%). C7 received one to three grey rami from the stellate ganglion and, in most cases, additional fibers from the vertebral plexus. There were more post-ganglionic fibers in C8 (25 to 45%) and T1 (15 to 30%). The C8 and T1 roots received post-ganglionic fibers from the stellate ganglion and the communication which T2 nerve may send to T1.

VASCULAR SUPPLY OF THE BRACHIAL PLEXUS

The main vascular supply of the brachial plexus is from three main branches: deep cervical arteries that arise from the subclavian artery for cervical nerves from C5 to T1, the scapular posterior artery for the upper and middle trunks, and branches arising directly from the subclavian artery. Branches arising from the transverse cervical artery or the axillary artery also participate in the vascularization of the medial and lateral cords. The microvascular architecture of the brachial plexus in five Japanese monkeys was investigated (Dohno *et al.* 1996). Segmental arterioles were observed in the brachial plexus, whereas hypovascular area was found in the brachial plexus, especially behind the clavicle. The extrafascicular capillary networks were few, whereas the intrafascicular capillaries were anastomosed with each other in that region. The brachial plexus has a greater tendency to be susceptible to ischemia with stretch and compression injuries compared with the peripheral nerves and spinal roots. In the peripheral nerves, the fascicles are vascularized segmentally by epineural vessels, and each fascicle presents a well-defined fascicular vascular organization composed of endoneurial and perineurial microvascular systems in combinations (Lundborg 1979).

REFERENCES

Adolphi H. Über das Verhalten der zweiten Brustnerven zum plexus brachialis beim Menschen, *Anat Anz* **XV**: 25–36, 1898.

Agostini C. Sulla Composizion del Plesso Brachiale e Sulle Origine dei Suo Rami Terminali, Pergui Vinzenzo, Santucci, 1887.

Alnot JY and Huten B. La systématisation du plexus brachiale, R*ev Chir Orthop* **63**: 27–34, 1977.

Billet H. *Les Troncs Primaires du Plexus Brachial*, CR Assoc Anat Lisbonne, pp. 32–63, 1933.

Bonnel F. Microscopic anatomy of the adult human brachial plexus: An anatomical and histological basis for microsurgery, *Microsurgery* **5**: 107–117, 1984.

Dohno H, Tamai K, Hirasawa Y, Okada N and Ohta Y. Microvascular pattern of brachial plexus in monkey, *Kotsu Kansetsu Jintai* **9**: 183–188, 1996 (in Japanese).

Flatow EL, Bigliani LU and April EW. An anatomic study of the musculocutaneous nerve and its relationship to the coracoid process, *Clin Orthop* **224**: 166–171, 1989.

Herringham H. The minute anatomy of the brachial plexus, *Proc R Soc Lond* **249**(XII): 423–441, 1886.

Jachimowicz J. Les variation du plexus brachial(résumé). Traduit par E. Loth. Mem Anat A Univ Varsoviensis, pp. 246–282, 1925.

Kerr, AT. Brachial plexus of nerves in man. The variations in its formation and branches, *Am J Anat* **23**: 285–395, 1918.

Ko Hirasawa. Über den Plexus Brachialis Mitterlung die Wurzeln des Plexus Brachial, Impressio séparata ex actis Scholac Medicinalis, Universitatis Imperialis Kiotoensis, 1928.

Lundborg G. The intrinsic vascularization of human peripheral nerves: Structural and functional aspects, *J Hand Surg* **4**: 34–41, 1979.

Moura WG. Surgical anatomy of the musculocutaneous nerve: A photographic essay, *J Reconstr Microsurg* **1**: 291–297, 1985.

Murase T and Kawai H. Microsurgical anatomy of the musculocutaneous nerve, *J Jpn SRM* **5**: 15–20, 1992.

Narakas A. Symposium on brachial plexus function and surgery, *Peripheral Nerve Repair and Regeneration* **1**: 59–68, 1986.

Narakas AO. Surgical treatment of traction injuries of the brachial plexus, *Clin Orthop* **133**: 71–90, 1978.

Narakas AO. The treatment of brachial plexus injuries, *International Orthopaedics* **9**: 29–36, 1985.

Seddon SH. Lesions of individual nerves: Upper limb. In: Seddon SH, ed., *Surgical Disorders of the Peripheral Nerves*, 2nd ed. Churchill Livingstone, Edinburgh, pp. 172–231, 1975.

Senecail B. Le plexus brachial de l'Homme, *These Reims* **66**, 1975.

Slingluff CL Jr, Terzis JK and Edgerton MT. The quantitative microanatomy of the brachial plexus in man: Reconstructive relevance, In: Terzis JA, ed., *Microreconstruction of Nerve Injuries*. WB Saunders, Philadelphia, pp. 285–324, 1987.

Sunderland S, Marshall RD and Swaney WE. The intraneural topography of the circumflex, musculocutaneous and obturator nerves, *Brain* **82**: 116–129, 1959.

Sunderland SS. The Brachial Plexus. Normal anatomy, In: Sunderland SS, ed., *Nerves and Nerve Injuries*. Churchill Livingstone, Edinburgh, pp. 854–869, 1978.

Tamura K. The funicular pattern of Japanese peripheral nerve, *Arch Jap Chir* **38**: 35–58, 1969.

Testut L. Recherchés anatomiques sur l'anastomosé du nerf musculocutané avec le médian, *J Anat Physiol* **19**: 103, 1883.

Yokoyama I. Study on the intraneural topography of the brachial plexus, *J Jpn Orthop Assoc* **63**: 1085–1102, 1989.

Yokoyama I, Matsuda H, Hashimoto T, Kureya S and Shimazu A. Intraneural topography of the brachial plexus — Microscopic dissection in human cadavers, *J Jpn Soc Surg Hand* **3**: 138–145, 1986.